UQAR
Université du Québec
à Rimouski

MODÉLISATION, CONTRÔLE DE VITESSE ET OPTIMISATION D'UN GÉNÉRATEUR DIESEL AVEC STATOR ROTATIF

Thèse présentée
dans le cadre du programme de doctorat en ingénierie

en vue de l'obtention du grade de Philosophiæ doctor

PAR

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Novembre 2020

Université du Québec
à Rimouski

MODELING, SPEED CONTROL, AND OPTIMIZATION OF A DIESEL GENERATOR SET WITH ROTATING STATOR

A Thesis presented to the
Université du Québec à Rimouski

In partial fulfillment of the requirements
for the degree of Doctor of Philosophy Ph.D.

By
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November 2020

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First draft submitted on September 16, 2020 Final submission on November 18 2020

To my love Farzaneh, who has been a constant source of support and encouragement during the challenges of graduate school and life. I am truly thankful for having you in my life.

DEDICATION AND GRATITUDE

I dedicate my dissertation work to my family and many friends. A special feeling of gratitude to my loving parents, Hassan and Azar whose words of encouragement and push for tenacity ring in my ears. My sisters Rozita, Raheleh, and my brother Payam have never left my side and are very special.

Special thanks to my French tutor, Nathalie Landreville for her indefatigable efforts during previous years. Without her encouragement, it was impossible for me to be adapted rapidly to the French language society and finding amazing friends.

I will always appreciate Lynda Larrivée who has supported me throughout the project from the very early days of my land at the city of Rimouski. I am truly grateful of your warm hospitality, support and guidance.

ACKNOWLEDGMENTS

And since dissertations can be written about everything under the sun, the number of topics is infinite. Sheets of papers covered with words pile up in archives sadder than cemeteries[...]

–M. Kundera, The unbearable lightness of being, 1984

It has been quite a long journey since I have started my Ph.D. career and I am very lucky to meet, live, learn, and enjoy my time with my caring friends and esteemed professors. Initially, earnest thanks to Université du Québec à Rimouski (UQAR) and Wind Energy Research Laboratory (LREE) for providing me an opportunity and financial support respectively during my Ph.D. study.

This project could not have been carried out without the support of many people to whom I wish to express my gratitude for having accompanied me during this period and whom I would like to thank for their support and for being actively involved in the development of this thesis work.

Firstly, I would like to express my sincere gratitude to my research supervisor and the director of LREE, Professor Adrian Ilinca for the continuous support of my Ph.D. study and related research, for his patience, motivation, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis. I am always grateful for his kind guidance, valuable contribution, and devoted support throughout this work.

Apart from my supervisor, I am pleased to express the gratitude to the rest of the team: Dr. Miloud Rezkallah from École de Technologie Supérieure and Dr. Mohamad Yasser Hayyani for giving the encouragement and sharing insightful suggestions. They all have played a major role in polishing my research writing skills. Their endless guidance is hard to forget throughout my life.

Thank you to all the technical support staff for assistance on the test facilities and instrumentation. These include Bruno Tremblay, Mohamad Issa, Ali Awada and the president of Genset-Synchro company Jean Fiset.

Finally, I thank my fellow labmates in the department of computer science and engineering for the stimulating discussions, for the sleepless nights we were working together before deadlines, and for all the fun we have had in the last four years. It was a pleasure to work with you.

Mohammadjavad Mobarra

Université du Québec à Rimouski, September 2020

RÉSUMÉ

Les groupes électrogènes à moteur diesel constituent un élément important dans un large éventail d'applications de production d'énergie électrique distribuée dans le monde entier. En raison de leur haute fiabilité et de leur faible coût, les groupes électrogènes à moteur diesel restent le choix préféré lorsque l'infrastructure électrique est faible ou nécessite une sauvegarde des applications de sécurité, telles que les hôpitaux, aux applications provisoires d'établissement de réseau et d'extension. Les groupes électrogènes à moteur diesel sont soumis à des exigences croissantes en termes d'efficacité et de performances, mais en même temps, ils doivent être faciles à mettre en service et résistants aux perturbations. De plus, les génératrices diesel (GD) sont configurés pour fonctionner comme source d'énergie de secours lors des pannes de courant ou pour supporter la charge dans les zones éloignées, non connectées au réseau national. La plupart du temps, ces DG fonctionnent à vitesse constante pour produire un courant alternatif fiable, tandis que la demande d'énergie électrique fluctue en fonction des besoins instantanés. Dans les régions éloignées, les charges électriques élevées ne se produisent que pendant quelques heures par jour, ce qui entraîne un surdimensionnement des DG. Lors d'une opération à faible charge, les DG sont confrontés à une faible efficacité énergétique et à la condensation des résidus de carburant sur les parois des cylindres du moteur, ce qui augmente la friction et l'usure prématurée. Lorsque la puissance de charge diminue, une réduction du couple mécanique et de la vitesse de rotation du moteur diesel maintiendra l'efficacité de la combustion près des niveaux du régime nominal. Par conséquent, le générateur lui-même devrait fonctionner à une vitesse variable qui nécessite normalement des convertisseurs d'électronique de puissance. Une solution pour augmenter l'efficacité de la combustion à faibles charges électriques est de réduire le régime du moteur diesel (MD) à son régime idéal en fonction du couple mécanique requis par le générateur électrique. Par conséquent, les génératrices diesel à vitesse variable (GDVS) permettent le fonctionnement du MD à une vitesse optimale en fonction de la charge électrique, mais nécessitent un équipement électrique et un contrôle supplémentaire pour maintenir la puissance de sortie aux normes électriques. Afin de réduire les difficultés ci-dessus, l'industrie concentre actuellement son attention sur la mise en œuvre de techniques de contrôle plus sophistiquées. À la lumière de cela, la présente thèse aborde les deux solutions principales suivantes concernant la commande du groupe électrogène à MD. Premièrement, nous explorons un nouveau concept de générateur qui utilise un stator tournant en sens inverse du rotor, comme la vitesse relative entre les deux composants reste constante lorsque le MD ralentit. Le stator lui-même est entraîné par un moteur synchrone compensateur (CM) ou la vitesse relative du rotor est constante, éliminant ainsi l'utilisation des convertisseurs de puissance. Le modèle développé pour la machine synchrone à stator tournant est basé sur la transformation de Park. Ce nouveau concept a été modélisé à l'aide de l'environnement MATLAB/Simulink. Une validation expérimentale a été réalisée à l'aide d'un groupe électrogène diesel de 500 kW équipé d'un générateur synchrone à aimant permanent (PMSG). Les résultats numériques et expérimentaux sont satisfaisants et démontrent que la consommation de carburant est réduite avec un stator à mode rotatif pour PMSG lors de faibles charges électriques.

Deuxièmement, la recherche porte sur le contrôle du moteur compensateur entraînant le stator du générateur à l'aide d'un variateur de fréquence par l'adaptation de la vitesse à sa valeur optimale en fonction de la variation de la charge électrique. Les performances de la stratégie de contrôle proposée ont été testées à l'aide d'une carte à microcontrôleur Freescale programmée en code C pour déterminer la tension appropriée pour le variateur de fréquence. L'algorithme de contrôle utilise une application en temps réel implémentée sur une carte processeur de signal FDRM-KL25Z. Les performances de contrôle d'un moteur asynchrone de 2 kW (LabVolt EMS 8503-00 / 208 V / 3 φ / 60 (50) Hz) ont été démontrées expérimentalement dans la présence des différentes conditions de fonctionnement.

Mots-clés: Des génératrices diesels, Stator rotatif, Efficacité énergétique, Impacts environnementaux, Régime de faible charge, Optimisation du carburant, Entraînement à fréquence variable, Algorithme de contrôle de la vitesse du moteur, Processeur de signal numérique

ABSTRACT

Diesel-driven generator sets constitute an important element in a broad spectrum of distributed electrical power generation applications worldwide. Due to their high reliability and low cost, diesel-driven generator sets continue to be the preferred choice whenever the power infrastructure is weak or requires backup from failsafe applications, such as hospitals, to interim mains establishment and expansion applications. Diesel-driven generator sets are subject to increasing demands regarding efficiency and performance, yet at the same time, they must be easy to commission and robust to disturbances. In addition, diesel generators (DGs) are set to work as a backup during power outages or to support the load in remote areas which are not connected to the national grid. Most of the time, DGs are working at a constant speed to produce reliable AC power, while electrical energy demand is fluctuating according to instantaneous power. In remote areas, high electric loads occur only during a few hours a day, which results in oversizing of DGs. During a low load operation, DGs are facing poor fuel efficiency and condensation of fuel residues on the walls of engine cylinders that increase friction and premature wear. When load power demand decreases, a reduction in both mechanical torque and rotational speed of the diesel engine will maintain the combustion efficiency near the levels of the nominal regime. Accordingly, the generator itself should operate at a variable speed, which normally requires power electronics converters. One solution to increase combustion efficiency at low electric loads is to reduce diesel engine (DE) speed to its ideal regime according to the mechanical torque required by the electrical generator. Therefore, Variable Speed Diesel Generators (VSDGs) allow the operation of the diesel engine at optimal speed according to the electrical load. This solution, require additional electrical equipment and control to maintain the power output to electrical standards. In order to reduce the above difficulties, the industry is currently directing its attention to the implementation of more sophisticated control techniques. In light of this, the present thesis addresses the following two main sections in relation to diesel-driven generator set control.

First, we are exploring a new generator concept that uses a stator rotating in opposite direction to the rotor such as the relative velocity between the two components remains constant when diesel engine slows down. The stator itself is driven by a compensator synchronous motor (CM) such as the relative velocity of the rotor is constant, eliminating as such sophisticated power electronics. The model developed for the synchronous machine with a rotating stator is based on Park's transformation. This new concept was modeled using MATLAB/Simulink software. Experimental analysis has been conducted using a 500-kW diesel Genset equipped with a permanent magnet synchronous generator (PMSG). The numerical and experimental results are in good agreement and demonstrate that fuel consumption is reduced with a rotating-mode stator for PMSG while supplying low electrical loads.

Second, the research addresses the control of the compensator motor driving the generator's stator using a variable-frequency drive that adapts the speed to its optimal value according to the electrical load power demand. The performance of the proposed control strategy was tested using a Freescale microcontroller card programmed in C-code to determine the appropriate voltage for the variable-frequency drive. The control algorithm uses a real-time application implemented on an FDRM-KL25Z signal processor board. The control performance of a 2-kW asynchronous motor (LabVolt EMS 8503-00/208 V/3 φ/60(50) Hz) was demonstrated experimentally at different operating conditions.

Keywords: Variable speed diesel generator, Rotating stator, Energy efficiency, Environmental impacts, Low load regime, Fuel optimization, Variable frequency drive, Motor speed control algorithm, Digital signal processor

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LIST OF ABBREVIATIONS

AC	Alternating Current.
ADC	Analog to Digital Card.
AVR	Automatic Voltage Regulator.
BESS	Battery Energy Storage System.
BSFC	Brake-Specific Fuel Consumption.
BTU	British Thermal Unit.
CM	Compensator Motor.
CO	Carbon Monoxide.
CO_2	Carbon Dioxide.
CVT	Continuously Variable Transmission.
DC	Direct Current.
DE	Diesel Engine.
DFIG	Doubly-Fed Induction Generator.
DG	Diesel Generator, the combination of a Diesel Engine with a Power Generator.
DPC	Direct Power Control.
DQ	Direct Quadrature.
DSM	Demand Side Management.

DTC	Direct Torque Control.
DSP	Digital Signal Processor.
FOC	Field Oriented Control.
FSDG	Fixed Speed Diesel Generator.
GENSET	Diesel Generator, the combination of a Diesel Engine with a Power Generator.
GHG	Greenhouse Gases.
GSC	Grid Side Converter.
ICE	Internal Combustion Engine.
IGBT	Insulated-Gate Bipolar Transistor.
ISO	International Organization for Standardization.
LCA	Life Cycle Analysis.
NO_X	Nitrogen Oxides.
O&M	Operation and Maintenance.
PCC	Point of Common Coupling.
PMSG	Permanent Magnet Synchronous Generator.
PV	Photovoltaic.
PWM	Pulse Width Modulation.
R/C	Resistor/Capacitor.
RIC	Reciprocating Internal Combustion.
rpm	Revolutions Per Minute.

RSC	Rotor Side Converter.
RSDG	Rotating-Stator Diesel Generator.
SC	Super Capacitor.
SCDG	Super-capacitor Diesel Generator.
SFC	Specific Fuel Consumption.
SG	Synchronous Generator.
SMC	Sliding Mode Control.
SOC	State of Charge.
SSC	Stator Side Converter.
SSM	Supply Side Management.
SVM	Space Vector Modulation.
THD	Total Harmonic Distortion.
VFD	Variable Frequency Drive.
VSDG	Variable Speed Diesel Generator.
WRIG	Wound-Rotor Induction Generator.

LIST OF SYMBOLS

P	Active power
Q	Reactive power
$\boldsymbol{V_f}$	Field voltage
$\boldsymbol{\omega_{ref}}$	Electric angular velocity
$\boldsymbol{\varphi}$	Magnetic flux
$\boldsymbol{\lambda}$	Flux leakage
$\boldsymbol{r_r}$	Rotor resistance
$\boldsymbol{r_s}$	Stator resistance
$\boldsymbol{L_s}$	Stator inductance
$\boldsymbol{L_r}$	Rotor inductance
$\boldsymbol{L_{sr}}$	Mutual inductance between rotor and stator windings
$\boldsymbol{K_d}$	Damper winding on d-axis
$\boldsymbol{K_{q1}}$,$\boldsymbol{K_{q2}}$	Damper windings on q-axis
$\boldsymbol{\theta_r}$	Rotor electric angle
$\boldsymbol{P_{Gen}}$	Genset produced power
$\boldsymbol{N_{Gen}}$	Number of generators

η_{Gen}	Generator efficiency
P_{η}	Nominal power
$n_{Synch\,(T)}$	Total synchronous speed
n_r, n_s	Rotor and stator speed respectively
N_s, N_r	Number of stator and rotor windings respectively
f_d	Field winding represents on d-axis
f_q	Field winding represents on q-axis
λ_{abcs}	Three-phase stator flux
λ_{qdr}	Rotor flux represents on dq-axis
x_d, x_q	d and q axis reactance
P_{g0}, P_{g1}	Load power
U_{g0}	Load voltage
τ_m	Mechanical torque
τ_e	Electrical torque
τ_{mT}	Total mechanical torque

GENERAL INTRODUCTION

There are currently 292 remote communities with a total population of approximately 194,281 people (2016 Statistics Canada Census) in Canada. These communities include Aboriginal and non-Aboriginal settlements, villages, or cities as well as long-term commercial outposts and camps for mining, fishing, and forestry activities.

Of these, 170 sites are identified as aboriginal communities (First Nations, Innu, Inuit, or Métis), with approximately 126,861 people living in these sites [1]. The remaining 122 communities are cities, villages, or commercial outposts that are predominately non-aboriginals or under non-aboriginal governments, with approximately 67,420 people living in them.

Over the past twenty-five years, the number of remote communities has decreased from 380 to 292, primarily as a result of grid extension and abandonment of communities due to relocation to larger villages or cities. The overall population from the 2016 census shows that there are just over 195,335 people living in these communities, which is practically the same as the 196,255 estimated in 2006. This shows that even when the number of communities has decreased, the populations have actually increased [2]. It is noteworthy that these estimates include those people living in three large communities of more than 10,000 people. The communities of Yellowknife (18,700), Whitehorse (22,900), and Magdalene Islands (13,180) represent about 28% of all people living in remote communities. The remaining 141,500 inhabitants are scattered over the majority of Canada's landmass, along the Atlantic, Arctic, and Pacific coasts, throughout the interior boreal forest and tundra of the three territories and northern areas of most provinces and in the interior mountain regions of British Columbia. It is also to be noted that Prince Edward Island, New Brunswick, and Nova Scotia do not have any off-grid communities.

Most Canadian households are connected to the electricity grid, and the electricity they consume is generated from multiple sources such as hydro, natural gas, coal, wind, solar, and nuclear, with hydropower being the main source. In contrast, remote communities are cut off from the national electricity grid and must produce electricity locally [3]. According to Natural Resources Canada's Remote Communities Energy Database, the large majority of remote communities, 70 percent, rely on inefficient diesel generators to produce electricity, while 13 percent rely on hydro, and 17 percent use a combination of other fossil fuels. Remote communities also use fossil fuels for space and water heating, with diesel providing for the vast majority of heating needs.

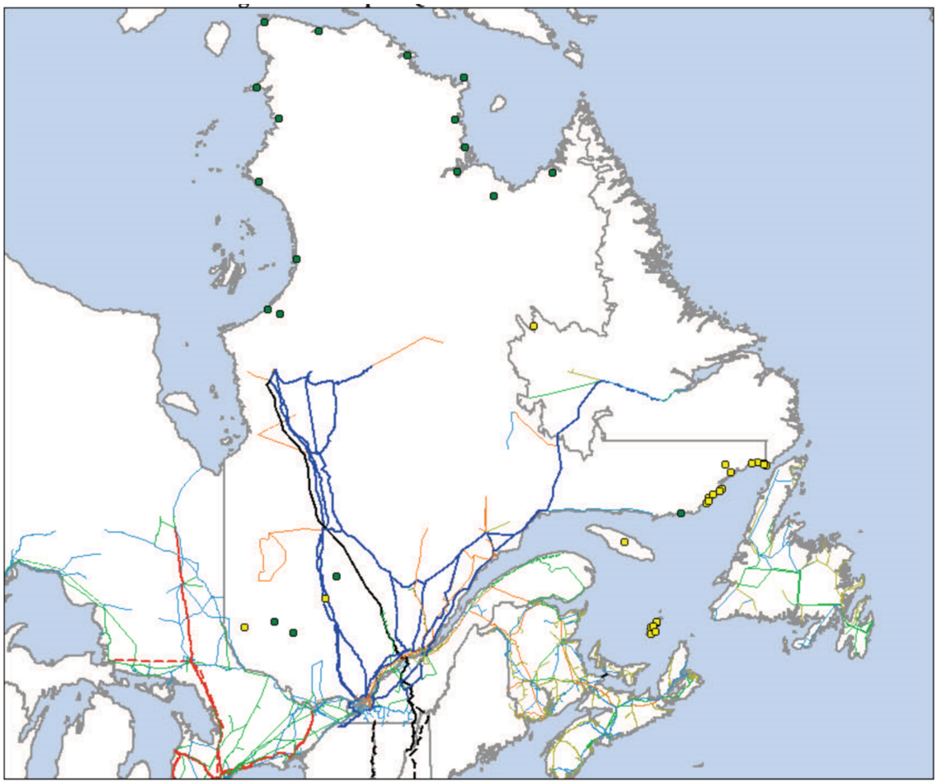


Figure 0-1. Québec remote areas [1]

Note, Green: Aboriginal communities / Yellow: Non-Aboriginal communities

Based on the best available data, remote communities in Canada collectively consume more than 90 million liters of diesel fuel every year for electricity generation. That's equivalent to 36 Olympic-size swimming pools of diesel being transported, stored, and burned. Nunavut, Ontario, and the Northwest Territories consume the largest amounts [4].

Turning to Canada off-grid electricity infrastructures for remote communities, they are diverse and vary depending on access to energy resources, the location remoteness, and the impact of climate. However, with the exception of a few local hydro grid-tied communities in Yukon, Northwest Territories, and Québec, the vast majority of remote communities across Canada rely on diesel generation for the production of electricity.

Thus, most of these communities are characterized by a high degree of dependence on imported fuel and high energy costs. A total of 251 communities have their own fossil fuel power plants totaling 453.3 MW. Of these, 176 are diesel-fueled, two are natural gas-powered, and 73 are from unknown sources but most likely diesel power plants or gasoline gen-sets in smaller settlements.

Over the last 25 years, the number of remote communities in Québec and their population did not change very much, going from 47 to 44 sites and from 35,000 to 34,729 persons. The total installed capacity in all of Québec's remote communities is estimated at 128 MW, of which 107 MW is fossil fuel-powered, and 21 MW is hydro [5]. Numbers for production are provided only for 18 sites totaling 37 MW. These are fossil fuel plants and have an estimated yearly production of 87,214 MWh/yr (2007), giving a capacity factor of 26.9 %.

There are three local grids in different regions of Québec that contribute significantly to the total installed capacity. Two are very large and tie several villages together while the other one is a small two-village grid.

The work presented in this thesis is organized as follows:

CHAPTER 1 presents a general overview of diesel generator performance and characteristics contained in different applications. Problematic, objectives, as well as, the methodology used to achieve the desired objectives such as conceptual survey and comparison of different VSDG techniques, mathematical modeling and simulation of a permanent magnet synchronous generator with the rotating stator, and develop and validate an adaptive speed control algorithm for the automatic GENSET controller are discussed in this chapter.

CHAPTER 2 discusses precisely all direct and indirect critical parameters that affect Genset performance. Furthermore, a completed exhaustive survey of existing variable speed diesel generators (VSDG) methods is discussed. Various landmark issues, such as system efficiency, economic aspects, and environmental impacts, are named and discussed in detail. Based on these important performance parameters, the existing variable speed generator approaches are compared. Results are analyzed according to selected parameters, and the most promising techniques are identified. To demonstrate the VSDG concept, a simulation of a DE driven variable speed doubly fed induction generator using Matlab/Simulink.

CHAPTER 3 introduces a new VSDG technology. In this technique, the speed control of the DG is done without using complicated mechanical or electrical power converters. The configuration of the electric generator is changed, the stator rotates, unlike conventional electric generators. A new mathematical model for the dynamic configuration of the new variable speed Permanent Magnet Synchronous Generator (PMSG), with a rotating stator is given in detail. The Matlab environment serves to simulate the operation of this new VSDG model. Finally, this chapter presents the experimental results of a VSDG completed collaboration with Genset Synchro company in Levis, Québec, on a 500-KW test prototype. Finally, a discussion is proposed regarding fuel consumption reduction achieved by the use of new electrical machine based on the rotating stator.

CHAPTER 4 presents a complete topology of an autonomous VSDG application. The aim of this section is to adjust the speed of an induction motor using a variable frequency drive. This chapter discussed in detail a robust and simple control algorithm method using an instantaneous power calculation technique. The control algorithm is designed to regulate the speed of the motor based on the electric grid demand. The obtained simulation results using Matlab software validate the controller performance. In addition, a real-time experiment has been completed in UQAR's laboratory to validate numerical development.

CHAPTER 5 presents the various advantages and disadvantages related to the use of VSDG as energy source to supply an isolated load. It contains critical points and essential tips. The main conclusion of the thesis and future recommendations are also provided in this chapter.

CHAPTER 1
DEFINITION AND ROLE OF DIESEL-GENERATOR IN STANDALONE OR GRID-CONNECTED POWER SYSTEMS

Résumé

Les génératrices diesel (DG), appelées aussi groupes électrogènes, sont des machines qui produisent de l'électricité en brûlant du carburant. Ces machines utilisent le couplage entre une génératrice électrique et un moteur diesel. Les moteurs diesel convertissent une partie de l'énergie chimique contenue dans le carburant diesel en énergie mécanique par combustion. Cette énergie mécanique est ensuite transmise au rotor de la génératrice qui tourne à l’intérieur du stator pour produire de l'électricité. Le courant électrique est induit dans les conducteurs lorsque le rotor de la génératrice tourne à l’intérieur du champ magnétique créé par le stator. Les groupes électrogènes contiennent un moteur, un système d'alimentation en carburant, un alternateur (génératrice) et un régulateur de tension, ainsi que des systèmes de refroidissement, d'échappement et de lubrification. Les DG sont utilisées dans de nombreuses applications et présentent de nombreux avantages. Elles sont fiables, répondent rapidement aux variations de charge, sont polluantes, mais leur coût de production est plus élevé et . Elles sont particulièrement bien adaptées pour produire de l’électricité dans des zones isolées, en dehors des grands réseaux électriques, ou être utilisées comme source d'alimentation de secours. Dans ces régions hors réseau, les charges électriques élevées n’apparaissent que pendant quelques heures par jour, ce qui entraîne un surdimensionnement des DG. Lors d'une opération à faible charge, les DG sont confrontés à une faible efficacité énergétique et à la condensation des résidus de carburant sur les parois des cylindres du moteur, ce qui augmente la friction et l'usure prématurée. Lorsque la puissance de charge diminue, une réduction du couple mécanique et de la vitesse de rotation du moteur diesel maintiendra l'efficacité de la combustion près des niveaux du régime nominal.

DEFINITION AND ROLE OF DIESEL-GENERATOR IN STANDALONE OR GRID-CONNECTED POWER SYSTEMS

1.1. INTRODUCTION

DGs meet the majority of power demand in remote areas in the world. In Canada, more than three-quarters of remote communities rely solely on DGs for electricity generation. The diesel dependency of remote communities has inflated local per capita greenhouse gas emissions and resulted in rising and inconsistent electricity prices that have made community viability reliant on government subsidies. Most small Island and remote communities in Canada are dependent on imported fossil fuels for most of their energy requirements. These communities are exposed to diesel fuel price volatility, frequent fuel spills, and high operation and maintenance costs, including fuel transportation and bulk storage.

In addition to remote area power systems, commercial and residential customers in urban areas are also seeking new sources of backup power located on their premises. DGs are a major source of backup power due to ease of transportation, installation and removal, as well as the mature and stable nature of the diesel industry with reliable suppliers. However, in the past decade, diesel prices increase more than doubled. High fuel costs have translated into tremendous increases in the cost of energy generation.

For instance, in the Canadian territory of Nunavut, providing power costs nearly 200$ million in fossil fuel annually. This, combined with distribution expenditures, totals approximately $350 million per fiscal year, a number that is steadily rising (Government of Nunavut, 2017).

For this type of system, the electricity generation costs are higher than the rest of the country and can vary significantly. In the Arctic, electricity rates can range from $0.49/kWh to $2.50/kWh, while for the rest of Canada, the average electricity rates range from $0.07/kWh to $0.17/kWh [6]. Moreover, DGs are a major source of pollution. DGs release many hazardous air contaminants and greenhouse gases (GHG), including particulate matter (diesel soot and aerosols), carbon monoxide, carbon dioxide, and oxides of nitrogen. Particulate matters are largely elemental and organic carbon soot, coated by gaseous organic substances such as formaldehyde and polycyclic aromatic hydrocarbons, which are highly toxic.

Diesel engines in generator configuration are normally optimized for operations at medium to high engine loads. It is suspected that operations at low loads may increase operational problems and thus the damage frequency. It is also suspected that negative effects off low load operations are aggravated by recent exhaust emission regulations. Low load operations of diesel engines are defined as engine operations below 40% of maximum continuous rating. Low load operations of diesel engines are normally classified as Table 1-1.

Table 1-1. Load levels in percentage of maximum continuous rating [7]

0 –25%	Extreme low load
25 – 40 %	Low load
40 – 80 %	Regular generator operation load
80 – 90 %	High load
90 – 100 %	Extreme high load

Low load operations are typical for, but not limited to, offshore vessels with dynamic positioning systems [8]. Low load operations of diesel engines cause lower cylinder pressure and thus lower temperature. Low temperature can lead to ignition problems and poor combustion which causes increased soot formation and aggregation of unburned fuel in the cylinder.

Low cylinder pressure, soot and unburned fuel deteriorate the piston ring sealing efficiency allowing hot combustion gases, soot particles and unburned fuel to leak past the piston rings. The mechanisms of low load lead to a cycle of degradation which means that diesel engines that run at low loads for longer periods of time can become irreversibly damaged. The major aim of this project is to reduce diesel engine speed at low regimes to maintain higher fuel consumption efficiency. In the meantime, the synchronous generator needs to rotate at its synchronous speed to produce high-quality power whatever the load. Therefore, this project presents the new system and develop a model for the synchronous machine with a rotating stator based on the d-q transformation.

Concerning power production, a DG is able to provide power quickly and continuously during an important time period. Generally, there are two types of method to energize a power grid with a diesel generator.

1.1.1. Power grid approach

Grid extension needs sophisticated design and standards. However, future energy augmentation demand should also take into account. Construction of the power grid could be very costly based on grid location. For instance, according to the existing market data, the typical grid extension cost for a remote consumer to be connected to the local grid using overhead-medium voltage lines is approximately 11500 $/km [9]. The United States practiced this strategy near to perfection, and now offers almost all of its citizens access to electricity for between 10 and 20 cents per kilowatt-hour [10].

Other countries that have achieved universal electrification through the grid include China, Brazil, and South Africa, through impressive amounts of sustained investment [11]. Extending a grid is seen as the most reliable manner to provide electricity because the centralized, state-run entities that distribute power through the grid usually have enough resources to supply consistent amounts of electricity to all who demand it.

Unfortunately, governments in least-developed countries often lack the capacity to serve even their existing customers with electricity. Furthermore, extending the grid to remote villages in countries without extensive highway systems can be incredibly expensive. The head of Malaysia's rural electrification programs indicated that 130 kilometers of grid extension would cost $80 million, which is simply not feasible for cash-strapped nations [10]. Many countries have made significant progress in terms of electrification. The success is not restricted to any specific region either. Urban areas of Latin America have traditionally performed well in terms of electrification. Still, East Asia, particularly China, has set an excellent example of achieving universal electrification despite its billion-plus population and vast rural population. Figure 1-1 indicates the grid extension status in different countries.

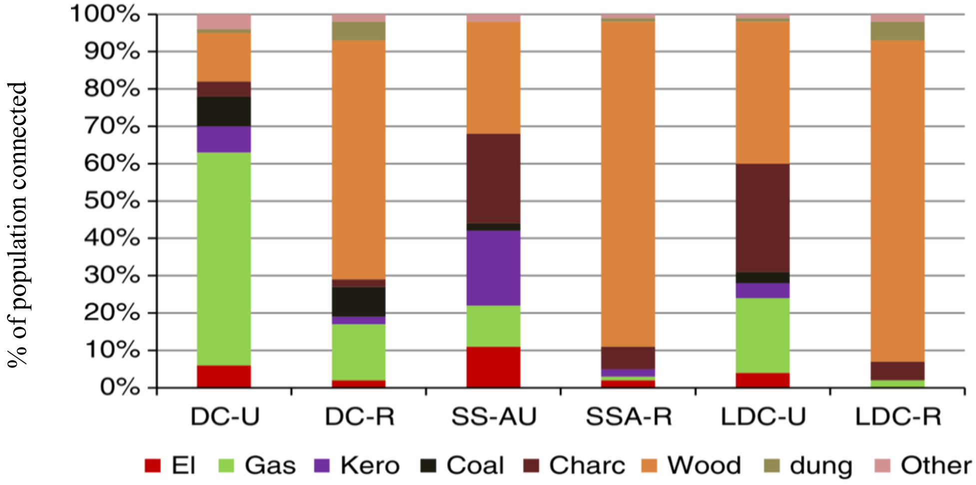


Figure 1-1. Bar chart diagram of urban-rural subscribers to the national grid [11]

Note: DC– Developing countries, SSA – Sub-Saharan Africa,

LDC – Least Developed Countries as per UN classification. U– urban, R – rural.

Legend: El– electricity, Kero – kerosene, Charc – charcoal.

Note: DC — developing countries, SSA — Sub-Saharan Africa, LDC — least developed countries as per UN classification. U —urban, R — rural. Legend: El — electricity, Kero — kerosene, Charc — charcoal.

1.1.2. Off-grid power systems

The Canadian territory of Nunavut covers one fifth of Canada's landmass and, without a road network or linked power grid, residents rely exclusively on off-grid diesel-generated power stations to supply electricity. Once considered convenient, these systems have now become inefficient and difficult to maintain. Economic, environmental, and social analyses must be conducted in order to recognize the viability of developing clean, renewable, and sustainable energy in the territory. Alternative renewable energy technologies such as wind and photovoltaic (PV) panels are increasingly being integrated into the power system. Diesel-based power systems are hybridized with renewable energies to increase system stability during peak load or unpredictable weather conditions. A battery energy storage system (BESS) is commonly integrated to increase system flexibility. Batteries facilitate higher penetrations of renewable energy yet add high cost and complexity to the system. Numerous researchers have investigated these integration challenges via optimization of the sizing and/or control of the BESS.

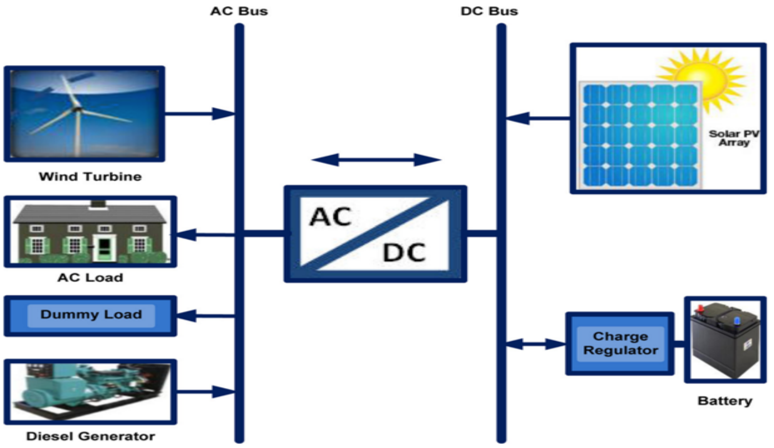


Figure 1-2. General diagram of a remote hybrid AC-DC distribution network [12]

The DG can supply energy to the load directly but also charge the batteries. As it is to be expected that some of the diesel generator production will be stored into the batteries, the DG is coupled to the DC bus using an AC/DC converter. In this configuration, the DG can operate at an optimal load with the advantage of higher fuel efficiency. Figure 1-2 illustrates the integration of renewable energy sources with a DG and batteries into a micro-power system.

1.2. THE PRINCIPAL ELEMENTS OF A DIESEL GENERATOR

DGs typically consist of three main functional units: a diesel engine, a synchronous generator with a voltage regulator, and a governor.

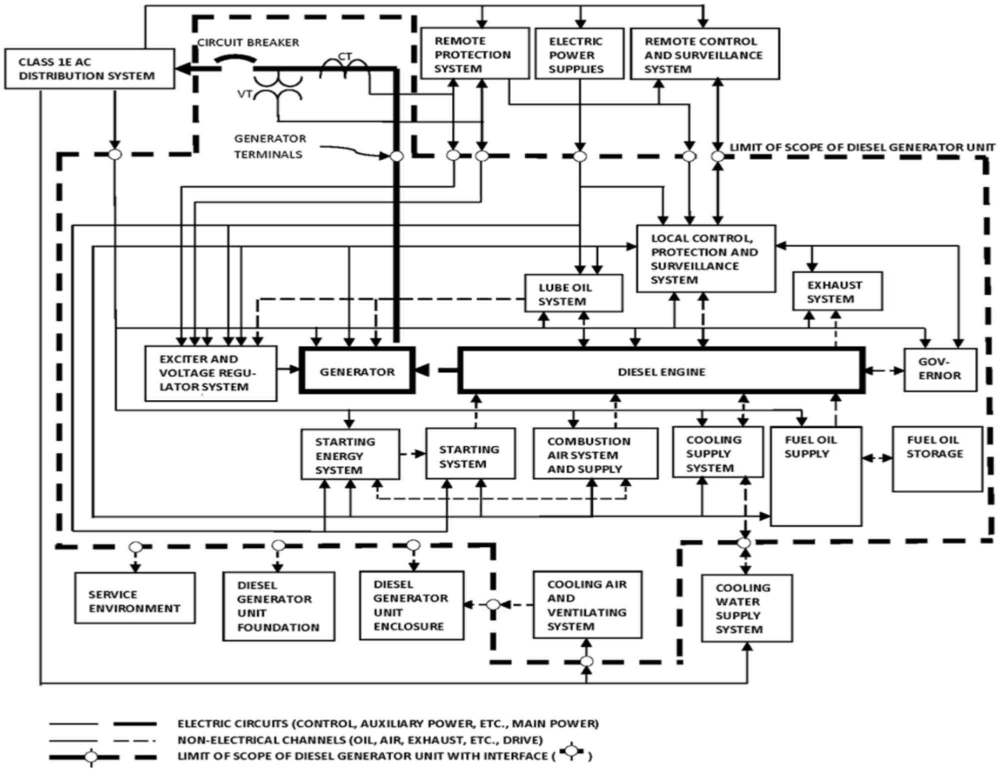


Figure 1-3. Scope diagram of a typical Genset [13]

The fuel injection system is an important part of the DE. Its function is to inject the proper amount of fuel into the proper cylinder at the appropriate time in the cycle. The timing of the injection is determined by the design of the engine itself; the amount of fuel is determined by the governor.

The diesel engine is normally connected directly to a SG. A voltage regulator ensures the proper voltage is produced. The frequency of the AC power is directly proportional to the engine speed, which in turn is controlled by the governor. Figure 1-3 illustrates the different parts of a DG set.

1.2.1. Engine

The DE has served as a power source for heavy-duty applications such as electrical generation, marine propulsion, and land traction because of its fuel economy advantage. However, the satisfactory operation of DEs depends on proper control of the fuel injection and air motion. The ideal engine system should have high efficiency, high output, low levels of noise, and exhaust emissions. To some extent, these requirements are in conflict with each other; for example, engine output is directly limited by the exhaust smoke levels.

High-speed DEs are often used as emergency and backup generators to provide power during grid outages. The ability of a DE to start rapidly, often in less than 10 seconds, makes them particularly attractive. Where even faster move-in is required, a diesel engine can be combined with a fast-acting energy storage system such as a supercapacitor or flywheel. Similar high-speed DEs are also used to provide power to remote communities that are not grid-connected.

Medium-speed DEs can also be used to both backup supply and supply power to remote communities. However, these engines are larger and more expensive than the high-speed engines, so economic considerations become important. This type of engine is often used to provide power for industrial units that require their own power supply or cannot afford to lose grid power. Medium-speed DEs are easy to install, and they can be used to provide base-load power in developing countries and to reinforce weak grid supplies.

Slow-speed DEs are the largest of the diesel fleet, and these are usually used for base-load duty. The engines are particularly attractive when there is a source of heavy fuel oil because it provides an economical source of power [14].

However, the engines can also be used in a grid support role or in a situation where the power demand fluctuates. Figure 1-4 indicates a comparative efficiency of low-speed diesel engines. One of the advantages of low-speed engines is their part-load efficiency, which varies very little over a range of outputs between 50% and 100% load.

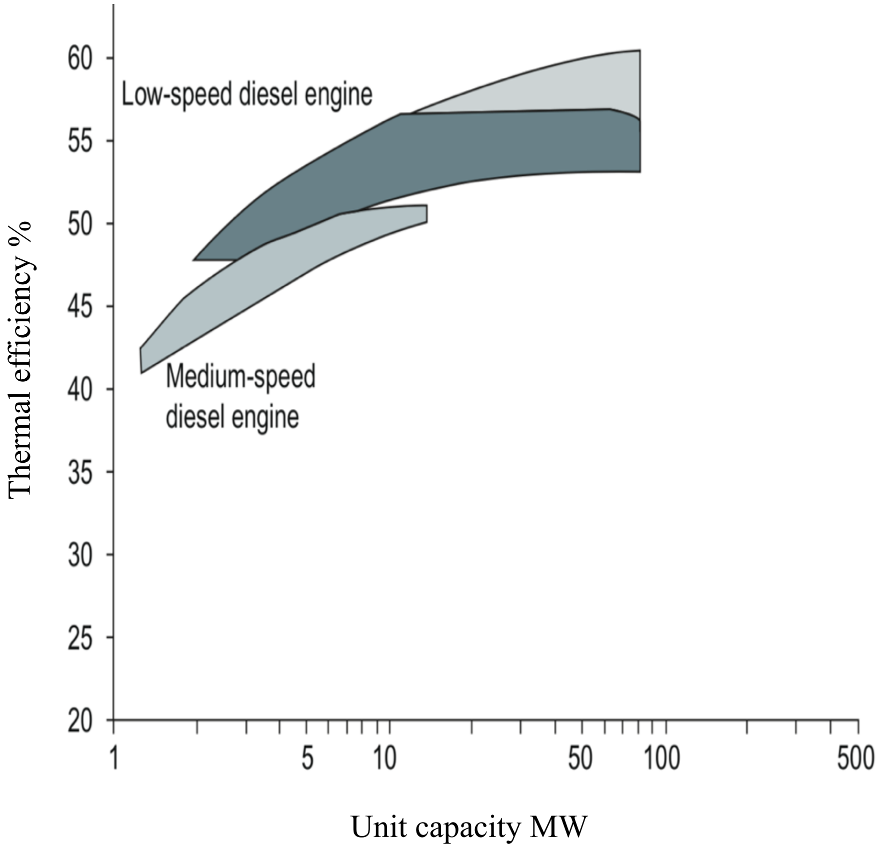


Figure 1-4. Combined cycle performance of low-speed diesel engine [15]

1.2.2. Alternator

There are many types of electrical machines that are used in Genset applications. There is no clear criterion for choosing a particular machine to work as a DG. Based on the power system, ambient condition, load type, and simplicity of control, an electric generator can be selected. Squirrel cage induction or SG are standard for medium and big size industrial applications.

Doubly fed induction generators (DFIGs) are commonly used for megawatt size power plants. Brushless DC (BLDC) and permanent magnet synchronous machines (PMSM) can also be used for microgrids applications [16]. Two most used AC alternators in Genset application are the squirrel cage induction machine and the permanent magnet synchronous generators.

- **Squirrel Cage Induction Machine**

The three-phase induction machines are common in industrial motor applications. However, they can also be effectively used as generators in electrical power systems. The main issue with induction machines as electric power generators is the need for an external reactive power source that will excite the induction machine, which is not required for synchronous machines in similar applications. If the induction machine is connected to the grid, the required reactive power can be provided by the power system [16]. The induction machine may be used in cogeneration with other SGs, or the excitation might be supplied from capacitor banks (only for standalone self-excited generator applications).

- **Permanent Magnet Synchronous Generators (PMSG)**

For both fixed and variable speed applications, PMSG can be used. The PMSG is very efficient and suitable for Genset applications. PMSGs allow direct-drive energy conversion for diesel applications. Direct-drive energy conversion helps to eliminate the complicated gearbox between the engine and generator; thus, these systems are less expensive, and less maintenance is required [17].

Moreover, the integration of BESS with PMSG system provides active power conditioning featuring power quality improvement. The principal of BESS in power system is to start charging during low electric load regime and replenish it at the time of peak load. Also, BESS has all four-quadrant operation in active and reactive powers. Figure 1-5 shows schematic diagram of DE driven controlled PMSG.

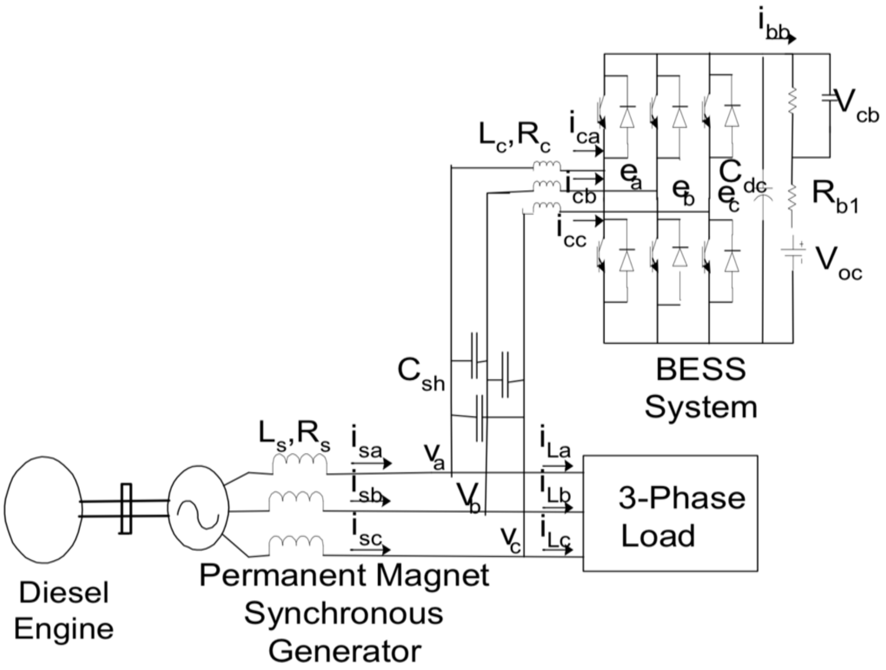


Figure 1-5. Schematic configuration of diesel engine driven PMSG using controlled storage system [18]

1.2.3. Fuel system

The diesel engine is an internal combustion engine using either a two- or four-stroke cycle. Burning or combustion of fuel within the engine cylinders is the source of power. The speed of a DE is controlled by the amount of fuel injected into the cylinders. In a gasoline engine, the speed of the engine is controlled by the amount of air entering into the carburetor or gasoline fuel injection system. The fuel supply system of spark ignition engine consists of:

- Fuel tank
- Fuel filter
- Sediment bowl
- Fuel lift pump
- Injector
- Fuel pipes
- Inlet manifold

Mechanically, the DE construction is similar to the gasoline engine. The intake compression, power, and exhaust strokes occur in the same order. The arrangement of the pistons, connecting rods, crankshaft, and engine valves is about the same. These phenomena are partially offset by higher initial cost, heavier construction needed for its high compression pressures, and the difficulty in starting.

1.2.4. Voltage regulator system

The voltage regulator system is a solid-state electronic device for automatically maintaining the generator output terminal voltage at a set value. Usually, in a generating set, the alternator manufacturer supplies an automatic voltage regulator with their AC alternator. The voltage regulator system controls output by sensing the voltage from the generator terminals and comparing it to a stable reference [19]. The error signal is then used to adjust the field current by increasing or decreasing the current flow to an exciter stator, which in turn will lead to a lower or higher voltage at the main stator terminals. Figure 1-6 shows a typical synchronous generator connected to the voltage regulator system.

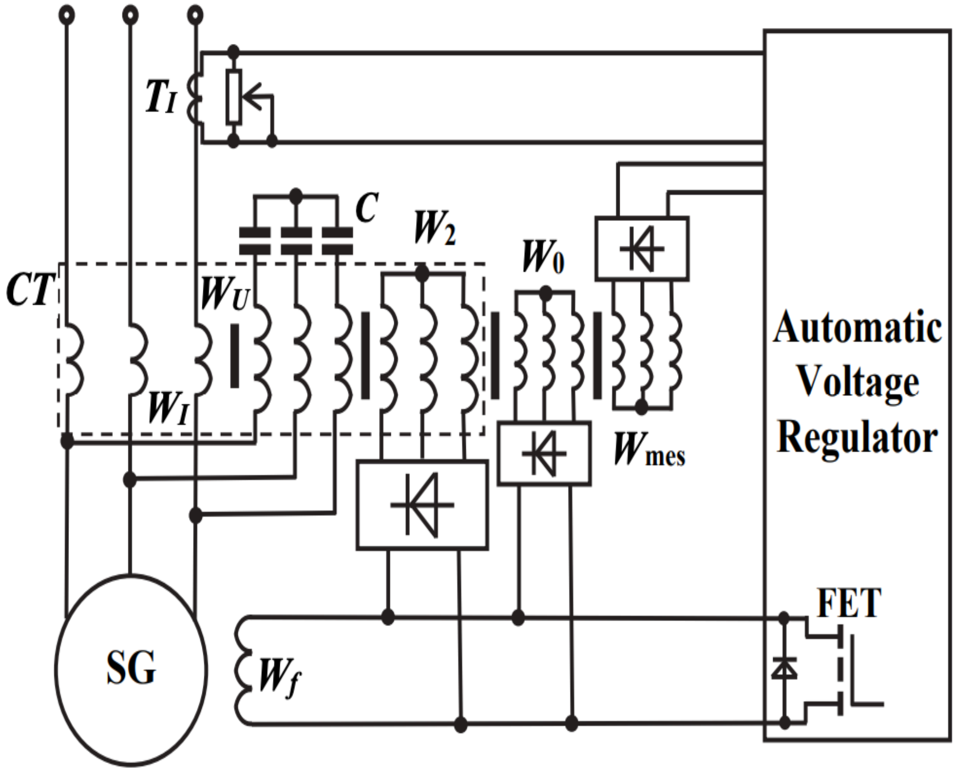


Figure 1-6. Diagram of a compound excitation system with AVR [20]

1.3. INTEGRATION OF DIESEL GENERATOR INTO THE POWER SYSTEM

Nowadays, several communities and different applications are relying on DGs to meet their energy demand. These Gensets are supposed to work for different applications at different ambient conditions. In every application, Gensets provide electricity for different purposes. In this section, the DG role is briefly discussed based on two general classifications.

1.3.1. Grid-connected DG

Centralized grids are larger in size and difficult to protect. They can include several hundred megawatts (MW) or even gigawatts (GW) of central generation capacity that can cover countries or even continents. Such grids include transmission at medium and high voltage (above 11 kilovolts, kV) to transport electricity over large distances. The important challenge of grid-connected communities is to have a constant power supply during different conditions [21].

The dispatchable energy source (such as DG) is used to increase the system reliability in deficit conditions. This strategy helps the power grid to supply a vast portion of consumers even in case of unpredictable faults. In modern countries, the integration of hybrid renewable energies technology (wind-PV-hydro, etc.) with DG introduces several advantages for demand and grid side management [22].

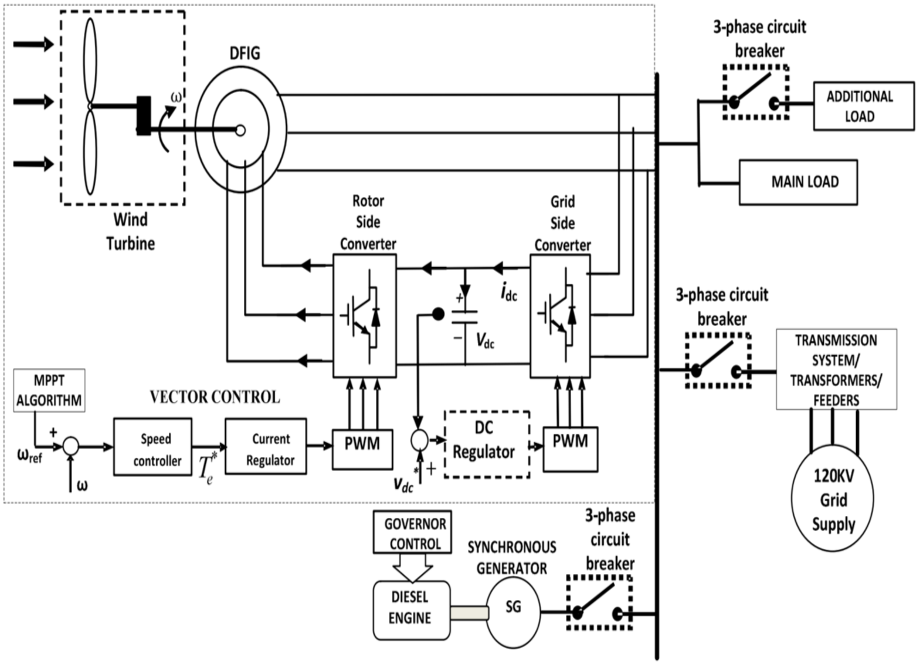


Figure 1-7. Active and reactive power control of a power system using hybrid energies [23]

The role of DG in these projects varies based on the penetration rate defined at the beginning of the project. In projects with low diesel penetration rate, DG starts to charge the battery or to meet the surplus loads. Figure 1-7 indicates a hybrid wind-diesel microgrid that can operate coupled or disconnected from the primary grid.

1.3.2. Standalone power system

In remote locations, standalone systems can be more cost-effective than extending a power line to the electricity grid (the cost of which can range from \$15,000 to \$50,000/km) [10]. But these systems are also used by people who live near the grid and wish to obtain independence from the power provider or demonstrate a commitment to non-polluting energy sources.

However, some remote sites are not connected to the national grid due to impassable ways or small consumption such as telecommunication towers, etc. Successful standalone systems generally take advantage of a combination of sources and technologies to generate reliable power, reduce costs, and minimize inconvenience. Some of these strategies include using fossil fuel or renewable hybrid systems and reducing the amount of electricity required to meet energy needs. Integration of renewable energy (RE) sources into fossil fuel-based power generation systems for remote areas can offer attractive economic and environmental merits, including considerable fuel savings and carbon dioxide emission reductions.

However, the intermittent aspect of RE sources, along with the highly variable nature of load demand for these applications, may lead to significant degradation of RE utilization due to the excess of RE energy losses [24]. The RE energy losses are considered as a portion of the energy that cannot be delivered to the system. The RE losses are more significant for a medium to high penetration of RE sources, especially when no electric energy storage is used. Two important challenges of every standalone power system are the frequency and voltage control.

1.3.2.1. Frequency control

The frequency of isolated communities varies considerably with the change in load, and the improved frequency regulation can be achieved using the governor control system. The governor control regulates the frequency by adjusting the engine fuel hatch according to the load demand. For small schemes, the use of governor is a costly affair because; the cost of the governor and its control does not decrease proportionally as the generator size reduces. Also, the governor adds complexity to the operation and requires routine maintenance [25]. The load controller can be used instead of a costly governor to regulate the generator frequency. The load controller maintains the speed and frequency at a constant level by dumping the excess generator power into the ballast or non-priority resistive load.

1.3.2.2. Voltage control

There are many remote locations where DG are the only source of electricity. For instance, many of the remote railway stations are operated with DG [22]. The consumption of fossil fuels must be reduced to avoid global warming. Hence, the use of renewable energy sources in combination with DG could help to reduce GHG emissions and the operating cost through a reduction in fuel consumption and increased system efficiency. For instance, PV power generation systems are expected to play an important role as a clean electricity power source in meeting electricity demands. However, the output power of PV always fluctuates because of weather conditions. One of the basic requirements of generation planning using a DG in off-grid power systems is an effective and comprehensive voltage regulation scheme [26]. The system voltage is really vulnerable, considering the unpredictable load characteristics, and the stochastic availability of renewable energy. Several energy source configurations and different control methods are proposed for standalone micro-grid to achieve constant system voltage.

1.4. PROBLEMATIC

Diesel-powered electric generators are typically sized to meet the peak demand during the evening but must run at very low loads during “off-peak” hours during the day and night. This low-load operation results in poor fuel efficiency and increased maintenance. The following list is an assessment of the concerns raised by diesel generation that remote communities face in terms of environmental, social, and economic sustainability.

Environmental Concerns

- Burning large amounts of diesel produce substantial greenhouse gas (GHG) emissions.
- Fuel must be transported long distances by airplane, truck, or barge, leading to a higher risk of fuel spills.
- The transportation of fuel by trucks on winter roads negatively impacts the environment through high greenhouse gas emissions from vehicles.
- Fuel spills may occur while the fuel is being transported and stored, posing environmental risks. Fuel tank leaks contaminate soil and groundwater.

Social Concerns

- Generators can be noisy and disruptive.
- Emissions from diesel generators could contribute to health problems for community members.
- Blackouts can occur if diesel generators break down or are not properly maintained. This can be dangerous in cold, remote locations.

Economic Concerns

- Cold, northern locations have a high demand for diesel and heating fuel, which contributes to high energy expenditures.
- Diesel fuel must be flown in, shipped in, or driven in on winter roads, which leads to high transportation costs and high energy expenditures.
- Diesel is a non-renewable resource; therefore, the price of diesel fuel will likely continue to fluctuate in the future, based on overall supply and demand.

1.4.1. Fixed speed DG

The operation of the DG set at an average load as low as 30 % of the full capacity is common. However, for a light load operation, the fuel efficiency is poor since not all fuel is burnt in the combustion process. The unburnt fuel dilutes the oil in the cylinders and causes excessive wear in the cylinder walls, cylinder glazing, and carbon build-up. These harmful and destructive conditions inflict severe deterioration to the engine performance and premature engine failure.

To prevent this condition, manufacturers insist that constant speed DG set operates with a load above 50 %. Also, remote areas with relatively small communities generally show significant variation between the daytime peak loads and the minimum night-time loads. In some remote locations, a dual DG system is employed. During low load regime, the smallest generator is used; as the load increased, the manual switch is transferred to the largest generator. This approach results in some fuel savings. However, managing this dual system is time-consuming and impractical. The typical fuel consumption characteristic of a 50 kVA DG is shown in Figure 1-8 .

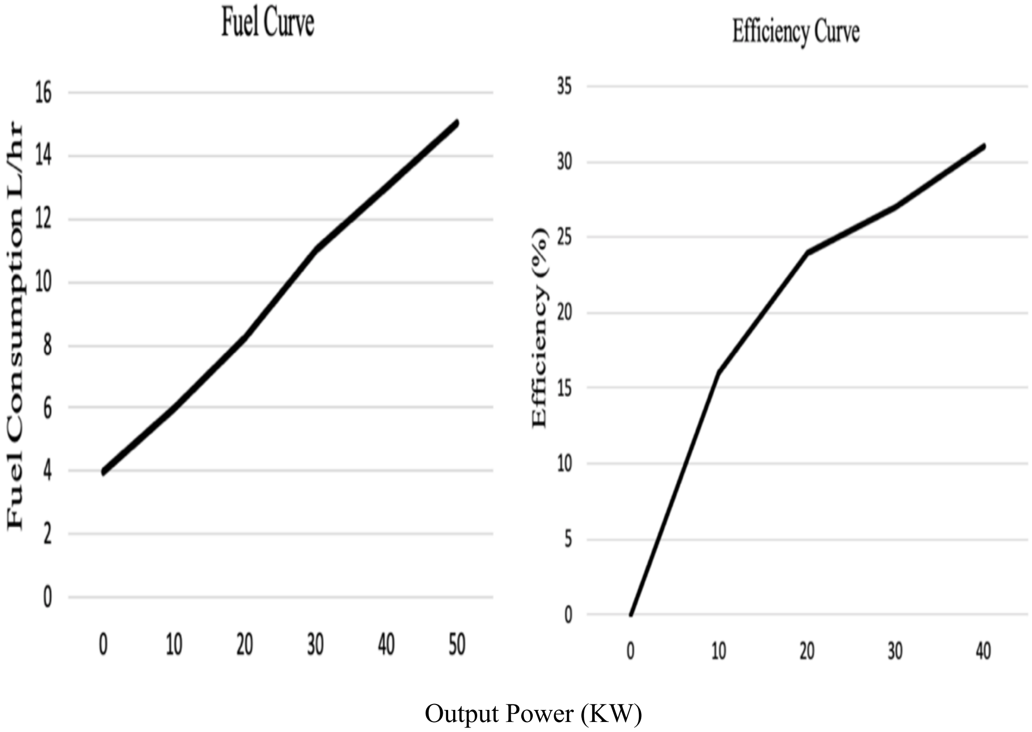


Figure 1-8. Fuel consumption characteristics of a fix speed DG [27]

1.4.2. Variable speed diesel generator

Modern DEs allow short term partial load application; however, low load efficiency is poor, constrained by the fixed speed design basis. Unchecked, partial loading can also result in engine damage, via cylinder glazing, and, in extreme cases, piston seizure. Besides, small and medium-sized DGs are particularly sensitive to the partial load operation.

For variable speed diesel generation, a power converter can also be used to condition a variable frequency variable voltage supply for network compliance. VSDG techniques allow the control system to operate the engine at its most efficient speed for the required load [28].

In this technique, the controller allows engine speed reduction as load diminishes. The controller maintains a higher cylinder fuel load per cycle, as required to maintain the thermal performance of the engine at partial load. To note, the controller also permits the engine to increase speed above rated loading, allowing the engine to exceed its rated power output by permitting an increase of the rated engine speed. Accordingly, both low and high load operating range of the engine is increased under a variable speed control methodology. The biggest challenge in variable speed Genset is to control generator output based on load variation.

Several methods and technical configurations are required to maintain grid stability by adjusting the electricity production to the load. The implementation of these solutions requires more complicated systems using advanced control algorithms that may result in grid harmonic pollution due to high-rated power converters. Figure 1-9 illustrates a typical PMSG using PWM rectifier, inverter, and DC-link.

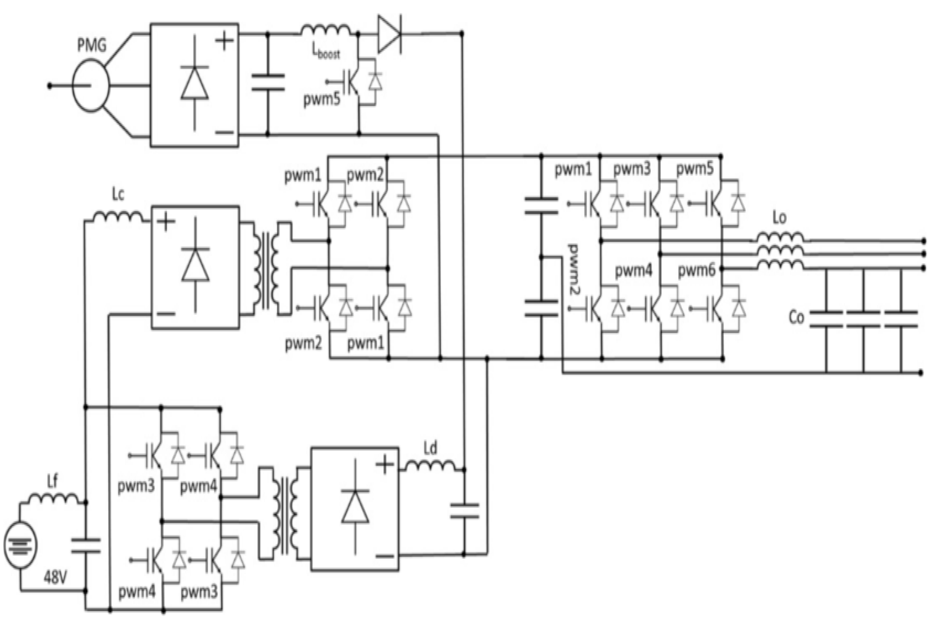


Figure 1-9. Variable speed DG using a full-power converter [29]

1.5. RESEARCH OBJECTIVES

One of the solutions to reduce fuel consumption of DG is to adapt the rotational speed to the mechanical torque of the crankshaft. When load power decreases, a reduction in both mechanical torque and rotational speed of the DE will maintain the combustion efficiency near the levels of the nominal regime. Accordingly, the generator itself should operate at a variable speed, which normally requires power electronics converters.

This project aims to explore a new generator concept that uses a stator rotating in the opposite direction to the rotor, such as the relative velocity between the two components remains constant when the DE slows down. The stator itself is driven by a compensator synchronous motor (CM) such as the relative velocity of the rotor is constant, eliminating as such sophisticated power electronics. More precisely, this project tries to achieve the following goals.

Conceptual survey and comparison of different VSDG techniques. Evaluate the performance of different VSDGs commissioning in grid-connected or isolated networks. This part aims to deeply understand the weakness and strength points of other approaches employed in VSDG.

Present a developed diesel-generator set based on a rotatory stator. A coherent explanation on a developed variable speed application facilitates the analysis process and addresses the parameters needed to be considered.

Mathematical modeling of permanent magnet synchronous generator with the rotating stator. Accurate modeling of the developed synchronous machine decreases the risk of errors during optimization progress. Therefore, the estimation of machine behavior during different conditions would be closer to the real application.

Form a simulation model based on relevant physical principles of a synchronous generator suitable for applying adaptive control algorithms. The availability of a simulation model facilitates the analysis of new control algorithms as part of the process of improving on the variable speed technique. Simulation can be a powerful tool in general problem analysis and by revealing details of a new solution before its implementation. Further, a simulation model can act as a source of information, mainly if based on physical principles and quantities.

Propose an adaptive speed control algorithm for the automatic GENSET controller. Any alternative supervisory control algorithm must be capable of providing, at least, a similar level of control performance to that of the existing methods.

Validate the proposed control technology on a test bench. Experimental results using a proof of concept represent the proper validation of the theoretical models. Furthermore, experience gained from working closely with actual DGs is used to improve and validate the characteristics of the simulation model.

1.6. METHODOLOGY

To achieve the objectives defined in the previous section, we are following the methodology described below.

One solution to improve energy efficiency in the development of both standalone or grid-connected systems is the use of VSDG power plants. The operation at variable speed allows the reduction of the specific fuel consumption when operating at lower charges. DG rpm control, according to load power, also allows to reduce harmful emissions into the atmosphere and to increase internal combustion engine service life. In such power plants, internal combustion engine rpm is adjusted depending on the power load and according to other operational characteristics.

The development of the VSDG using a rotating stator eliminates electrical and mechanical converters, minimizes fuel consumption, synchronizes energy production and consumption, provides continuous power supply to the load, and ensures the stability of the VSDG in the presence of variable conditions.

The first step is to model the variable speed PMSG with a rotating stator. A d-q transformation was chosen to model the SG because of its accuracy and simplicity. The model has been adapted to introduce a separate mechanical input for the stator. This input is synchronized with the rotation of the rotor and determines the speed of the stator.

More importantly, the synchronous speed is achieved by changing or adjusting the speed of the rotor and stator. The purpose of this development is to control the synchronous speed of the machine using the stator, rotor, or a combination of both. The mathematical modeling of the developed synchronous machine is deployed in new MATLAB block diagrams since no machine exists in the Matlab/Simulation library with the rotating stator.

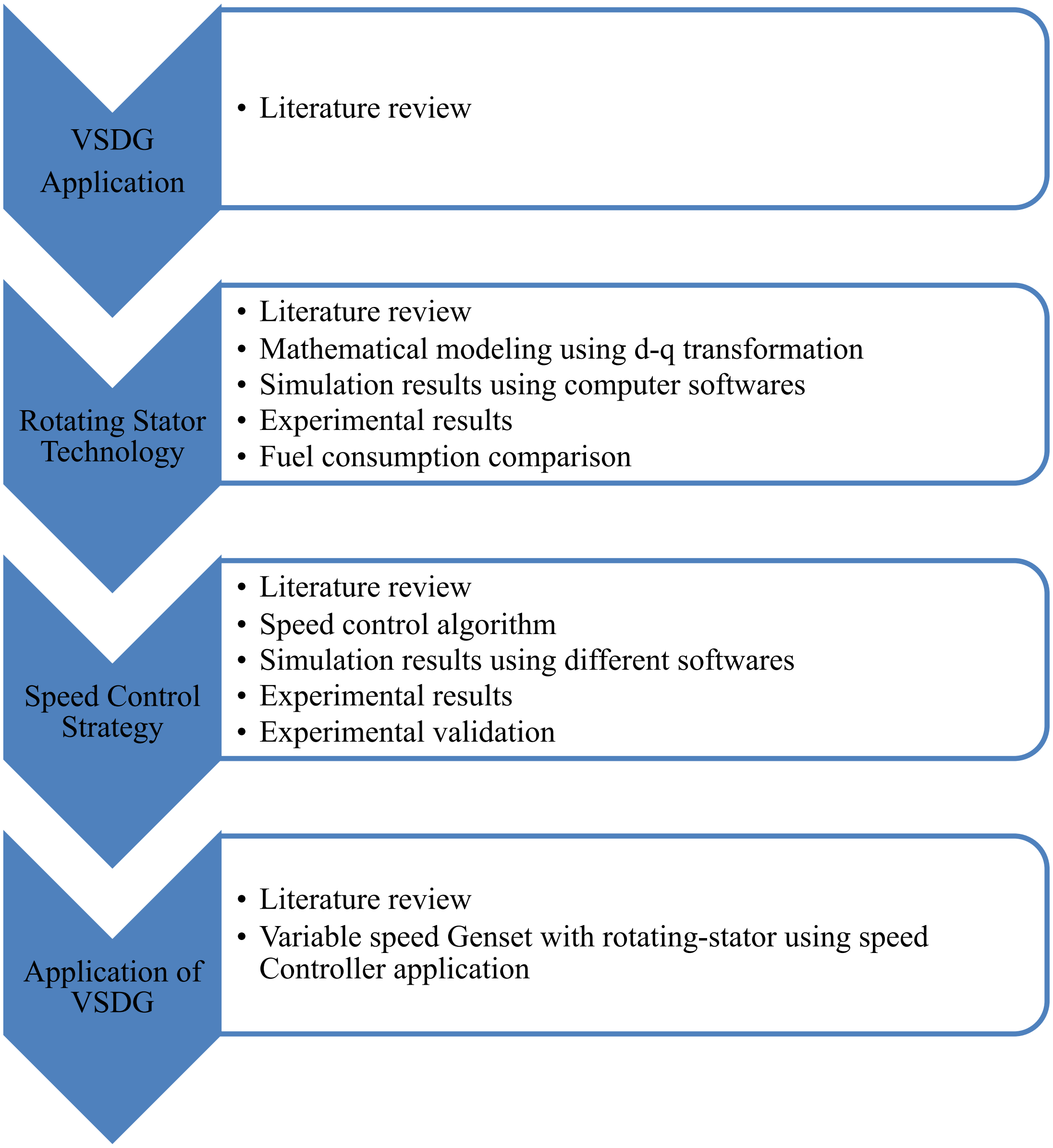


Figure 1-10. The general aspect of project methodology

The control of VSDG is of particular interest for autonomous grids as the DE can adapt its speed to the most efficient regime in accordance to load variation. At medium to high loads, the VSDG stator is fixed, and the DE rotates at 1500 rpm (50 Hz current) or 1800 rpm (60 Hz). For low loads, a compensator motor serves to turn the stator and slow down the rotor, such as the DE operates at higher efficiency. By continuously monitoring the load condition, the controller algorithm sends the appropriate signal to the Variable Frequency Drive (VFD) of the compensator motor. This strategy allows the DE to turn at lower speeds and higher efficiency during low load conditions while keeping a synchronous speed for the generator and a fixed frequency. Figure 1-10 shows the step-by-step process to achieve project objectives.

The simple but robust speed control algorithm is defined to adjust the speed of the compensator motor (CM). The speed control strategy is programed and loaded in a microprocessor card to adjust the speed of the CM according to the variation of the load. An instantaneous active power load tracking strategy is used in the controller to vary the speed of the CM according to the variation of the load. A 4 kW inverter with direct power control strategy adjusts the ideal frequency for the CM.

CHAPTER 2

ASSESSMENT OF THE OPTIMUM PERFORMANCE FOR VARIABLE SPEED DIESEL GENERATOR IN POWER SYSTEM

Résumé

Les génératrices diesel (DG) sont configurées pour fonctionner comme une source d’urgence pendant les pannes de courant ou pour supporter la charge dans les régions éloignées, non connectées au réseau national. La plupart du temps, ces DG travaillent à une vitesse constante pour produire une alimentation CA fiable, tandis que la demande d'énergie électrique fluctue en fonction des besoins instantanés. Dans les régions éloignées, des charges électriques élevées ne surviennent que quelques heures par jour, ce qui entraîne un surdimensionnement des DG. Lors d'une opération à faible charge, les DG sont confrontés à une plus grande consommation spécifique de carburant (quantité de carburant utilisée pour produire 1kWh) et à la condensation de résidus de carburant sur les parois des cylindres du moteur qui augmentent le frottement et l'usure prématurée. Une solution pour augmenter l'efficacité de la combustion à faibles charges électriques consiste à réduire le régime du moteur diesel (DE) à son régime idéal en fonction du couple mécanique requis par la génératrice électrique. Par conséquent, les génératrices diesel à vitesse variable (VSDG) permettent le fonctionnement du moteur diesel à une vitesse optimale en fonction de la charge électrique, mais nécessitent un équipement électrique supplémentaire et un contrôle pour maintenir la puissance de sortie aux normes électriques. L'objectif principal de cette recherche est de présenter l'état de l'art des technologies VSDG et de comparer leurs performances en termes d'économie de carburant, d'augmentation de la durée de vie du moteur et de réduction des émissions de gaz à effet de serre (GES). Divers concepts et les dernières technologies VSDG ont été évalués dans ce chapitre en fonction de leurs performances et de leur degré d'innovation. Pour démontrer le concept VSDG, une simulation

utilisant Matlab / Simulink d'un générateur à induction à double alimentation à vitesse variable est proposée.

ASSESSMENT OF THE OPTIMUM PERFORMANCE FOR VARIABLE SPEED DIESEL GENERATOR IN POWER SYSTEM

2.1. INTRODUCTION

Despite all improvements in renewable energy technologies, numerous remote sites and applications are still dependent on DGs and fossil fuels to produce electricity. DGs are still commonly used to provide electricity in isolated communities as renewable energies are unpredictable, intermittent, and the storage capacity is limited [30].

DGs are also widely used as a backup in countries with a high frequency of electric shortage both for residential and commercial sectors and as a primary source of energy production in some power plants. Stability, reliability, and ease of production are some of the advantages of DGs for electricity generation [30].

On the other hand, diesel engines have some major drawbacks, such as greenhouse gas (GHG) emission and high fuel consumption. Nitrogen oxides (NOx) and carbon monoxide (CO) are two hazardous and destructive gases produced during incomplete diesel combustion, among other particulate emissions.

Extensive research and several studies have been carried out, such as post-combustion and pre-combustion, to reduce soot emission. For instance, it is possible to reduce the NOx species from the diesel chamber during the combustion process using a pre-combustion method in a very early stage of ignition [31].

However, during different load regime, these technologies are insufficient to control fuel consumption and environmental emission.Also, fuel quality and economy play an important role in diesel performance and the cost of electricity, respectively. The fluctuation of fuel prices in global markets and its transportation to the remote areas are reasons for researchers to improve Genset efficiency. Diesel-driven generator sets are subject to increasing demands regarding efficiency and performance, yet at the same time, they must be easy to commission and robust to disturbances.

In addition, diesel generators (DGs) are set to work as a backup during power outages or to support the load in remote areas which are not connected to the national grid. Most of the time, DGs are working at a constant speed to produce reliable AC power, while electrical energy demand is fluctuating according to instantaneous power.

Genset system efficiency is a ratio between electricity production and fuel consumption [32]. Thus, the increase in the energy efficiency of the Genset system reduces fuel consumption. In [32], engine temperature and electric load oscillations are two significant parameters affecting fuel consumption.

However, in [33], DG sizing is mentioned as a critical parameter for fuel economy in a power system with a typical load. Based on the explanation above, every diesel engine (DE) fuel consumption profile is affected by these operational parameters. More precisely, the mechanical load from the electrical generator applied to the engine crankshaft undoubtedly affects fuel consumption [34].

As stated earlier, one of the most challenging issues for DG performance is that the DE efficiency is optimal during nominal power operations, and it decreases sharply at lower regimes. In other words, DE should run at a constant speed to provide reliable synchronous speed for the electrical generator while the production varies based on load oscillations. This phenomenon decreases DG efficiency, especially during low electric loads.

This thesis proposes a comprehensive study of VSDGs based on the latest existing techniques. It highlights the critical parameters to be considered when the system is connected to variable loads.

2.2. DIESEL GENERATOR CHARACTERISTICS ASSOCIATED WITH THE LOW LOAD OPERATION

Conventional DGs need to run at a constant speed of 1500 rpm or 1800 rpm to provide constant 50 Hz or 60 Hz frequency, respectively. The grid-connected power plants or isolated communities powered by fixed speed Genset applications always faced low efficiency due to fluctuations of electrical loads from the demand-side. In a typical electric grid, there is a huge difference between peak loads, low loads, or even base loads [35]. A sample of the annual variation of the hourly electric-load profile appears in Figure 2-1.

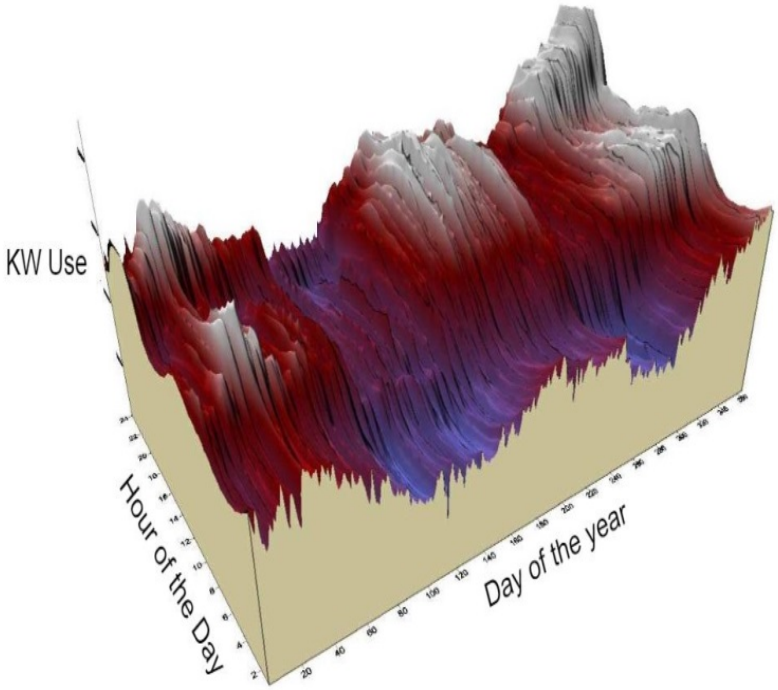


Figure 2-1. Typical load graph for a remote area (Loads: minimum, average and maximum values) [36]

In a typical power system, DG sizing is based on peak loads to avoid any load curtailment. As a result, the reliability of the system increases, and DG can support electric demand at any time. On the other hand, during low electrical loads, DE speed remains almost constant, which is the main reason for low diesel efficiency [29, 37]. The speed and the mechanical torque of the DE are two parameters affecting overall DG efficiency, and they are controlled and adjusted by the amount of fuel injected in the diesel cylinder. Diesel torque characteristic is relatively flat over a wide range of speeds, whereas DE speed is more sensitive to load variation [37].

Rotational speed affects engine consumption when the mechanical load decreases to follow the electric load variation. Therefore, to increase the fuel efficiency of the system, DE speed should synchronize with load variation. During low electric load demand, DE speed should be reduced to avoid producing unnecessary mechanical torque [29].

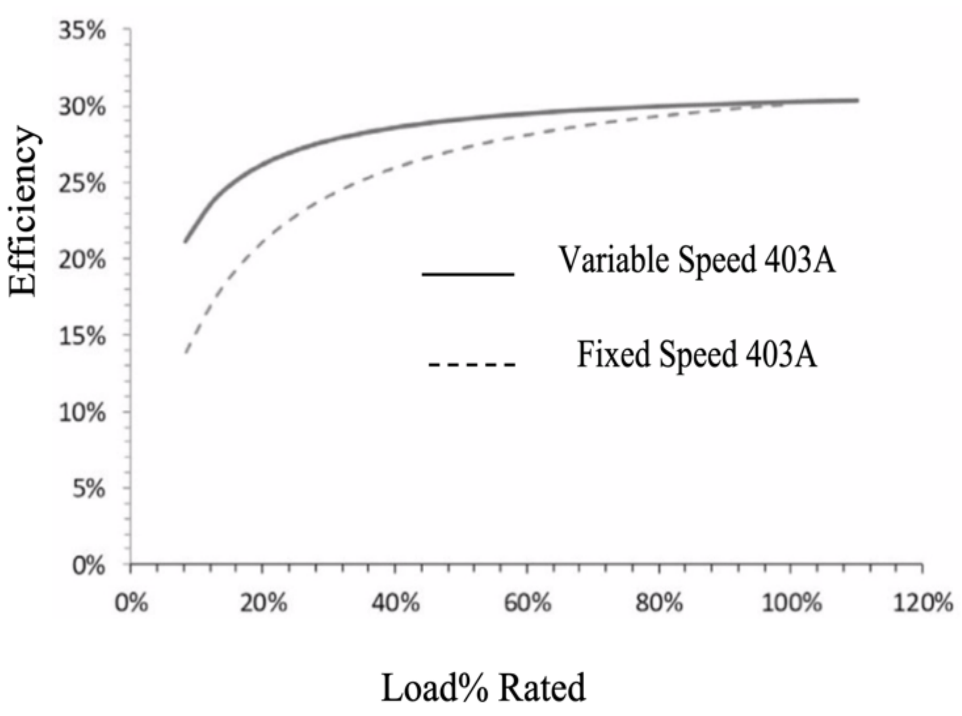


Figure 2-2. Fixed speed vs. variable speed DG performance [29]

For conventional DGs, this ruins the power quality of the produced output power since the DE crankshaft rotates solidary with the rotor of the electric generator. Various studies and different solutions have been proposed to pair the demand-side with the flexible DE speed and simultaneously regulate the produced electric power. The major aim of this study is to assess existing variable speed technologies and evaluate them according to a series of performance criteria. Figure 2-2 illustrates the efficiency improvement of using a VSDG rather than a fixed speed one, especially at low charges.

2.3. OVERVIEW OF VARIABLE SPEED DIESEL GENERATOR

Fixed speed diesel generators are designed for a limited speed range variation of the DE, and their efficiency drops sharply during low electric load operations [29, 38]. High fuel consumption per kWh is the consequence of running the DE at a constant speed for partial or low load regime. Also, high maintenance fee affects the system during low loading operations due to the cylinder glazing or, in worse cases, piston seizure [38].

VSDG is a solution to optimize engine consumption and increase system efficiency during different regimes. It improves system behavior by adapting DE speed with demanded mechanical load from the generator. VSDG improves efficiency, increases engine lifetime, reduces fuel consumption, and GHG emissions [39]. Conventional fixed speed DG are rarely able to operate at less than 50% of the maximal load, while VSDGs can operate for a long period at low rotational speed to support lower loads [40].

Several solutions are proposed in the literature to link the diesel engine speed with the mechanical torque required by the generator [41-44]. Some methods are focused on electric output treatment, while others are based on mechanical conversion to synchronize DE speed with the variable electric load profile.

2.3.1. Electrical approach to VSDG

Rotational speed and the output voltage of the DG are directly related. Moreover, the sinusoidal waveform produced by the generator itself may be distorted and affected due to the reduction of DE speed or even by non-linear load or load oscillations [45]. One technique to adjust and control the output voltage frequency and amplitude is to use power electronics. There are two different configurations to couple a power converter with a DG [40]. For the first, the power treatment uses a full-power converter connected to the power generator output. In this method, DE speed is adjusted to load variation. This configuration has shown fragile control system capability since there is no connection between the power converter output and the generator magnetic field [46]. With power drives, a robust DC-link is placed in parallel with two series of power switches to create constant, reliable DC voltage. The power is then converted to the desired three-phase AC voltage and frequency using a high power PWM inverter. However, this technique has no control over the power switches performance [46].

In the second configuration, the power generator and the converter are arranged to produce power based on the stator field or rotor position calculation. Robust but sophisticated control strategy made this technique popular. In [47], a variable speed diesel generator uses a back-to-back PWM voltage fed inverter.

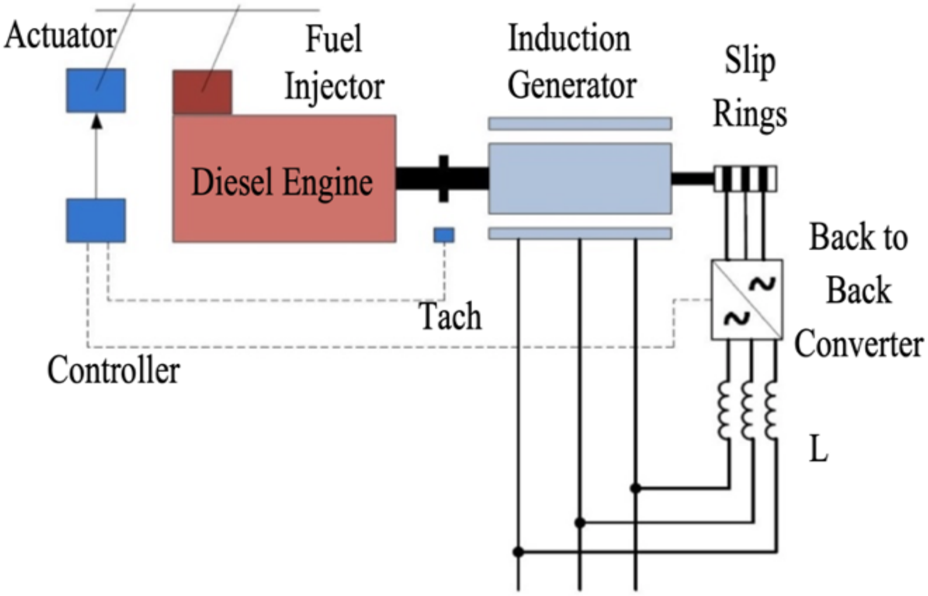


Figure 2-3. Variable speed diesel-engine with DFIG [40]

This inverter is integrated with the generator and connects the stator windings with the rotor shaft to regulate rotor magnetic flux based on load fluctuations. The magnitude of the produced voltage is controlled using a stator flux orientation strategy (Figure 2-3). In this topology, DE speed variation depends on the capacity of the back-to-back converter, and it could cover a similar range of operation regimes as the first technique.

VSDG using a power converter reduces fuel consumption by 20 to 50% [29]. Accordingly, this increases system efficiency, reduces GHG emissions, and improves fuel combustion. Maintenance fees decrease as fewer cylinder glazing, typical for the engine operation in a low load regime, occurs [48].

2.3.2. The mechanical approach to VSDG

A DG consists of two main components, a DE and an electric generator. Ambient temperature, fuel quality, air injection, and load variation are the main parameters that affect the DG performance. The operation of the DG outside prescribed values of these parameters may result in unintentional high fuel consumption, higher engine overall maintenance fees, and poor-quality electric production [49]. Mechanical techniques are available to maximize DG efficiency according to the variation of these parameters. Multi-cylinder ignition or cylinder deactivation management have extended engine life and optimized engine fuel profile compared to the conventional configurations. The load variation is a critical parameter that significantly affects the DE operation and performance. A mechanical converter or a flywheel storage system are used to improve DG efficiency during variable load conditions [50-53].

The mechanical techniques analyzed in this survey are already available in the industry sector. These methods concentrated on the diesel engine, such as to maintain a fixed speed at the electrical generator shaft and do not require power electronics to stabilize the voltage frequency and amplitude.

2.4. TECHNICAL AND ECONOMICAL ASPECTS OF VSDG

In a conventional DG, the DE runs at a constant speed to provide specific mechanical torque for an electric power generator without monitoring the electric load variation or engine efficiency [54]. The VSDG deals with the constraints mentioned above and adapts the operation, such as to improve efficiency while supply and demand are still balanced. Figure 2-4 illustrates a performance comparison between VSDG and conventional DG under different climate conditions [55].

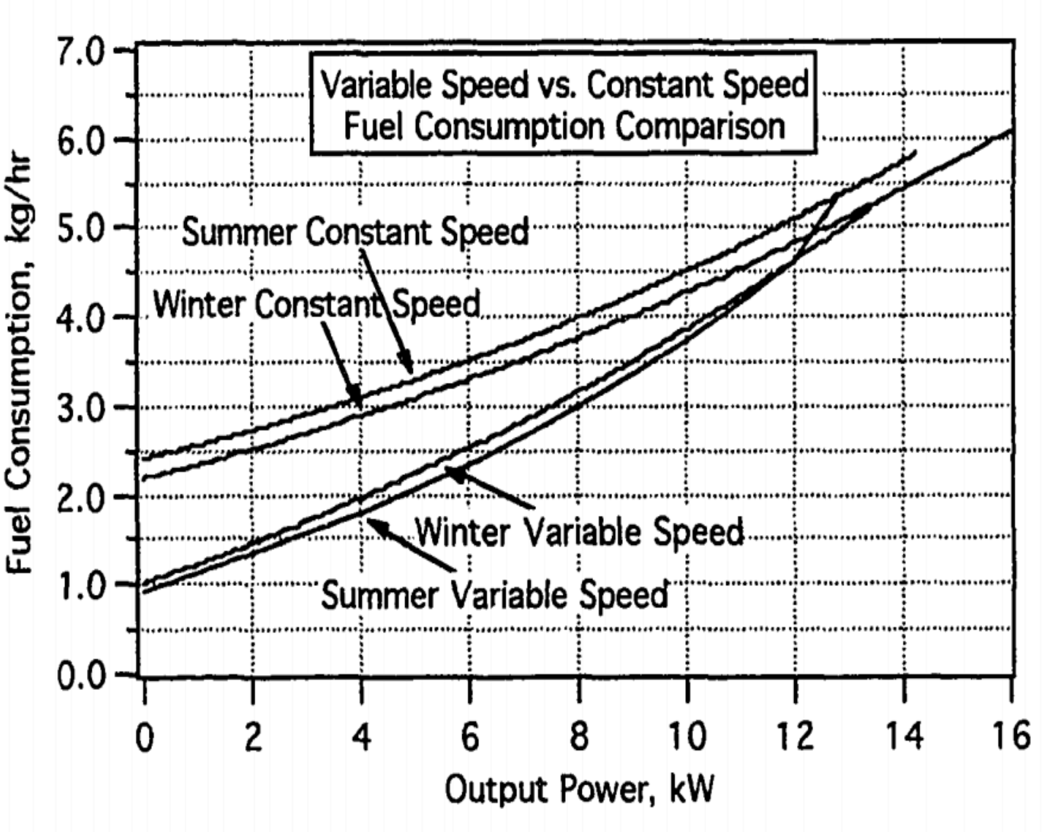


Figure 2-4. Comparison of different Genset applications [55]

Economic Improvement. As seen in Figure 2-4, the fuel consumption of a fixed speed diesel generator (FSDG) is higher than the one of a VSDG when the load decreases [56]. In

[57], the brake-specific fuel consumption (BSFC) profile of FSDG increases dramatically when the electric load is 30-40% of the full load while it remains almost constant for the VSDG, when DE speed is reduced and synchronized with the load. As a VSDG allow DE operation DE at its most efficient speed according to the load [58], the following advantages are expected:

- Better fuel efficiency (based on load characteristic)
- Engine lifetime augmentation
- Increase the time between engine overhaul

Technical Aspects. The amount of current absorbed from the generator varies according to load value, while the voltage and frequency should remain constant. In the generator, the stator poles absorb more magnetic flux from the rotor windings during peak loads. Consequently, to maintain the fixed speed required by a fixed voltage frequency and amplitude, the mechanical torque applied on the rotor shaft will inevitably increase [59].

The DE crankshaft, fixed with the rotor of the power generator, should provide enough mechanical torque to maintain power quality production. As the load decreases, in an FSDG, the DE crankshaft will maintain a fixed speed at lower torque this resulting in lower efficiency.

The VSDG equilibrates the operation of the power system to avoid excessive mechanical torque production during low load demand and to increase system efficiency. In VSDG, the DE, which provides mechanical torque for the power generator, slows down during low electric demand. This strategy saves fuel by adjusting the DE speed closer to its ideal regime to produce the required torque. Figure 2-5 illustrates how the engine torque and speed should be adapted to optimize fuel efficiency.

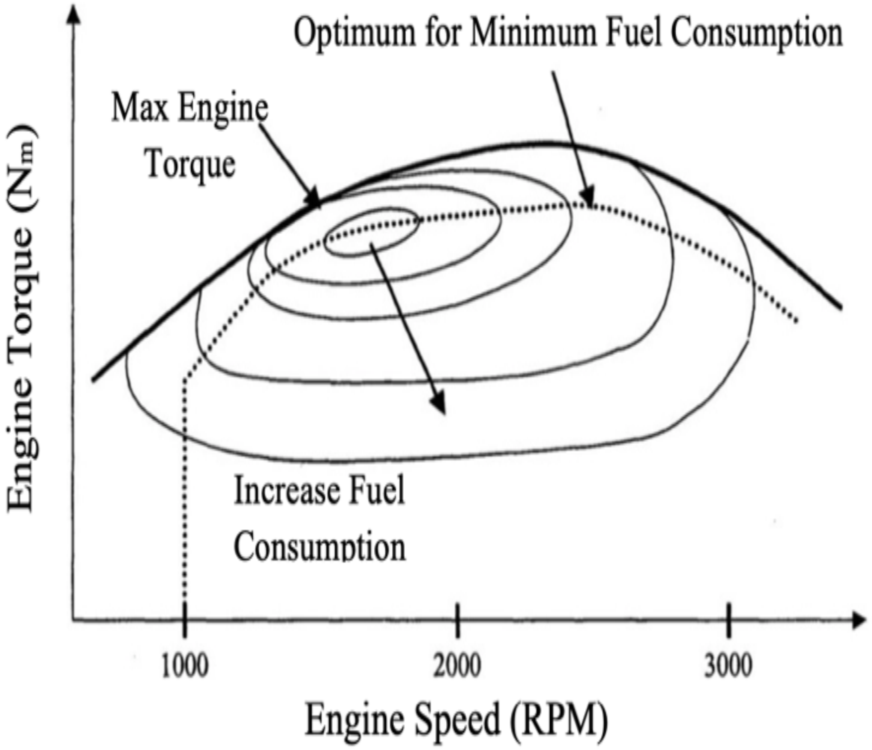


Figure 2-5. Example of DE characteristics connected with a two-pole generator [60]

2.5. OVERVIEW OF DIESEL ENGINE OPERATION CHARACTERISTICS AND PERFORMANCES

Diesel generators (DG) are extensively used in different sectors due to their reliability, availability, and durability. In this section, the main characteristics of DG operation and their influence on the DE performance requirements are addressed. Then, the study explores how the variable speed operation can reduce or eliminate some of the operational drawbacks associated with these requirements. For instance, by controlling the internal combustion quality of the DE, the amount of hazardous gas emission from the exhaust could be significantly reduced [61, 62].

An extensive survey of DE operational characteristics is expensive and complicated. One solution to avoid unnecessary expenses and torturous experiment process is to use models of the DE using sophisticated computer software and appropriate mathematical models. In [63], is presented a DE model that allows a better understanding of its performance and GHG emissions. The three most significant parameters to be considered in the DE analysis are the load characteristics, fuel consumption, and GHG emissions.

2.5.1. Load characteristics

Recently, intelligent DG systems are programmed to track demand-side behavior and adapt themselves within the most efficient operation level. Thus, electric production is maintained at a level close to existing or predicted load profiles. The electric production adapts itself with load variation. This strategy decreases system losses and increases production efficiency [64, 65].

These DGs are equipped with a DE designed and sized to meet the maximal load in every single application. These engines are working near to their optimum level while they supply 70-80% of full load [66, 67].

However, during low load operations, the DE efficiency declines sharply due to unnecessary or idle speed operation. One solution to avoid low efficiency is to adjust DE speed and mechanical torque with the load demand [68].

In the worst-case scenario, caused by load oscillations, the speed of a DG system fluctuates sharply in the event of a shortage due to an unpredictable line fault or when connecting to a large load. The risk of generator tripping is high due to a mismatch between the mechanical torque demanded on the crankshaft of the power generation system and its speed, especially in remote areas where there is no connection to the national grid [69].

Accordingly, sudden or/and considerable load variation could have significant drawbacks on generation systems such as:

- Increase the generator’s winding temperature

- Increase generators tripping risk
- Increased DG maintenance fee
- Uncomplete fuel burn and more air pollution

To avoid generator failure at idle or during large load variations, VSDG decreases the excessive speed of the DE and maintains appropriate mechanical torque in a steady-state condition.

2.5.2. Fuel consumption

Based on the above explanations, FSDG systems have reduced energy efficiency when operating at low loads. VSDG offers better partial load efficiency by reducing engine speed to an optimized value. These systems can yield a better efficiency by adjusting and programming DE speed with demanded load from the control unit [70]. Figure 2-6 shows the comparison between FSDG and VSDG of the specific fuel consumption (SFC) as a function of the load and engine speed. Instead of using VSDG, it is possible to use batteries or other forms of energy storage and stop the FSDG during low load conditions. When this method is used, the engine restarts when the load increases or the battery level is critical [71].

Another method proposed controlling the strength of the stator electrical field, based on load variation [58]. The system provides a suitable torque to meet the electrical demand. In fact, by weakening the stator field of synchronous generators during low electric load, the overall fuel efficiency improves.

An incremental algorithm has been proposed in [72] to track the minimum specific fuel consumption (SFC) operational points of energy conversion for a particular load. This algorithm avoids torque peaks during sudden changes if the system speed deviates from the reference speed. The research presents the modeling and speed control of diesel engines and power converters. During load fluctuations, an optimum operation point is reached using an efficient increment algorithm of SFC tracking. Also, this control method reduces the transient time of the output voltage when considering the load torque limitation and speed range.

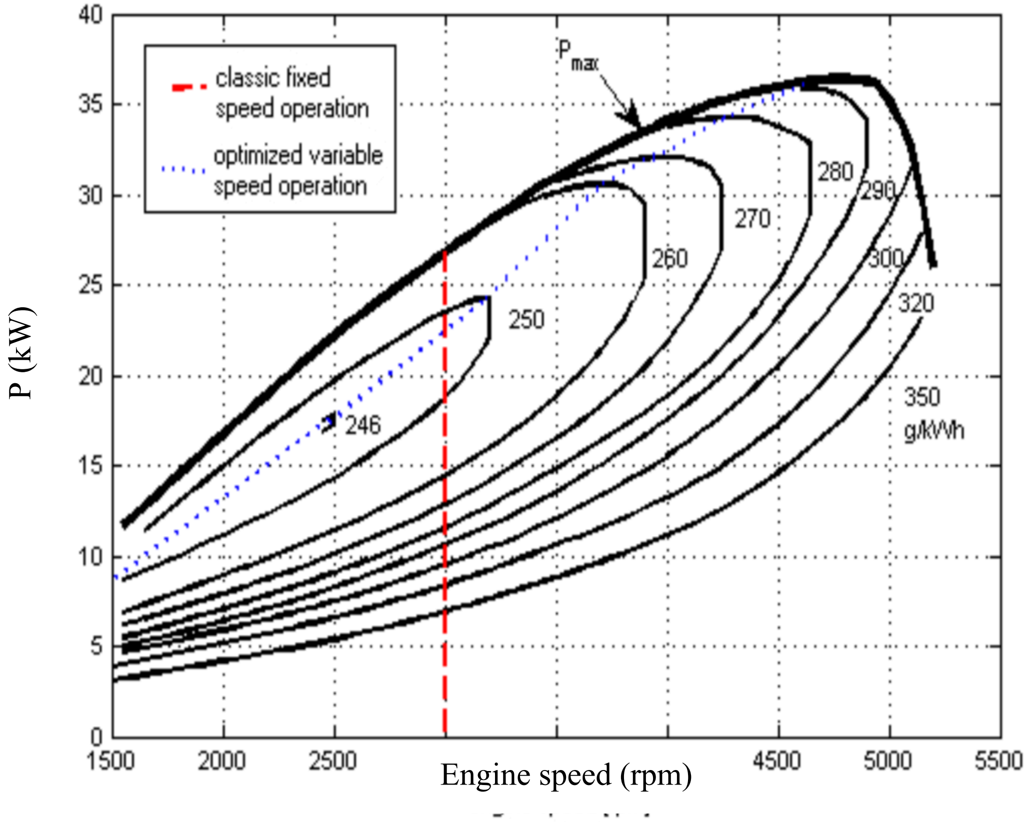


Figure 2-6. Fuel map of 25 kW (3000 rpm) diesel engine [71]

2.5.3. GHG emission

The effect of GHG emission is not limited only to climate change and global warming. The world health organization named various diseases, such as cardiovascular mortality and lung cancer, due to air pollution [73]. Based on the research proposed in [74], around 3.2 million people died in 2010 due to hazardous gas emission from diesel soot and exhaust gases.

The most damaging species of diesel exhaust gas are carbon dioxide (CO_2) and nitrogen oxides (NO_x). Global warming and human health risks are the two main reasons to reduce these emissions [75].

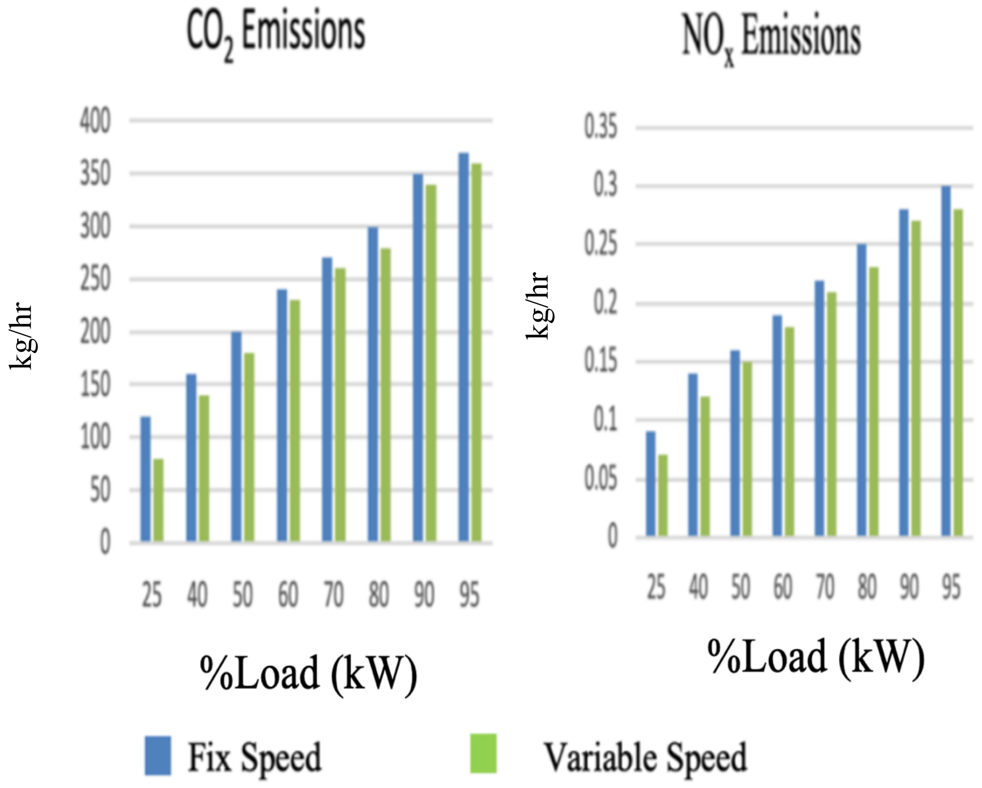


Figure 2-7. Improved GHG emission at different load levels [76]

Fuel standards have been tightened in recent years. For example, the sulfur concentration is limited in both gasoline and diesel [61, 77, 78]. Apart from fuel quality, the operation of DE at its ideal speed and cylinder ignition control associated with different load regimes reduce air pollution [79, 80]. Figure 2-7 illustrates the impact of using VSDG instead of FSDG on GHG emissions [43].

2.6. VARIABLE SPEED DIESEL GENERATOR TECHNOLOGIES

In this section, the characteristics of the most important technologies used for VSDGs, in particular the electrical and mechanical approaches that allow variable speed operation of the DE according to load variation, are presented. This study shows that the use of VSDGs increases fuel efficiency and reduces GHG emissions when operating with variable loads, typical of the use of DGs in standby or off-grid applications.

A VSDG is particularly suitable for hybrid systems that include highly variable renewable energy sources like wind and solar. These hybrid systems are optimized by introducing storage, especially for isolated communities where there is no national grid connection. This operational flexibility of VSDGs improves the efficiency of such systems by optimizing both Supply Side Management (SSM) and Demand Side Management (DSM) strategies, impossible to be done using the conventional FSDGs [81, 82].

2.6.1. Diesel engine driven double fed induction generator (DFIG)

Generally, for variable speed applications, power electronics are used to treat and regulate the output frequency and voltage, respectively. For a DFIG, the frequency and the output voltage are determined only by the power converters. In this topology, the engine speed can change within the power converters capacity.

The DE speed reduces or increases with electric load variation and within the capacity of power electronics [83]. Figure 2-8 indicates the schematic diagram of a back-to-back power converter connected to the DFIG.

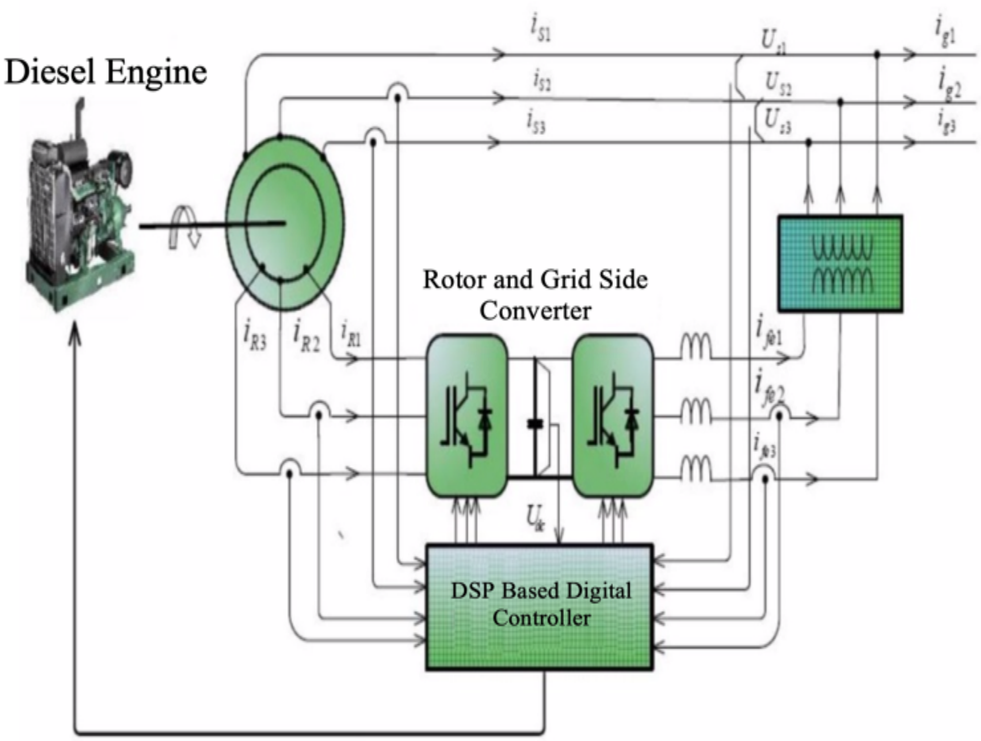


Figure 2-8. The basic configuration of DFIG coupled by diesel engine [83]

The power converter size is determined by the power production required, has to maintain power quality and avoid high system losses. These design constraints increase system security and power quality, respectively. One traditional method to determine power converter capacity is to size it at 30% of the total capacity of the machine rated power. Consequently, if DFIG operates beyond the recognized speed, output results may affect by the unwanted harmonics [84].

In the double-fed arrangement, stator outputs deliver fixed frequency and voltage to the AC load. One popular method to control the stator converter is vector controlled front-end converters. Normally, the aim of the stator side converter and its vector control method is to regulate the common DC-link. The common DC link is connected between the grid and the supply-side converter. On the other side, a three-phase voltage source PWM rotor inverter provides a reliable voltage for rotor windings.

The principle of this converter is to control produced voltage by sending feedback signals to the rotor as a reference parameter with the appropriate magnitude and position. Recently, researchers have chosen a sophisticated field orientation control (using sensors or sensorless) method to control the rotor side converter. This method provides a fast response by evaluating the rotor position. Thus, converters empower variable applications to operate below or above the required speed [85]. In DFIG applications, it is essential to assess the performance reliability of the system while the operation is under different loads [84].

2.6.2. Diesel driven wound-rotor induction generator (WRIG)

The VSDGs are widely used in different applications such as backup-supply, grid-connected and isolated communities. In variable speed applications, it is necessary to monitor the voltage amplitude and frequency deviation. However, in grid-connected applications, the regulation of the output voltage and frequency is less critical since they are dictated by the utility grid itself [86]. For standalone applications, these parameters are more difficult to maintain within operational constraints with rotor speed variation and electrical load fluctuations [87-89].

Among the various methods to control the VSDG output affected by rotor speed variation, only some of them focused on the effect of load fluctuations in the generation system. The most commonly used generators in DG sets are wound-rotor generators. This type of generator is assembled with a separate exciter system for voltage control and a speed governor for frequency control. The principle of this strategy is to keep the frequency and voltage constant by adjusting the current controller parameters equal to the practical machine constants [58, 90]. The wound-rotor generator with external excitation control configuration is shown in Figure 2-9.

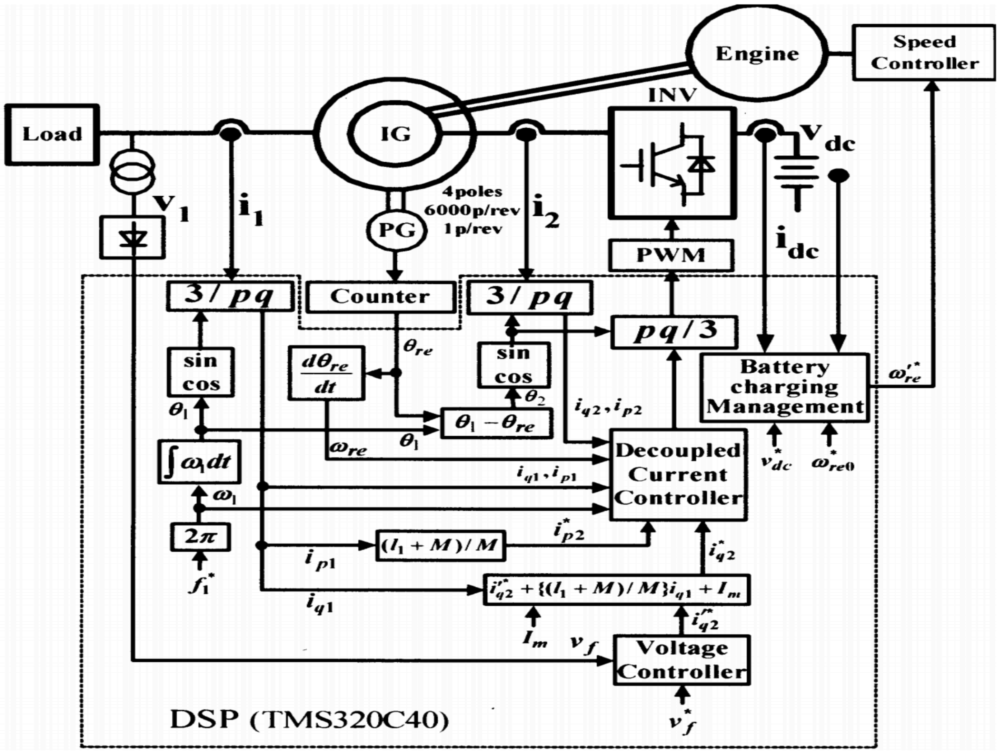


Figure 2-9. Wound rotor induction generator [91]

This configuration is close to DFIG as the capacitor and load are connected to the stator side, while the rotor side is connected to the inverter. The aim of the stator side capacitor is to repel the output voltage ripples coming from the inverters. Another advantage of using the stator side capacitor is to neutralize the inverter current, and it also provides the magnetizing current for the induction machine. Moreover, system voltage amplitude varies by controlling the stator side capacitor.

A controlled inverter stabilizes the voltage while the rotor speed varies with the load. Moreover, frequency regulation achieves by controlling the electric rotor angle (θ_r) [92]. The inverter and battery also serve for engine start-ups, and the battery charges and discharges depending on the power flow. As long as the engine uses the battery to start, it is essential to control battery SOC conditions during system operation to avoid the next start-up failure [91].

2.6.3. Diesel engine driven permanent magnet synchronous generator (PMSG)

A combination of PMSG with power conversion systems improves Genset performance, reduces power system harmonics, and develops a self-excitation control system in variable speed applications. Consequently, different studies focused on the integration of variable speed PMSG driven by a DE [93, 94]. These projects aim to control system outputs considering variable rotor speed according to the required engine torque, such as to meet maximum efficiency [95]. The solution proposed in [96] uses a fixed Capacitor-Thyristor controlled method to evaluate system stability during load variation. The goal is to maintain the frequency and voltage constant while PMSG is running in a standalone microgrid.

In [97], two parallel resonant amplifiers are used to regulate PMSG output voltage. These amplifiers are designed to repel maximum frequency disturbance using an LC filter. Voltage ripple treatment and third harmonic elimination have been accomplished in this research using a fully digital panel control.

In [98], an adaptive direct-tuning method controls the system DC-link voltage. Power converters, in parallel with the energy storage systems, improve system flexibility in case of dynamic performance and voltage control. The authors developed a transfer function control method named closed-form to control the DC-link voltage without being affected by non-linear loads.

Figure 2-10 proposes variable speed technology using a controlled battery system. In this study, a controlled three-phase PWM converter containing a bidirectional boost converter has been used to charge or discharge the battery based on different loads levels. In this DG set, PMSG speed varies based on a stop-start strategy. During low power demand, when the Internal Combustion Engine (ICE) would have operated at low efficiency, the control system stops ICE and battery banks energize the grid. Otherwise, the engine starts to support peak load or when the battery SOC decreases under its lower limit [96].

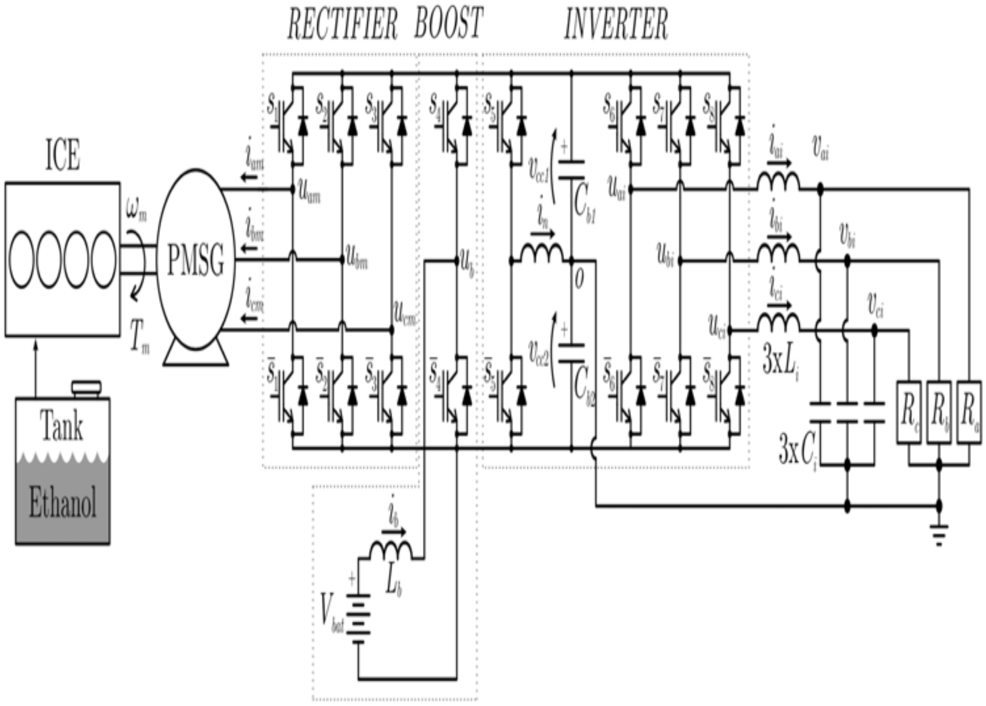


Figure 2-10. Variable speed stop-start technique for engine-generator system [96]

2.6.4. Engine-Generator Application with Super-Capacitor (EGSC)

The purpose of using a super-capacitor diesel generator (SCDG) in the power system is to compensate for substantial or sudden load change or to protect the grid as a backup choice in case of a power shortage.

One significant advantage of using this solution is to minimize the impact of the load fluctuation on the diesel engine. However, preparing such an arrangement with controlled rectifiers is complicated and not sufficient enough to produce a constant DC voltage during an unexpected load change [99].

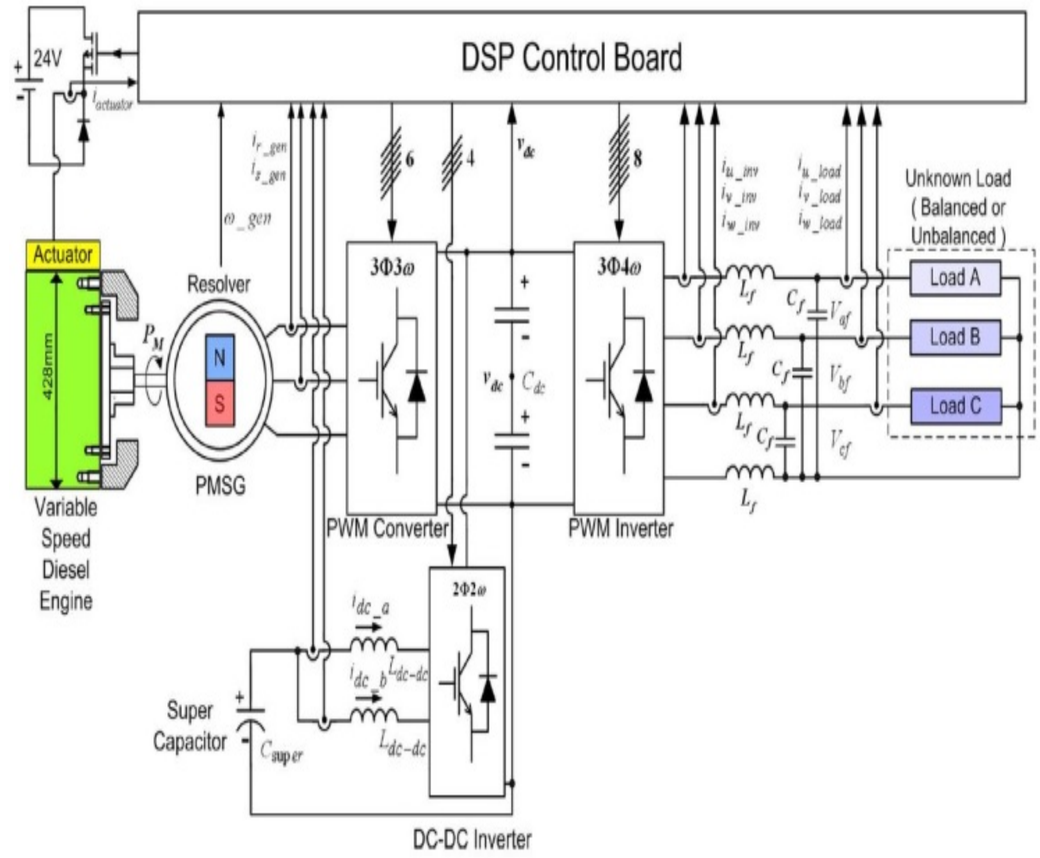


Figure 2-11. Configuration of VSDG based on super-capacitor [100]

The traditional method to meet different electric power demands is to adjust DE fuel hatch using a mechanical governor. However, the sluggish dynamic reaction of the DE produces high harmonic pollution [46, 101, 102]. In [103], a sophisticated storage system is integrated with an electric boat DG application to control voltage instability during transient loads. This configuration uses two separate bidirectional DC-DC converters for the super-capacitor and the battery storage. The advantage of such a design is to independently control the SC and the battery, based on the dynamic response limits. The reason behind using SC with battery storage simultaneously is the limitation of the battery SOC and the time of depletion.

Figure 2-11 illustrates a typical VSDG controlled by SC and power converters. Another method to repel the effect of instant load variation on DG performance is presented in [104], where buck-boost bidirectional DC-DC converters serve as an energy buffer with the SCs. In this design, the converters use AC/DC/AC conversion to provide constant frequency and voltage.

The authors have suggested two different circuit topologies and compared the results. In both configurations, energy buffers are connected to the DC-DC converter. As for the first connection, the buffer system is connected to the rectifier directly to simplify the system with a simple buck-boost converter. For the second connection, both buffer and inverter are connected using transformers. The role of transformers is to separately meet demand instabilities by isolating the input from output parameters.

2.6.5. Rotating-Stator mode for the Diesel Generator (RSDG)

This technology allows the DE to operate within its optimum range of speed while there is a considerable change in the electric load. Unlike other variable speed methods, this technique eliminates the sophisticated power electronics as the speed regulation is obtained through a new generator structure [27]. Figure 2-12 shows the PMSG generator using a rotating stator. In this technology, the rotor, fixed to the DE crankshaft, can slow down to increase efficiency, and the power generator achieves synchronous speed by rotating the stator in the opposite direction to the rotor. Accordingly, the resulting operation of the generator is not limited by the rotor shaft speed anymore.

The stator is equipped with several bearings installed on its outer layer. These bearings, located between the stator and the generator casing, allow the stator rotation driven by an external compensator motor. A pulley is fixed at the generator end and connected to the stator [105]. Therefore, by connecting the pulley to the external compensator motor, we can rotate the stator, such as the relative velocity between the stator and the rotor remains constant and synchronized. It is essential to mention that rotor and stator windings and all other components stay the same as the conventional one [76].

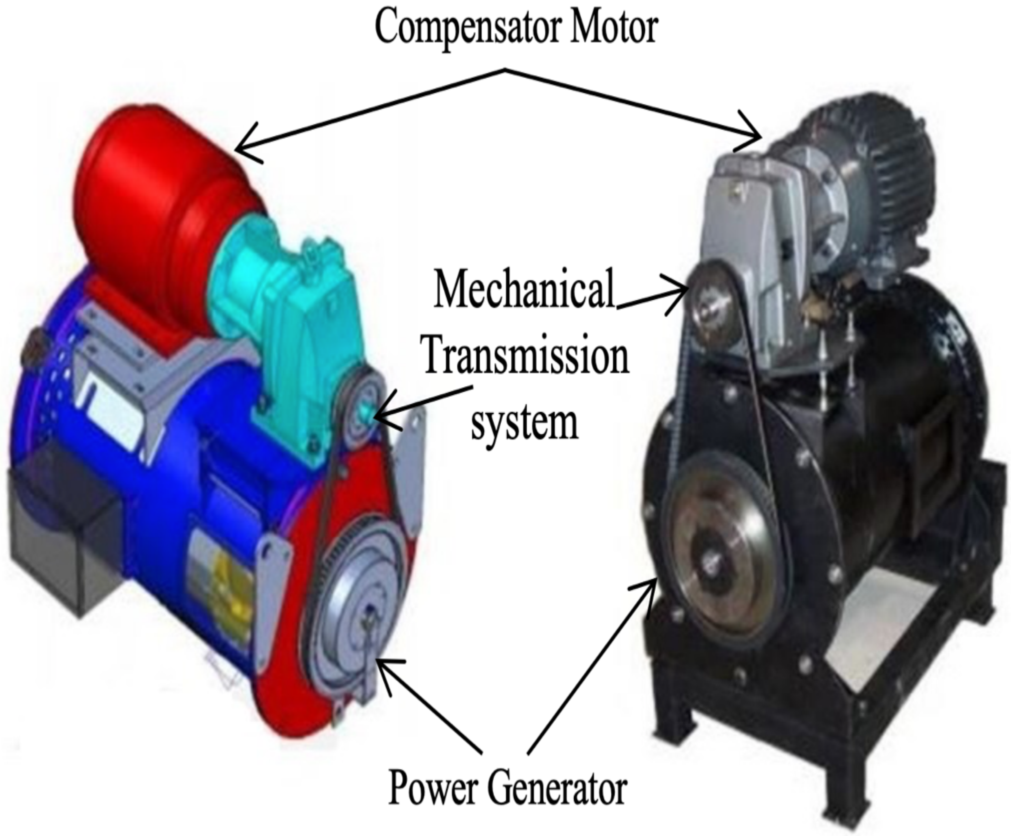


Figure 2-12. PMSG Configuration using a rotating stator [106]

The compensator motor (CM) is mounted on the generator casing and connected to the stator pulley using a timing-belt. The CM rotates the generator's stator part at different speeds in both directions. This motor works at both 50 and 60 Hz frequency, and the generator itself supplies its energy. The generator's rotor is coupled with the DE crankshaft and rotates solidarily at the same speed. During a low load operation, the DE speed slows to maintain the efficiency, and the compensator motor turns the stator in the opposite direction to maintain a synchronized relative speed [107].

For example, if we consider that according to the load value, the engine speed should be 1545 rpm to have maximum efficiency, then the rotor will also turn at 1545 rpm. The compensator motor drives the stator rotation in the opposite direction to the rotor, at 255 rpm.

Therefore, the rotor will rotate at a total relative speed of 1800 rpm to the stator as in a fixed speed generator, without using advanced power control or complicated excitation system [106]. As a result, we reduce the DE speed at the value corresponding to optimal efficiency and maintain the relative speed between the generator's rotor and stator.

2.6.6. Continuously Variable Transmission (CVT)

Continuously Variable Transmission (CVT) is a mechanical solution to adjust the DE speed with the demanded load. It enables the engine to run at different speeds without interfering with the powertrain. The CVT is installed between the DE and the generator to ensure the required synchronous speed when the DE slows down [108].

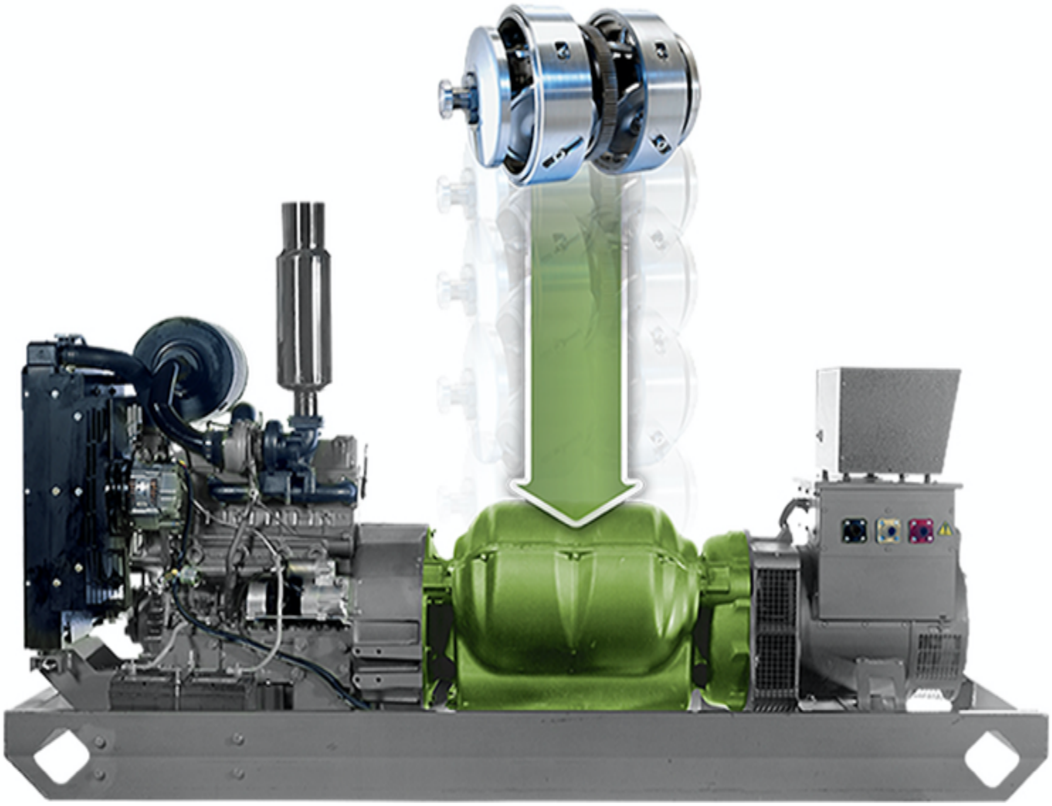


Figure 2-13. 125 kW Powertrain using CVT technology [108]

In the CVT technique, the engine crankshaft and the generator's rotor are coupled using a sophisticated variable gearbox. This mechanical device increases the system resilience by adapting DE speed with a demanded load while providing ideal speed for the generator itself [109]. Figure 2-13 indicates the developed Genset schema with a proposed CVT system. The variation of DE speed in this DG depends on CVT flexibility and electric demand.

More precisely, the voltages and frequency are maintained constant if load variations never exceed or fall beyond the CVT limits. This CVT operation saves up to 25% of fuel consumption in grid-connected applications. The integration of CVT technology with wind-solar applications reduces system complexity and improve DG reaction to load changes.

2.7. PERFORMANCE CRITERIA FOR DGS

DGs and, more specifically, the VSDGs, are frequently used for power production for their robustness, reliability, ease of use, immediate availability in different grid or off-grid configurations, and harsh climatic conditions in comparison with other electrical energy sources. However, there are circumstances when DGs performance is significantly affected by ambient conditions, load variation, and other operational characteristics. One purpose of this thesis is to highlight the critical points and parameters which could have tremendous consequences on the DG performance either in transient or steady-state situations. This part focuses on a few challenging factors of VSDG use.

2.7.1. Rate of adaptation to the power system

The characteristics and performances of VSDG applications are affected by their role and the integration with the power system.

Grid-connected DG. Grid-connected DGs are generally used to maintain grid conditions inside operational limits during unpredictable faults. The central grid stability improves with the availability of multiple, distributed, reliable, and predictable DGs, especially with the increased percentage of variable renewable energy sources connected to the grid. Therefore, a power shut down has fewer negative consequences on the consumers when local subgrids are powered with DG energy.

As electric grid connections are configured like a web, smaller areas are affected by a lack of electricity during power shortage [110, 111]. Starting, stopping, and synchronization of a typical VSDG system in a grid-connected application is simple and fast because the grid parameters never rely on a specific source of energy. One important advantage of VSDG when connected to the central grid is the capacity to synchronize DG speed to prevent alternator damage [112]. In conclusion, the most important role played by grid-connected GDs is to maintain grid parameters within acceptable limits during unpredictable faults [113, 114].

Standalone DG. Isolated electrical grids are more sensitive to electric loads fluctuation and engine speed variation. Therefore, for these applications, the objective is to minimize the cost of energy and control the system, such as to maintain output parameters within acceptable limits [115, 116].

Managing such a system is complicated and requires a comprehensive study of the load characteristics and the power switches limits. In [117], the VSDG is connected to the DC bus using power converters. The rotor speed follows the power demand from the DC bus side of the grid. The load power variation and the state of charge (SOC) of the batteries determine the control of different system parameters.

2.7.2. Diesel capacity and available power

Design choices (air-cooled or water-cooled) and sizing of every DG application depend on the required power, the operating and ambient conditions. The electric load and the instantaneous production from renewable sources are two momentous parameters that have major impacts on the DG performance [118]. In [24], the power-flow for a hybrid, standalone electrical grid was monitored for two years. A model based on field measurements was developed to increase efficiency and minimize fuel consumption. The main parameters influencing the design and sizing of the diesel generator for the hybrid system are:

- Annual Load Fluctuation (daily and seasonal graph)
- Annual Load Growth
- Incorporation of Diesel Constraint

Typical standalone electrical grids in remote communities are characterized by high load fluctuations with a peak load of 4 to 5 times higher than the average load. The traditional method defines the DG characteristics based on the peak load, safety margins, and future load growth prediction. However, low system efficiency and high maintenance fees are associated with this approach due to an oversized diesel plant [119, 120]. One way to avoid running a single, large diesel generator is to install multiple DGs with lower capacity and support the load using diesel cycling and dispatch strategy [24].

2.7.3. Efficiency

Load characteristics, fuel quality, ambient condition, engine design and capacity, humidity, and operation hours are the main parameters that affect DG’s efficiency. For instance, a low electric load or a high load fluctuation result in diesel engine idling time. Subsequently, the operation of diesel engine during idling time impair DE fuel consumption efficiency and power quality. Several standards and guidelines define how the manufacturers measure DG efficiency at the production line [121].

As a result, they define the operational limits that DGs should meet to supply an electric grid [122, 123]. Based on different conditions and criteria, several studies estimated how to improve DG performances. The German association VDEW-profile has introduced different DE duty cycles based on measured value and the real demand [124]. One practical method to increase efficiency is to calculate the engine fuel consumption based on a typical load profile using computer simulations. This method quickly identifies the errors in the simulation by comparing the results with the ones available from experimental tests. Accordingly, the analysis of the final results based on the different load's characteristics helps the engine control system to determine and adjust the optimal required rotational speed based on the load [125].

The energy efficiency of a DG is a combination of efficiencies of its two main components, the DE and the electric alternator. The overall Genset efficiency over a given period, i.e., in terms of energy, is defined by [126]:

$$\text{Genset Efficiency (\%)} = \frac{\text{Alternator Output Energy}_{kWh}}{\text{Caloric Energy of Burned Fuel}_{kWh}} \times 100 \tag{2.1}$$

In every single Genset application, several common and specific factors affect system efficiency. For instance, the penetration of an engine generator set in a hybrid standalone application may affect efficiency based on operation hours or the number of start-stops during a day. Moreover, a precise evaluation of DG sizing for a given application also may augment system efficiency [127, 128].

Genset system consists of an engine, and an electric generator that could have a separate efficiency of 30% to 60% and 85% to 95%, respectively. The combination of both, while operating as a main source of energy, varies from 30% to 55% [129, 130]. It is essential to mention that DG set efficiency may change during its operation according to several ambient conditions such as engine temperature or load condition.

2.7.4. Durability

Durability or endurance is an important factor that can significantly affect the feasibility, equipment availability, and maintenance fees under different operation conditions. This parameter is particularly critical for the engine part of the DG set. The durability of the engine is the probability that its structural material will withstand several charges that may or may not be time-dependent, such as fatigue, wear, corrosion, thermal equilibrium, mechanical stresses, chemical mechanisms, etc. [131]. Figure 2-14 indicates the stress and strength interference diagram that will characterize the durability and reliability of the Genset. In this graph, the stress represents the load, and the strength means the structural hardware capability. A durability test for engine components is conducted to check the threshold tolerance point of the different parts of the engine. During this test, sufficient mechanical or thermal stress is applied based on engine specific operation conditions [132].

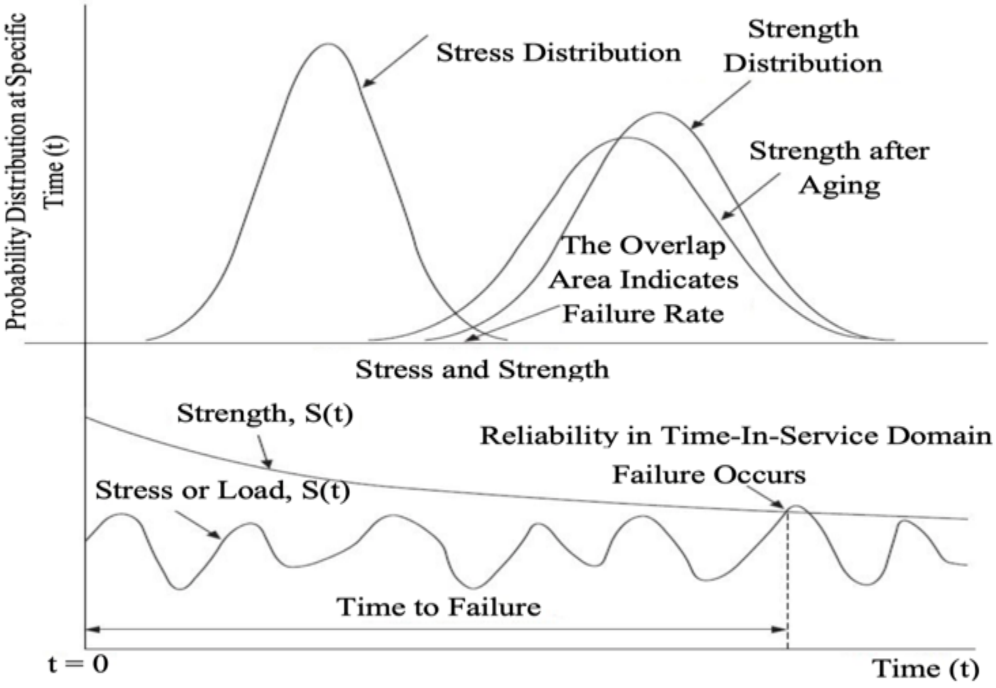


Figure 2-14. The random probability distribution of stress-strength [132]

For the electric generator, the durability is also vital, but mechanical failures are less frequent due to developed power switches and advanced monitoring techniques. However, long operation of the generator under the peak load regime or the unpredictable overload condition may increase the temperature of the windings and impair system isolation.

2.7.5. Genset criteria

One of the methods to ensure safe power quality for the end-user and to match the parameters of the different components is to define appropriate specifications for the power supply system. In the ISO 8528-1 standard for the power and performance of diesel generators, different rules and specifications are defined for the alternating current of the generator, the reciprocating internal combustion engine (RIC), greenhouse gas emissions, fuel type, and auxiliary equipment.

The ISO manual specifies four different classifications to help manufacturers and consumers have an everyday basis and a better understanding of the limitations of the system [133, 134].

- Emergency Standby Power
- Prime Rated Power
- Limited-Time Power
- Continuous Operating Power

Also, in each installation of a generator set, several factors are dictated by the ISO standards to be followed during production, such as maximum and minimum load demand, harmonics, power factors, and fuel quality [135]. These instructions make it possible to provide high-quality and efficient power on the demand side and simultaneously improve customer loyalty and retention.

2.7.6. Monitoring and system control

Each autonomous DG system must monitor its production and analyze the state of the system by receiving high-precision feedback during the various conditions mentioned above. Standalone grids in isolated communities require a sophisticated control method to regulate the system's frequency and voltage.

At the same time, grid-connected applications monitor the power system to be more flexible and secure in the event of a power outage. Speed estimation and adjustment are essential factors in variable speed control projects. One way to evaluate rotor position and speed is to use mechanical devices such as camshaft sensors or to use mathematical prediction of the rotor position without sensors [136]. Most of these methods used the same principle (d-q projection) to control the output power. For example, in [137], a hybrid wind-diesel system is controlled by an indirect vectorial approach. The author used d-q reference frames to model the generator.

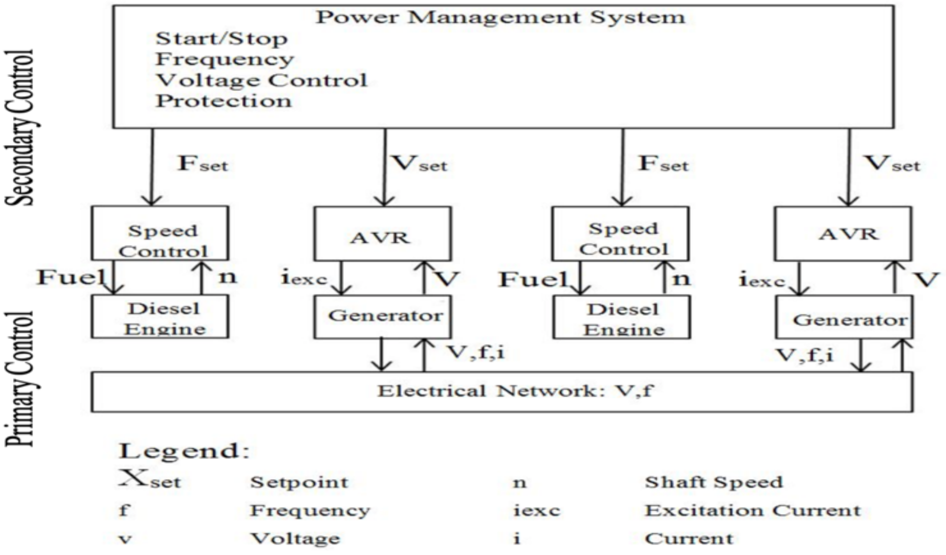


Figure 2-15. Schematic diagram of the control plan for frequency treatment [138]

The goal of this project is to couple the speed of the diesel engine with load variation and to adjust the electrical torque of the wind-powered generators to increase production efficiency. Figure 2-15 shows a typical strategy for monitoring and controlling the generator's power to produce a fixed frequency. In this method, both speed and voltage are maintained at a specific set point to keep the system output within the standard acceptable range.

During load fluctuations, the proposed energy management system provides an automatic start and stop function to protect the online system from overloads. Another method is proposed in [139] to compensate for the slow and non-linear characteristics of the diesel engine. The Sliding Mode Control (SMC) method for variable speed operation is used to control the system output using mathematical models.

An 11% fuel consumption reduction is achieved by designing a single sliding surface with a command law to track the oscillations appearing in the system based on the reference speed. In this technique, the command law is applied to the SMC controller to obtain a fast reference tracking and update the reference speed reference with the load variation. The author mentions that the SMC method monitors the system performance with zero steady-state error.

2.7.7. Fuel cost

Several parameters and phenomena affecting DG performances have been discussed above. Besides, ambient temperature, the power rating of the Genset, and fuel quality are essential factors that will affect fuel consumption. There is a relationship between fuel consumption and electricity production [140], and the fuel cost is calculated as [141]:

$$FC_i(t)=a_iP_{gen}^2(i,t)+b_iP_{gen}(i,t)+c_i(\$/h) \qquad (2.2)$$

$\mathrm{a_i}$, $\mathrm{b_i}$ and $\mathrm{c_i}$ are the cost coefficients of the diesel generator, FC_i is fuel cost and P_{gen} is the power produced by the DG.

2.7.8. Output power

DG production is within the maximum and minimum capacity limits released by the manufacturers. The rotational speed of the rotor, load impedance, and rotor excitation system affect the generator output. The power generated by the DG is defined as [141, 142]:

$$P_{gen}=P_n \times N_{gen} \times \eta_{gen} \tag{2.3}$$

N_{gen} is the number of generators, P_{gen} and P_n are the alternator generated power and nominal power in kW respectively and η_{gen} is the overall efficiency of the DG system.

2.7.9. Other aspects

Diesel-Generators are quick to start, durable in long operation hours, and can operate in various climate conditions. These characteristics made the use of DGs suitable to power multiple applications such as grid-connected, standalone, and emergency backup [143]. Moreover, the integration of DGs with renewable energies in distributed generation applications can highly increase system efficiency. Below are several aspects that need to be considered in every diesel-generator set:

- Timely repair or upgrade components
- Scheduled water and oil check
- Periodical service (oil changing-fuel, oil, and air filter changing)
- Battery inspection
- Generator inspection and connections cleaning
- Genset control panel and indicators

- Biweekly engine start (Back-up applications) [144]
- Verify exhaust and input air

2.8. OVERALL COMPARISON OF VSDG

We discussed, in the previous sections, several VSDG technologies and operational parameters for different applications. Each VSDG technique has advantages and inconveniences that make it better for a specific application and not necessarily for all of them. In this section, we evaluate how each VSDG solution is suitable for four different operation conditions: grid-connected application, island-mode operation with low load, fast load oscillation, and integration in a hybrid system.

2.8.1. Grid-connected applications (regulate frequency variation or to meet peak leveling period)

In grid-connected communities with slight load fluctuation or long periods of low load, CVT and RSDG are more efficient solutions due to low initial cost and simple control systems [107, 108]. However, the elimination of a power converter in RSDG made the system more efficient but in long-term projects. This technology can reduce by 20 to 50% fuel consumption depending on the load level. RSDG proved more efficient during low loads. In contrast, CVT can save fuel during load variation, but its speed variation cannot cover a wide range. In addition, these technologies may serve in grid-connected applications for frequency regulation and stability augmentation.

As for power quality, both technologies are vulnerable to unpredictable and fast load variations. The RSDG follows load variation and tries to adapt to it using a small control drive. This strategy may impair power quality for a few seconds. By design, the CVT technology adapts rapidly to load variation, but attenuation of different speeds may produce harmonic pollution.

2.8.2. Islanded mode operation with long low load operation

In the case of islanding with limited access to the national grid, an important parameter to be controlled is the apparent power.

Variable speed PMSG and DFIG may not be the best option for every application, but they are able to fairly adapt to both grid-connected and isolated operations. Low maintenance fees and high fuel-saving made these systems popular, among other methods. These techniques are better adapted for ramp-up operations. However, power converters are expensive and have limited capacity. The overall speed of the generation systems cannot move beyond or under converter capacity. Several studies are showing significant achievements by integrating variable engine driven PMSG or DFIG with renewable technologies in distributed generation applications. The majority have chosen different vector control strategies such as FOC or DTC using sensors or sensor-less methods [145, 146].

These methods are well developed to treat rotor or stator parameters and can be used efficiently in hybrid standalone or isolated applications (mines, telecommunication towers, etc.). The DFIG is easier to integrate with renewable energies as the power converter scheme uses a DC-link for SSC and RSC. This feature enables DFIG to operate in both sub and super synchronous speed. However, this arrangement increases control complexity and, in some cases, produces harmonic pollution in the power grid [147, 148].

Turning to PMSG driven by DE, brushless construction is an ideal AC machine for a DG set. However, this application needs energy storage to avoid low power quality in different unbalanced load conditions. For instance, the integration of PMSG with BESS provides active power conditioning and has shown its effectiveness in delivering standard power along with power factor correction and voltage regulation [18, 29]. A critical role of BESS is to save surplus active energy, which is produced during low electric load and releases it during unbalanced load conditions.

2.8.3. Fast load oscillation

In a typical power system, a large load fluctuation requires a sophisticated compensator storage system to avoid harmonic pollution. Therefore, a combination of power storage systems with variable speed power production, like in the SCDG, will cope with these challenges. Supercapacitors can provide more power density, farads, and life cycles. However, system control and operation are more complicated as the storage system needs to adapt to the system uncertainties [149]. It is essential to control the supercapacitor discharge process and improve its charging procedure. Also, the accurate sizing and control of the supercapacitor in a typical power system are necessary to avoid capacitor failure are other serious challenges. Due to the mentioned parameters and based on a typical load, the system cost is more expensive compared to other VSDG techniques, including high maintenance or renovation fees. Overall, SCDG has shown reliable performance when the storage system compensates voltage fluctuations, and the power converter regulates output frequency. One advantage of using supercapacitors is the ability to supply excessive power for a few seconds, even out of engine capacity.

2.8.4. Integration in a hybrid system (penetration of VSDG in renewable energy applications)

WRIG is more efficient in grid-connected applications or combined with other renewable sources of energy as its dynamic response is slow and cannot support sudden large load changes [150]. However, WRIG can reduce fuel consumption and pollution in standby or autonomous operation of large DG, up to 20–40 MW. Moreover, below 1.5–2 MW/unit, the use of WRIG is not justified in terms of cost versus performance when compared with full-power rating converter synchronous or cage-rotor induction generator systems [151].

On the other hand, this method needs an extra mechanical device (flywheel) to avoid harmful effects on the rotor shaft in the case of a grid power shortage. Since the excitation system is controlled directly by the limited capacity inverter, a sudden and huge change may ruin rotor winding [86]. However, WRIG is less expensive than other techniques since its structure is simple and needs less maintenance.A power converter installed on the stator side of the machine improves the power quality. Therefore, the converter capacitors can provide magnetizing current for the machine itself. This configuration reduces the ripple coming from the power grid.

2.9. CASE STUDY OF DE DRIVEN VARIABLE SPEED DOUBLY-FED INDUCTION GENERATOR

To increase the efficiency of diesel engine driven DFIG and to control electric generator output while the power system experiences abnormal conditions, different power converter interfaces have been suggested. Back to back power converters are divided into the rotor side converter (RSC) and stator side converter (SSC). These converters update generator parameters instantly using the vector control method. Rectifiers, inverters, and choppers are the recognized controlled power switches to achieve ideal voltage and frequency at the point of common coupling (PCC). Moreover, in isolated communities with backup storage systems, these components integrate the storage system with the PCC [142].

However, the presence of different power switches generate losses, impair power quality, and increase capacitor breakdown risk. Diesel generators use an AVR system to control the rotor magnetic field. This electric device maintains the output voltage at a reference value during steady-state operation. However, the AVR system is not adequate to maintain the output voltage constant during the transient behavior of the power grid.

Consequently, an additional controller package is installed in a Genset application to control the system during unpredictable circumstances. Two types of back-to-back power converter topologies are used with doubly-fed variable speed induction generators as follows.

2.9.1. Control of the rotor side converter

The basis of this arrangement is to inject controlled three-phase voltage into the rotor circuit and to regulate produced power within the standard grid codes while DE speed slows down in a low load regime [152]. Besides, different applicable control methods are projected with RSC arrangement to tackle the challenges of integrating the VSDG in the power system.

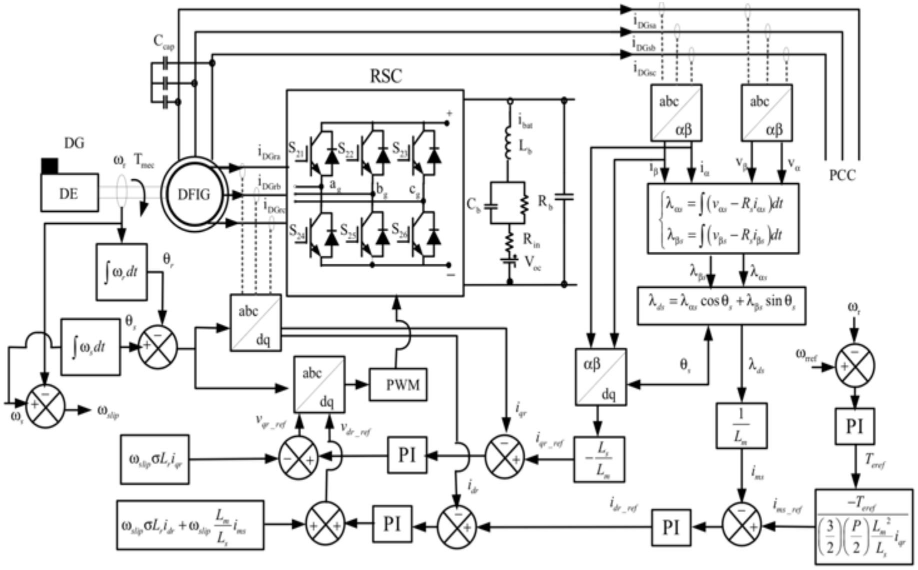


Figure 2-16. Indirect stator flux-oriented control for rotor side converter [153]

One purpose of the RSC is to treat generated active power while the generator is operating at super or sub synchronous mode. The principle structure of RSC is simply matched with the generator model presented in dq-projection. Accordingly, the active and the reactive power of the generator are represented by the d and q axis of the rotor, respectively. Consequently, the generator excitation current is an important parameter that can be provided and adjusted by RSC [154]. The indirect stator flux-oriented control algorithm is a typical control method to adapt to the RSC and regulate the produced electric energy through stator flux [153, 155, 156]. Figure 2-16 indicates a popular control technique for a DFIG using a vector control strategy. In this method, the dq-transformation separates the active and reactive current. The q-axis current represents DFIG torque and controls the active power, while d-axis characterizes machine flux to control reactive power [157].

2.9.2. Control of the stator side converter

Stator Side Converter (SSC) is mostly employed to control the available power of DC-Link considering demand-side slip magnitude or to supply electric load by controlling reactive power [158, 159].

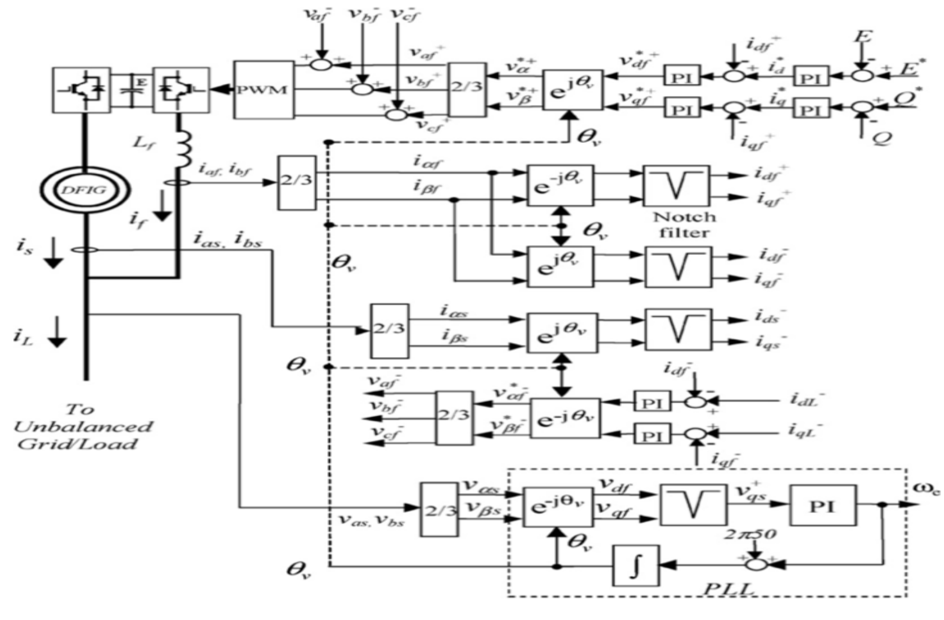


Figure 2-17. Stator side converter using vector control technique [160]

The main objective of the stator-side converter is to maintain the DC-link voltage constant regardless of the magnitude and direction of the slip power. A current-regulated

PWM scheme is used, where q and d axes currents regulate DC-link voltage and reactive power, respectively.

Figure 2-17 indicates a negative sequence stator voltage control algorithm using SSC arrangement. Several studies have targeted SSC structure to develop a control method for a specific application.

In [159], symmetrical components and a vector control scheme are applied to the SCC. The SSC serves as an active shunt filter to control unbalanced load conditions and compensate reactive power for the demand side. Two RSC and SSC power inverters have been used in [160] as a control drive. The role of the SSC is to compensate for the voltage and current uncertainties by sending regulated current into the grid.

This vector controller uses negative sequence currents to compensate for the stator voltage connecting to the unbalanced load. The control algorithm uses notch filters and a PI controller to adjust the orientation of the reference frame. The authors consider the proposed technique as a reliable application in different grid-connected or standalone communities using fixed or variable speed production.

2.10. DISCUSSION

DGs are set to work as a backup during power outages or to support the load in remote areas not connected to the national grid. Most of the time, these DGs are working at a constant speed to produce reliable AC power, while electrical energy demand is fluctuating according to instantaneous needs. In remote areas, high electric loads occur only during a few hours a day, which results in oversizing of DGs.

During a low load operation, DGs are facing poor fuel efficiency and condensation of fuel residues on the walls of engine cylinders that increase friction and premature wear. When load power decreases, a reduction in both mechanical torque and rotational speed of the diesel engine will maintain the combustion efficiency near the levels of the nominal regime. Accordingly, the generator itself should operate at a variable speed, which normally requires power electronics converters. One solution to increase combustion efficiency at low electric loads is to reduce diesel engine (DE) speed to its ideal regime according to the mechanical torque required by the electrical generator. Therefore, Variable Speed Diesel Generators (VSDGs) allow operation of the diesel engine at optimal speed according to the electrical load but require additional electrical equipment and control to maintain the power output to electrical standards.

In this chapter, several variable speed power generators (VSDG) techniques have presented. The essential characteristics and parameters and identified the comparison criteria for various applications are discussed in detailed. The design of VSDG's control algorithm should achieve voltage and frequency regulation, harmonic minimization, optimum engine speed, GHG emission reduction and etc. The use of one of the different VSDG solutions may reduce by up to 40% fuel consumption according to specific application conditions.

The majority of the VSDG solutions are inefficient during huge electric load oscillations. In terms of hybridization, the integration of VSDG with renewable energy technologies in standalone application considerably increase engine efficiency, improve system stability, and optimize energy cost.

CHAPTER 3

MODELING AND SIMULATION OF A NOVEL ROTATING-STATOR STRUCTURE FOR DIESEL ENGINE DRIVEN PERMANENT MAGNET SYNCHRONOUS GENERATOR

Résumé

Une des solutions pour réduire la consommation de carburant des génératrices diesel (DG) est d'adapter la vitesse de rotation au couple mécanique du vilebrequin. Lorsque la puissance de charge diminue, une réduction à la fois du couple mécanique et de la vitesse de rotation du moteur diesel maintiendra l'efficacité de la combustion près des niveaux du régime nominal. En conséquence, le générateur lui-même doit fonctionner à une vitesse variable qui nécessite normalement des convertisseurs d'électronique de puissance. Dans ce chapitre, nous explorons un nouveau concept de générateur qui utilise un stator tournant dans le sens opposé au rotor tel que la vitesse relative entre les deux composants reste constante lorsque le moteur diesel ralentit. Le stator lui-même est entraîné par un moteur synchrone compensateur (CM) tel que la vitesse relative du rotor est constante, éliminant ainsi l'électronique de puissance sophistiquée. Le modèle développé pour la machine synchrone à stator rotatif est basé sur la transformation de Park. Ce nouveau concept a été modélisé à l'aide du logiciel MATLAB. Une analyse expérimentale a été menée à l'aide d'un GENSET diesel de 500 kW équipé d'un générateur synchrone à aimant permanent (PMSG). Les résultats numériques et expérimentaux sont en bon accord et démontrent que la consommation de carburant est réduite avec un stator rotatif pour PMSG lors de faibles charges électriques.

MODELING AND SIMULATION OF A NOVEL ROTATING-STATOR STRUCTURE FOR DIESEL-DRIVEN PERMANENT MAGNET SYNCHRONOUS GENERATOR

3.1. INTRODUCTION

Regardless of all improvements in renewable energy sustainability, various applications and communities are still dependent on DG to meet their energy demand. Durability and reliability of DG made this application popular compared to other power sources in remote sites, with electric load oscillations and/or facing difficult weather conditions [161].

In Canada, there are numerous remote areas with limited accessibility, especially during winter months, where diesel engines (DE) are used to meet electricity demand such as telecommunication stations, mines, and villages.

In these sites, diesel engines are working non-stop even during low-load demand, which results in important GHG emissions and other negative consequences. For instance, high energy costs and environmental risks and impacts are associated with fuel transportation and storage in these remote areas [162-166].

Diesel engine and generator speed are synchronized. The crankshaft of DE is coupled to the rotor of the SG. The SG needs to rotate at its nominal speed to produce reliable electricity either in full load or low load. Thus, the DE, coupled with the SG rotor, should inevitably rotate at SG's nominal speed [81]. The variation of diesel engine speed results in poor power quality production. Electronic devices and electric apparatuses are sensitive to and affected by poor power quality and high harmonics [167].

Therefore, it is critical to control the DE speed to produce a constant frequency and voltage. The fuel governor is a mechanical device that adjusts the fuel injection to maintain the nominal speed when load power and associated torque vary. However, this controller accuracy is limited, and the adaptation of DE speed is relatively slow during electrical load oscillations [168].

Consequently, the DE runs at a fixed speed at all regimes with its best fuel efficiency at nominal power. When DE operates at different regimes than nominal, its efficiency is reduced, sometimes significantly. Especially at low regimes, poor fuel efficiency and high maintenance cost significantly affect DG operation [169-171]. Specific fuel consumption (SFC) rate for DE is also affected by other operating parameters such as appropriate maintenance, loads, and ambient temperature [172].

Therefore, a major inconvenience of operating DE at a fixed speed is that its efficiency is optimal at nominal power but decreases sharply at lower regimes [173]. One solution to improve the operation efficiency of the DE is to adapt its rotational speed to the load power (torque of the generator), such as to operate at maximum efficiency at all regimes [81].

This means that it is necessary to reduce the rotational speed of the DE at the lower regime and, consequently, have a diesel generator that can operate at variable speed.

The “classic” solution to adapt the DE speed to the required torque from the generator is to use power converters [35, 174] or variable speed gearbox [175, 176].

To decrease fuel consumption, the synchronous generator should operate at variable speed, the one that is optimal for the diesel engine. A sophisticated electrical power converter could compensate for the voltage and power output when the synchronous generator operates at variable speed. However, the other way to provide the desired torque for the generator is to use a complicated mechanical gearbox [175]. Continuously variable transmission (CVT) enables the generator to produce constant frequency while the engine revolution per minute (rpm) varies.

CVT provides adequate mechanical torque for the electrical generator while it is transferring rotational energy from the diesel engine. This study proposes a new solution to operate the diesel generator at variable speed using a synchronous generator with a rotating stator [177-179]. The stator of this new generator rotates in the opposite direction to the rotor, such as the relative velocity between the two components remains constant when the diesel engine slows down. The stator itself is driven by a compensator synchronous motor (CM) such as the relative velocity of the rotor is constant to avoid any harmonics or poor power quality and to eliminate sophisticated power electronics or complicated variable transmission. This technology could lead the system to provide a better fuel efficiency profile by running the diesel engine at its most ideal throttle. As a result, this causes the combustion chamber to avoid bore glazing issues and increase DE life [172].

This chapter presents the new system and develop a model for the synchronous machine with a rotating stator based on the d-q transformation. Numerical modeling with MATLAB and experimental analysis conducted for a 500-kW DG with a rotating stator demonstrate the fuel consumption reduction during low electrical loads.

3.2. APPLICATION OF VSDG AND ROTATING STATOR MODEL

3.2.1. System description

The major aim of this project is to reduce DE speed at low regimes to maintain higher fuel consumption efficiency. In the meantime, the synchronous generator needs to rotate at its synchronous speed to produce high-quality power whatever the load. In a conventional GENSET system, the diesel engine crankshaft connected to the rotor of the SG runs at 1800 rpm to produce 60 Hz frequency [175].

In this research, the electrical generator is modified to reach the resulting synchronous speed while the rotor slows down to increase efficiency. In this new SG concept, an innovative rotating-mode stator design has been introduced to keep total synchronous speed constant while DE speed reduces to its ideal regime. The original idea has focused on the stator part of PMSG. Thus, obtaining a nominal speed for the electrical generator is not limited to rotor speed anymore. Synchronous speed could be achieved by controlling the compound speed (Rotor and Stator Speed).

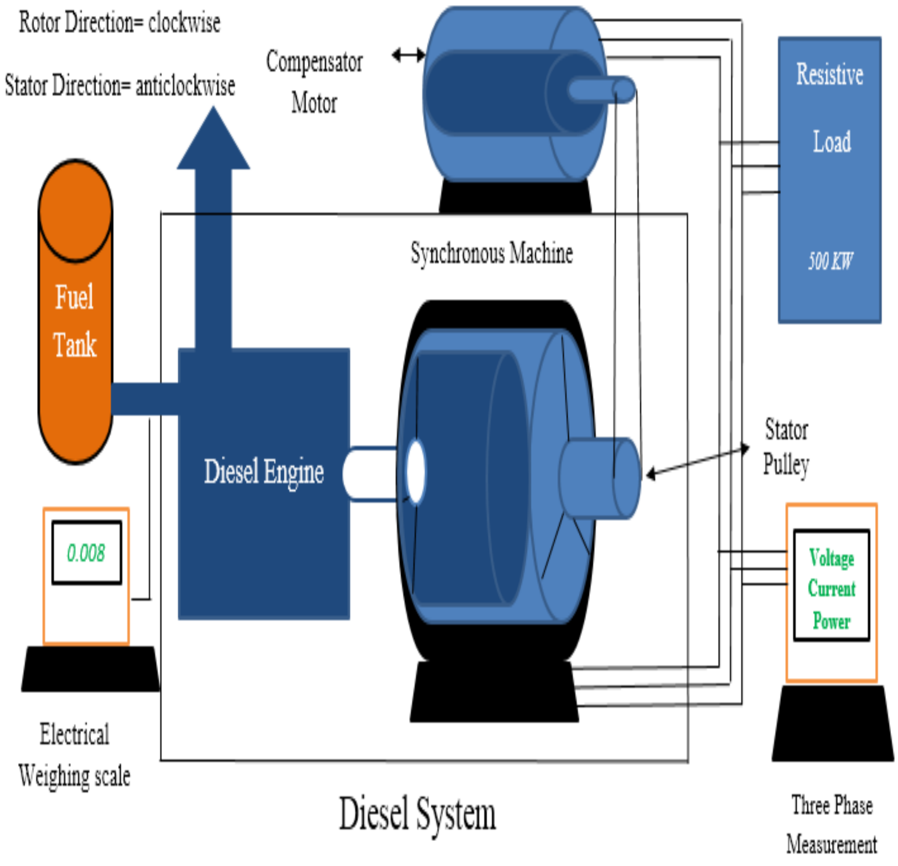


Figure 3-1. VSDG based on rotating stator

The major aim of this project is to reduce DE speed at low regimes to maintain higher fuel consumption efficiency. In the meantime, the SG needs to rotate at its synchronous speed to produce high-quality power whatever the load. In a conventional GENSET system, the diesel engine crankshaft connected to the rotor of the SG runs at 1800 rpm to produce 60 Hz frequency [175].

Figure 3-1 illustrates the GENSET scheme using a rotating synchronous stator. The stator of the SG is coupled with a compensator motor, and the rotor moves solidarily with the DE crankshaft. The CM rotates the stator in the opposite direction of the rotor speed variation to compensate and maintain the synchronous speed for the PMSG.

3.2.2. Rotating stator concept

Based on the explanation before, this research proposes a rotating stator for a PMSG structure and simultaneously tries to follow the standard limitations regarding harmonics, voltages and currents. In this application, PMSG has developed by a series of separate bearings installed on the external body of the stator end and it was tried to make it rotatory with minimum friction. Regarding conventional SG structure, stator is fixed with machine casing [180]. But in this research both rotor and stator are rotating around the same axis. Moreover, the stator windings and connections remain the same as the conventional one.

A pulley has attached at the end of synchronous machine casing and connected to the stator. Therefore, by applying dynamic force on the pulley, stator starts to rotate at our ideal direction and speed. The 75-kW synchronous motor (compensator motor) is mounted on the body of the 500-kW generator and coupled by the stator pulley using timing-belt.

In this study, CM has adjusted to rotate the stator in the reverse direction of rotor rotation (Rotor has already coupled by the crankshaft of DG). The compensator motor supplied by the PMSG production during low load connection. Thus, the small fraction of GENSET production consumed by itself (compensator motor). Finally, this technology helps DE to reduce the speed to its ideal regime whereas SG total speed kept constant by the help of CM. Design of the rotating stator machine and system parameters are established in Canadian intellectual property and the detailed patent is given in appendix IV.

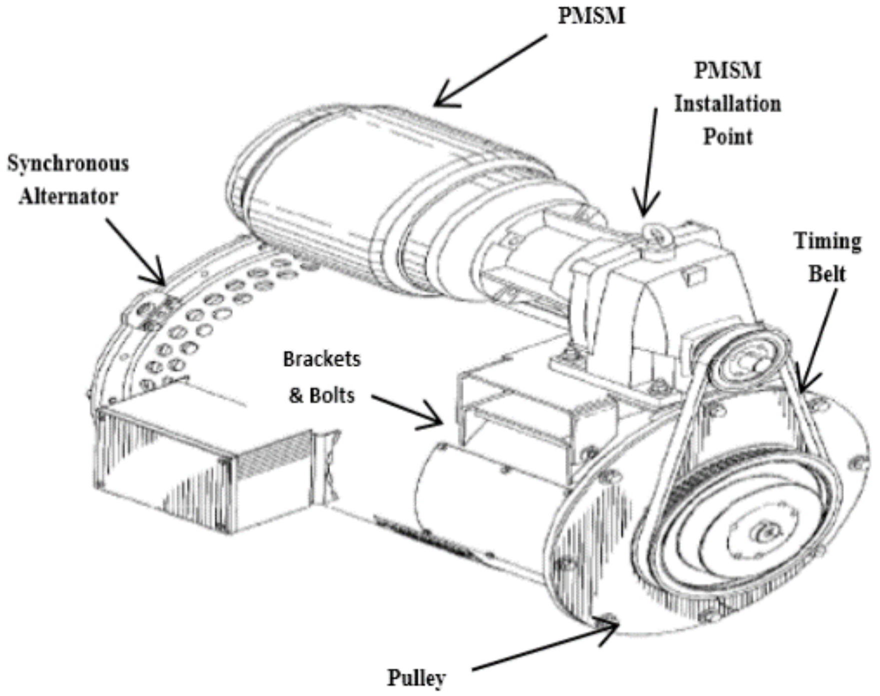


Figure 3-2. Rotating-Mode stator scheme for PMSG

Figure 3-2 illustrates the primary portrait of a rotating stator connected to the synchronous motor via a timing belt. One side of the SG is connected with the compensator motor, and the other side (rotor) is fixed to the DE (crankshaft). In terms of different regimes, controlling synchronous speed (η_{sync}) for variable speed GENSET application is one of the major challenges in electric production [181].

Variable speed stator technology for the SG, leads this application to achieve synchronous speed without any interference on DE performance or using power converters. In this new structure, both rotor and stator rotate around the same axis but in different directions. Stator speed rotation (η_s) is in a reverse direction of rotor speed rotation (η_r) to compensate for producing synchronous speed. Therefore, the primary assumption equation is written as follow:

$$\eta_{sync(Total)} = \eta_{Rotor} + \eta_{Stator} \tag{3.1}$$

Harmonic treatment and low power quality compensation need sophisticated power converters in case of variable speed production. Accordingly, 1800 rpm is necessary for PMSG to produce 60 Hz frequency [35]. Rotating stator technology operates in a wide range of speeds and increases system durability by eliminating complicated mechanical gearbox or electrical converters.

3.2.3. Proposed SG model using d-q projection

The SGs as electrical machine are important in power generation, and the need for precise modeling is critical during the time of optimization or development research [182]. The main purpose of the investigation on PMSG model using Park transformation is to adapt the existing model with a rotating-mode stator. Existing synchronous machines in MATLAB power system library propose conventional PMSG with a fixed stator part.

Therefore, the development of a synchronous machine model is necessary to adapt the rotatory stator for new PMSG. The new model is capable of showing SG performance using two independent mechanical inputs. This projection leads PMSG model to achieve synchronous speed using either rotor speed, stator speed, or the combination of both stator and rotor speed. This model could also be used in a transient state, unbalance load, or line faults. The full order model of SG represents four different sets of windings.

The direct axis (D) represents field winding (f_d) and a damper winding (k_d), both are assumed on D-axis. To create symmetry, an excitation winding is also considered on the quadrature axis (q). Two damper windings k_{q1} and k_{q2} are defined on the q-axis, which is perpendicular to the d-axis position [183, 184]. By considering the stator and rotor windings for a sinusoidal distribution, the primary equations could illustrate in a matrix format shown as (3.2).

$$\begin{cases} V_{abcs} = r_s i_{abcs} + p\lambda_{abcs} \\ V_{qdr} = r_r\, i_{qdr} + \mathrm{p}\, \lambda_{qdr} \end{cases} \tag{3.2}$$

Index (s) and (r) are the stator and rotor parameters. r_s and r_r are the diagonal matrices for a linear magnetic system. The rotor equations are transferred to the stator side to keep both machine parts in the same reference frame and facilitate the calculations of the salient rotor synchronous machine [185]. The leakage flux of the synchronous machine, including the stator and rotor flux equations, is shown in (2).

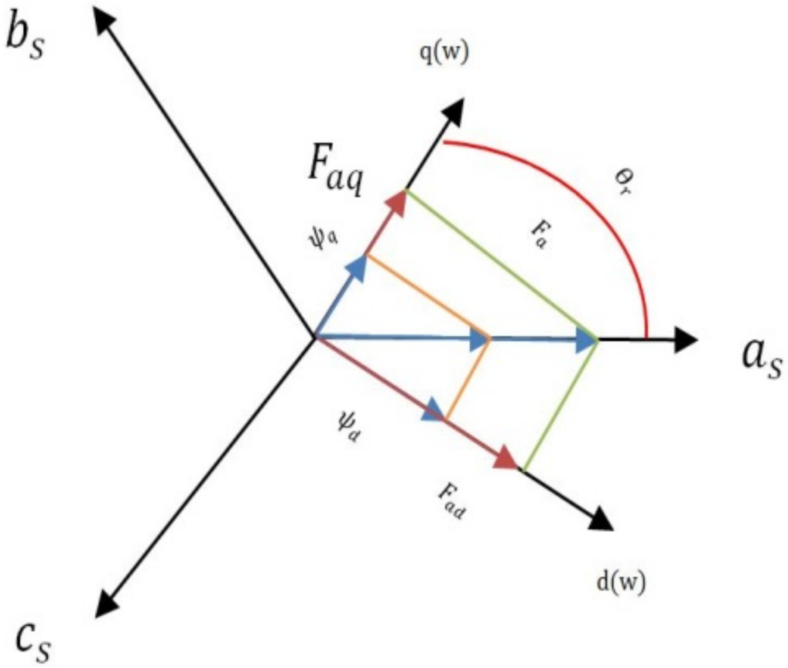


Figure 3-3. d-q axis phasor diagram [185]

$$\begin{bmatrix} \lambda_{abcs} \\ \lambda_{qdr} \end{bmatrix} = \begin{bmatrix} L_s & L_{sr} \\ L_{sr}^T & L_r \end{bmatrix} \begin{bmatrix} i_{abcs} \\ i_{qdr} \end{bmatrix} \tag{3.3}$$

(L_s) is the inductance between the stator windings, (L_r) is the inductance between the rotor windings and(L_{sr}) is the mutual inductance between the stator windings and the rotor windings. It is essential to consider the stator windings flux variable with time due to the dynamic behavior of the salient rotor machine. Figure 3-3 illustrates the graphical evaluation to find the stator inductance position (L_s) using salient rotor [182, 184].

The stator inductance varies with time, while the salient rotor is rotating around its axis. In (3), the primary flux inductance equations are expanded.

$$\begin{cases} \lambda_{aa} & = \mathrm{N}_a \varphi_a \\ \lambda_{aa} & = \mathrm{N}_a(\varphi_q \cos\theta_r + \varphi_d \sin\theta_r) \\ \varphi_q & = \mathrm{F}_a \mathrm{P}_q \cos\theta_r \text{ , } \varphi_d = \mathrm{F}_a \mathrm{P}_d \sin\theta_r \\ \lambda_{aa} & = \mathrm{N}_a \mathrm{F}_a \left[\mathrm{P}_q cos^2\theta_r + \mathrm{P}_d sin^2\theta_r\right] \end{cases} \tag{3.4}$$

Here, (φ) and (λ) are the magnetic flux through the winding surface and the flux leakage. (P) is the permeance, the path of the flux (opposite of magnetic resistivity). Thus, once again, for calculating stator winding inductances in a specific position and time and by simplifying previous equations, (L_{aa}) and (L_{ab}) are given by:

$$\begin{cases} L_{aa} = N_a^2 \left[\frac{P_d + P_q}{2} - \left(\frac{P_d - P_q}{2}\right) COS2\theta_r\right] \\ L_{ba} = N_a^2 \left[-\frac{P_d+P_q}{4} - \left(\frac{P_d-P_q}{2}\right) COS\left(2\theta_r - \frac{2\pi}{3}\right)\right] \\ L_A = N_a^2 \left(\frac{P_d+P_q}{2}\right), L_B = N_a^2 \left(\frac{P_d-P_q}{2}\right) \end{cases} \tag{3.5}$$

The three-phase stator winding made L_s elements 3×3. In a stator inductance matrix, all diagonal elements are belonging to the self-mutual inductances and leakage plus mutual. On the other hand, off-diagonal inductances are mutual inductances between two different sets of windings. They are negative due to the 120-degree phase difference between each axis and regarding the flux effect of one winding into another [185]. Back to equation (2), all matrix elements of the inductances are calculated from (3) and (4) as:

$$\begin{cases} i'_j = \frac{2}{3} \left(\frac{N_j}{N_s}\right) i_j \\ v'_j = \left(\frac{N_s}{N_J}\right) v_j \\ \lambda'_j = \left(\frac{N_s}{N_J}\right) \lambda_j \qquad \text{j= Kq1, Kq2, Fd, Kd} \\ r'_j = \frac{3}{2} \left(\frac{N_s}{N_j}\right) i_j \\ i'_j = \frac{3}{2} \left(\frac{N_s}{N_j}\right) i_j \end{cases} \tag{3.6}$$

In this step, all parameters like voltage, current, flux, and the inductance of the winding leakage and their resistance refer to the stator side. Considering the number of stator (N_s) and rotor (N_r) windings, equation (5) illustrates the transformer equations.

In summation, by replacing all calculated elements for system inductances and rewriting the primary matrix equation, the voltage equation writes as :

$$\begin{bmatrix} V_{abcs} \\ V'_{qdr} \end{bmatrix} = \begin{bmatrix} r_s + pL_s & pL'_{sr} \\ \frac{2}{3}p(L'_{sr})^T & r_r + pL'_r \end{bmatrix} \begin{bmatrix} i_{abcs} \\ i'_{qdr} \end{bmatrix} \tag{3.7}$$

From equation (6), all calculations are transferred to the stator side. Still, these equations are getting more complex since all phases quantities and matrix inductances are not independent of each other, and they are variable with time. dq0 transformation (Park transformation) is a projection to simplify the equations by transforming stator quantities from the stationary reference frame to rotating dq0 reference frame [185].

$$K_s^r = \frac{2}{3} \begin{bmatrix} cos\theta_r & cos(\theta_r - \frac{2\pi}{3}) & cos(\theta_r + \frac{2\pi}{3}) \\ sin\theta_r & sin(\theta_r - \frac{2\pi}{3}) & sin(\theta_r + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{3.8}$$

This study has used dq0 transformation that rotates at synchronous speed just for stator components because rotor components are already located at the reference frame. Equation (7) shows the dq0 matrix for transferring stator components to the reference frame.

To avoid unwilling harmonics from PMSG production, providing a constant 60 Hz frequency (1800rpm) for SG is necessary. Rotating stator technology aims to achieve this speed by combining rotor and stator speed either in the same or opposite direction. Since SG rotor speed is reduced to adapt DE speed with the load, another concept introduced for the SG stator to rotate around the rotor axis but in the reverse direction to compensate the total speed. Figure 3-4 indicates the developed stator structure for SG.

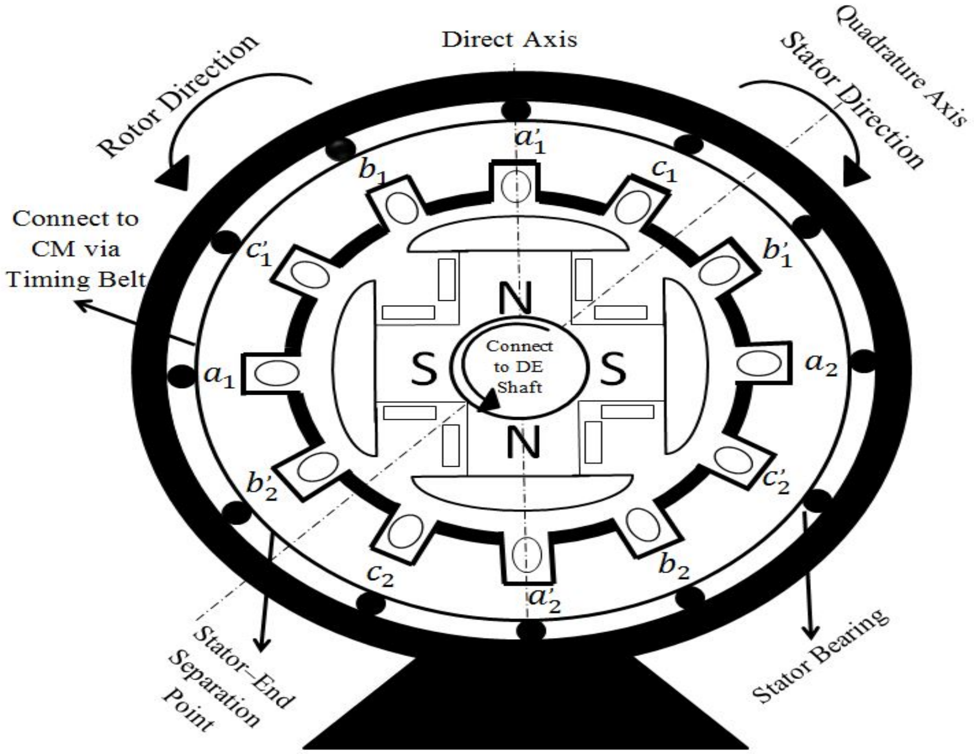


Figure 3-4. Cross schematic of the non-static stator

SG modeling carries on by presenting two independent mechanical inputs. (w_{rr}) which is assumed as rotor speed and (w_{rs}), which is assumed as stator speed, are two independent angular velocities for PMSG. (w_{rt}) is the total angular velocity, which leads the SG speed to achieve ideal frequency.

$$Wrt = Wrr \pm Wrs$$

- Stator and Rotor Rotate at the Same Direction (3.9)

+ Stator and Rotor Rotate at the Reverse Direction

The Matlab codes of developed PMSG with rotating stator are given in appendix II. Generator components are also precisely valued as well as the connected loads. Simulation results prove that the sinusoidal waveform of PMSG output produces same to the conventional generator.

In this simulation for 500-kW PMSG, the stator speed has been fixed at 255 rpm in the opposite direction of the rotor. Thus, in this case, the rotor speed could decrease to 1545 rpm, which directly helps the DE crankshaft to reduce its speed. However, the total relative speed of the synchronous machine remained constant at 1800 rpm.

Finally, by transferring the above equations to the reference frame using dq0 transformation, and by simplifying the calculations, voltage equations in the reference frame are calculated in (3.10). The first part is related to the ohmic voltage, the second part is related to the total speed rotating voltages, which include two different inputs, and the third part is related to the transformer voltage.

$$\begin{cases} V_{qd0s}^{r} = r_s i_{qd0s}^{r} + w_{rt}\lambda_{dqs}^{r} + p\lambda_{qd0s}^{r} \\ V_{qdr}^{\prime r} = r_r^{\prime} i_{qdr}^{\prime r} + \mathrm{p}\lambda_{qdr}^{\prime r} \\ (\lambda_{dqs}^{r})^{T} = \left[\lambda_{ds}^{r} \;\; -\lambda_{qs}^{r} \;\; 0\right] \end{cases} \tag{3.10}$$

By expanding the dq matrix calculation, the synchronous equation becomes:

$$\begin{cases} v_{qs}^{r} = r_s i_{qs}^{r} + w_{rT}\lambda_{ds}^{r} + \rho\lambda_{qs}^{r} \\ v_{ds}^{r} = r_s i_{ds}^{r} - w_T\lambda_{qs}^{r} + \rho\lambda_{ds}^{r} \\ v_{0s} = r_s i_{0s} + \rho\lambda_{0s} \\ v_{kq1}^{'r} = r_{kq1}^{'} i_{kq1}^{'r} + \rho\lambda_{kq1}^{'r} \\ v_{kq2}^{'r} = r_{kq2}^{'} i_{kq2}^{'r} + \rho\lambda_{kq2}^{'r} \\ v_{fd}^{'r} = r_{fd}^{'} i_{fd}^{'r} + \rho\lambda_{fd}^{'r} \\ v_{kd}^{'r} = r_{kd}^{'} i_{kd}^{'r} + \rho\lambda_{kd}^{'r} \end{cases} \tag{3.11}$$

Also, the values of leakage flux are calculated by expanding matrice $\begin{bmatrix}\lambda_{qd0s}^{r} \\ V_{qdr}^{\prime r}\end{bmatrix}$ as (3.12).

$$\begin{cases} \lambda_{qs}^{r} = L_{ls} i_{qs}^{r} + L_{mq}(i_{qs}^{r} + i_{kq1}^{\prime r} + i_{kq2}^{\prime r}) \\ \lambda_{ds}^{r} = L_{ls} i_{ds}^{r} + L_{md}(i_{ds}^{r} + i_{fd}^{\prime r} + i_{kd}^{\prime r}) \\ \lambda_{0s} = L_{ls} i_{0s} \\ \lambda_{kq1}^{\prime r} = L_{lkq1}^{\prime} i_{kq1}^{\prime r} + L_{mq}(i_{qs}^{r} + i_{kq1}^{\prime r} + i_{kq2}^{\prime r}) \\ \lambda_{kq2}^{\prime r} = L_{lkq2}^{\prime} i_{kq2}^{\prime r} + L_{mq}(i_{qs}^{r} + i_{kq1}^{\prime r} + i_{kq2}^{\prime r}) \\ \lambda_{fd}^{\prime r} = L_{lfd}^{\prime} i_{fd}^{\prime r} + L_{md}(i_{ds}^{r} + i_{fd}^{\prime r} + i_{kd}^{\prime r}) \\ \lambda_{kd}^{\prime r} = L_{lkd}^{\prime} i_{kd}^{\prime r} + L_{md}(i_{ds}^{r} + i_{fd}^{\prime r} + i_{kd}^{\prime r}) \end{cases} \tag{3.12}$$

As a final step before deploying these equations into MATLAB block diagrams, flux leakages and currents are given in (3.13). (w_{ref}) is the base electrical angular velocity to obtain primary inductive reactance during system simulation.

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left(\lambda_{ds}^{r} i_{qs}^{r} - \lambda_{qs}^{r} i_{ds}^{r}\right) \tag{3.13}$$

3.2.4 Numerical modeling for developed Genset

Figure 3-5 indicates a schematic view of Genset system using a rotating stator. Synchronous machine simulation starts with dq-transformation and continues by adding internal excitation and mechanical governor system into it. The excitation system is important in the synchronous machine due to the production of flux by passing a current through the rotor field winding.

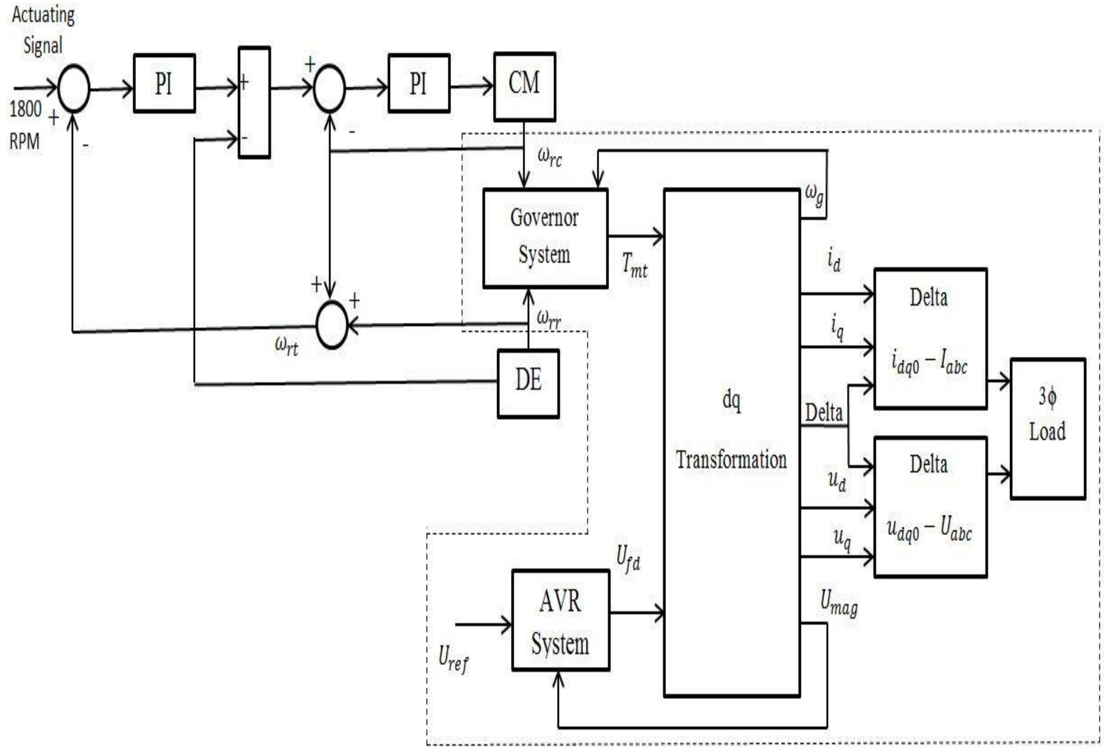


Figure 3-5. Control schema of VSDG

The aim of every excitation system is the reliability of production under different conditions, simplicity of control, ease of maintenance, and fast transient response [186-189].

This research has used automatic voltage regulation (AVR) to control the output terminal voltage of the alternator while it is connected to the loads. The principle of this excitation system is to follow the reference flux and adjust itself with it to avoid any voltage drop during load variation. However, the objective of the simulation is to develop a mechanical torque and governor system, where two different mechanical inputs are fixed to illustrate the effect of rotor and stator rotation. This project uses the full order model method to model PMSG in Matlab environment and detailed block diagrams are presented in appendix I.

As for total mechanical torque (T_{mt}) of synchronous machine, a dual PI controller system is used to reduce the errors for total angular velocity (w_{rt}). The aim of the first controller is to track DE and CM speed and reduce the possible errors by considering reference speed. DE mechanical torque output may vary to reach its appropriate regime. Thus, the second PI controller follows the registered command for CM to rotate at a speed that leads PMSG to reach 1800 rpm. However, in this simulation, the DE speed is fixed at 1545 rpm and rotates in a clockwise direction.

In continue, this simulation introduces another independent input to compensate for the required speed for SG (synchronous motor (CM)). CM speed is valued at 255 rpm and rotates in the anticlockwise direction. Therefore, developing a governor system simulation to have a compound speed leads SG to control total angular velocity either with CM or DE. Synchronous machine simulation was carried out by projecting a-b-c three-phase onto the d-q axis. One feature of dq-projection is the ability to specify the d-q axis speed to be any that is convenient for the user [182]. Two separate dq0 block diagrams for current and voltage are placed after dq transformation block to produce three-phase power. It is important to mention here that three-phase loads consist of resistive panel plus CM. A small fraction of SG production is used by the CM itself.

Figure 3-6 indicates the conditions on which the governor system produces appropriate T_m. A conditional switch with three in-puts W_{rr}, W_{r}, and W_{rc}, are placed to obtain different system speed. First and third inputs are for both rotor and stator speed while the second input is fixed at 1800 rpm. The function of this switch is based on the total system speed.

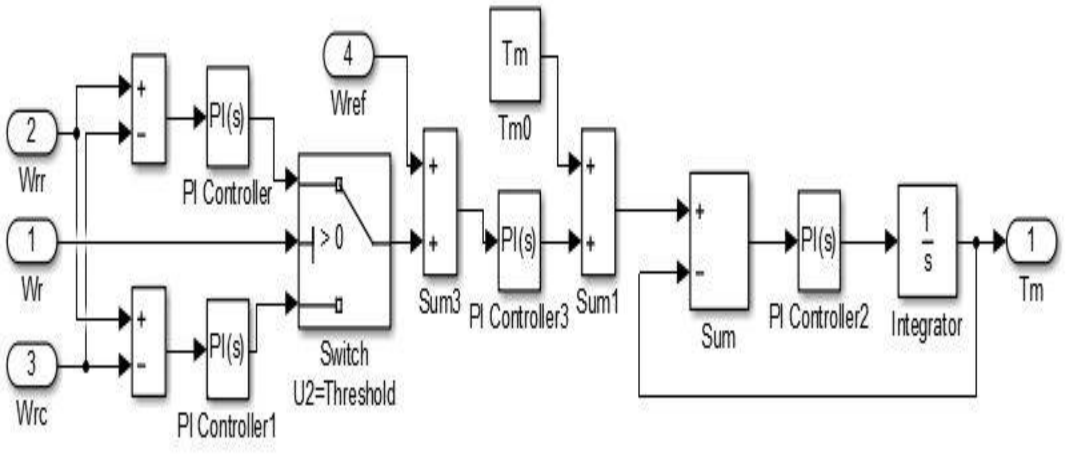


Figure 3-6. The proposed input control system

If the system speed is less than 1800 rpm then, the logic switch passes the third input to compensate for the speed. Otherwise, the switch block passes the first input to reduce total SG speed. Figure 3-7 shows swing equations for the SG, while the system works under normal conditions. Therefore, the relative position of the rotor and the magnetic axis are fixed. In the full order modeling of the SG, the internal excitation produces fluxes (9) and (10) in rotor windings, respectively [190]. Therefore, fluxes cross stator windings to produce currents.

Figure 3-8 shows the field and quadrature current using dq0 transformation. By implementing Park transformation in a balanced system, field current (i_d) and quadrature current (i_q) carry the same performance and characteristic of the three-phase SG system during different conditions. Table 3-1 has given the machine per unit values, which runs by MATLAB software for 5 seconds.

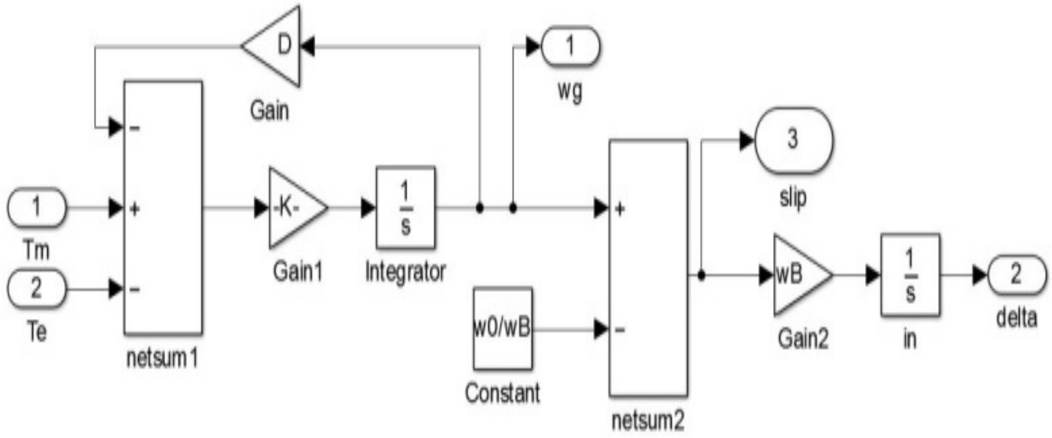


Figure 3-7. Governor model with total mechanical torque

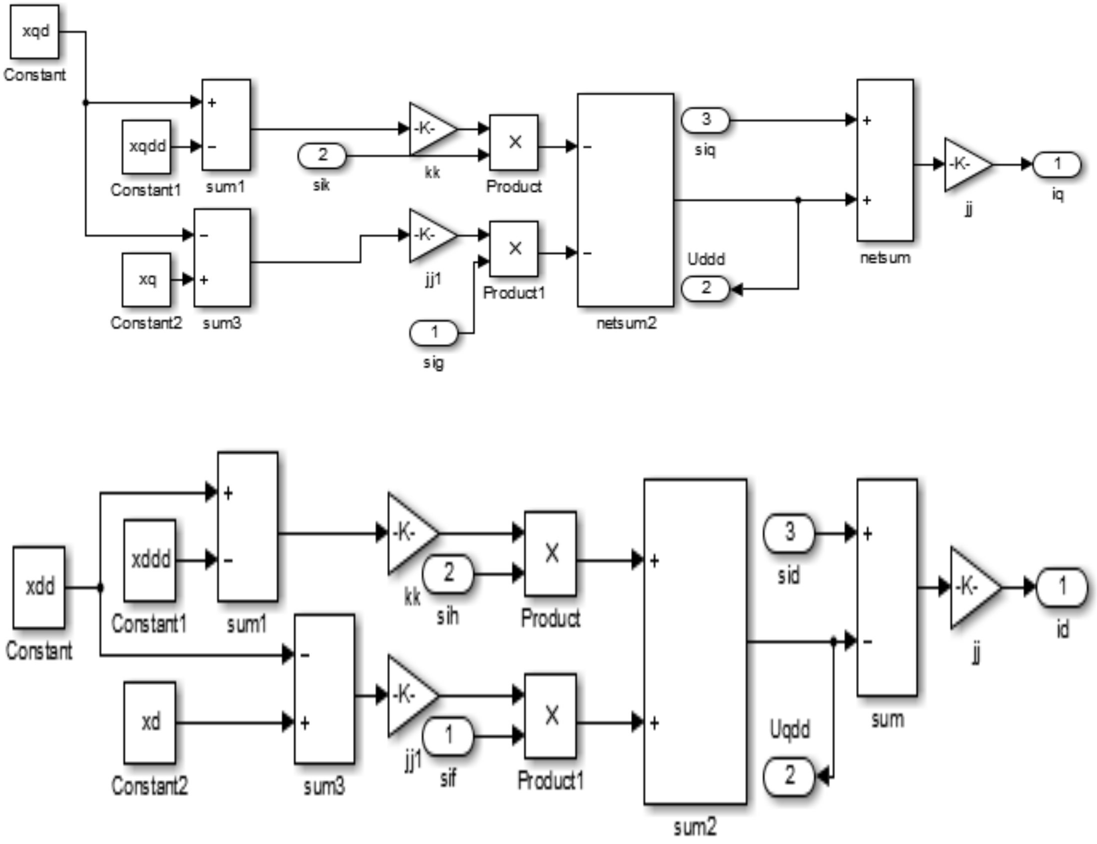


Figure 3-8. Schematic diagrams of the field and quadrature current

Table 3-1. PMSG parameters

Variables	***Nominal Values***	***Variables***	***Nominal Values***
x_d	*1.79Ω*	T_{q0dd}	*3.3*
x_{dd}	*0.169 Ω*	w_B	*60(HZ)*2*pi*
x_{ddd}	*0.135 Ω*	w_{rr}	*51.5 (HZ)*2*pi*
T_{d0d}	*2*	w_{rc}	*8.5(HZ)*2pi*
T_{d0dd}	*2.3*	*H1*	*2*
x_q	*1.71 Ω*	*H2*	*0.86*
x_{qd}	*0.228 Ω*	R_a	*0.01 Ω*
x_{qdd}	*0.2 Ω*	*Pg0*	*0.625 W*
T_{q0d}	*3*	*Pg1*	*0.617 W*
T_{q0dd}	*3.3*	*Ug0*	*0.884 V*

3.3. SIMULATION RESULTS

Modeling and simulation of PMSG using a rotating stator have been carried out. Two different mechanical inputs are implemented. One input controls the rotor speed, and the other one adjusts the stator speed. This modeling adds both values (mechanical inputs) and considers them as one for a PMSG mechanical prime mover. The results below released from MATLAB software using a per-unit system showing the three-phase voltages, currents, power, etc. Two different stages of loads are applied in this project, respectively. The initial speed of the machine has fixed at 1500 rpm, as reference speed. The total speed of PMSG at rpm form is the summation of two mechanical inputs. Regarding the value of inductances in the previous section, (L_s) change as the rotor rotates (salient rotor). Therefore, the stator inductance values change over time.

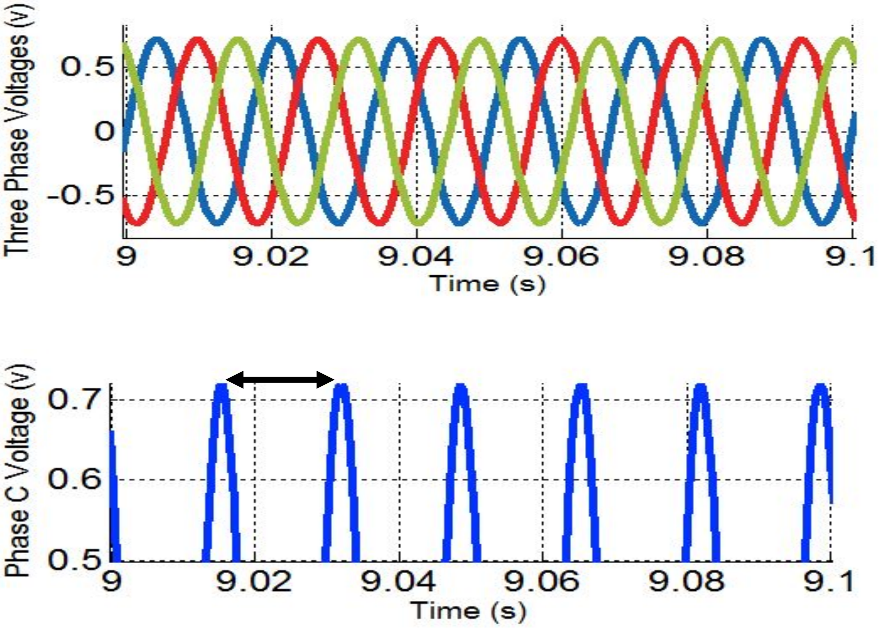
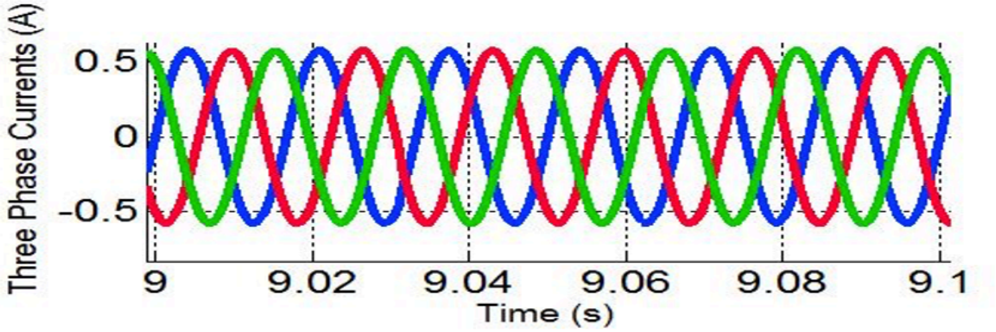
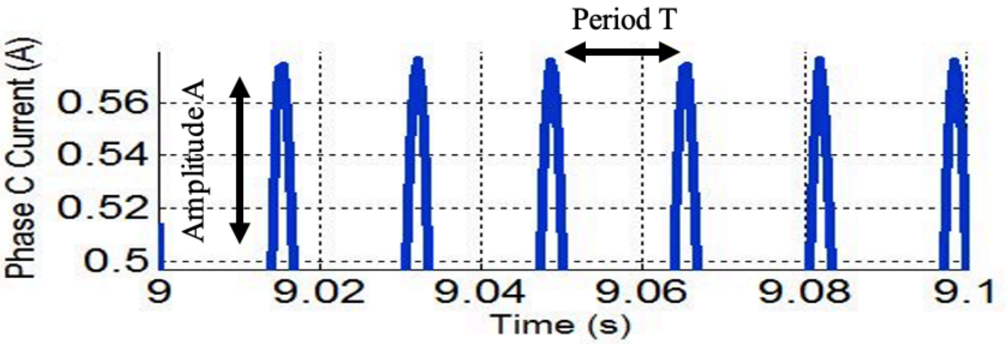
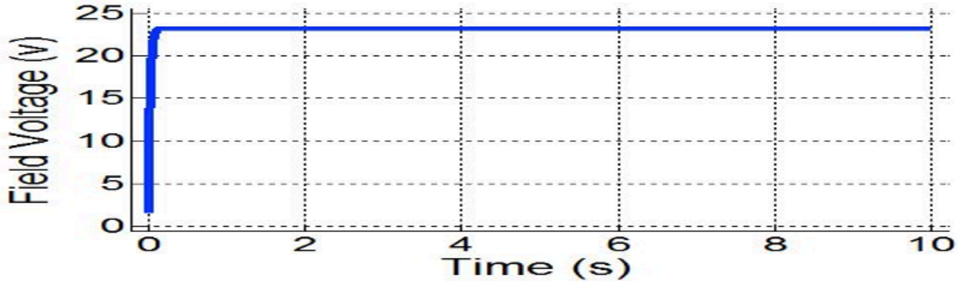


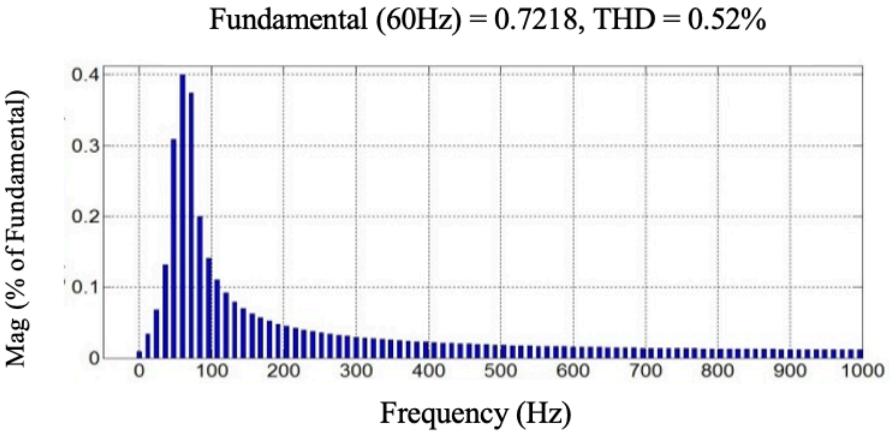
Figure 3-9. PMSG voltage phases using compound prime-mover (unity PF)

Therefore, the stator inductance values change over time. For the first scenario, the generator has been connected to a 196 kW load, and the results are shown in Figure 3-9 and Figure 3-10. The aim of this modeling is to simulate PMSG with a rotating stator and compare the results with the experimental ones. Three-phase sinusoidal waveforms are achieved using a precise AVR system and appropriate dq-abc transformation. Also, the need for synchronous speed is critical for achieving a 60 Hz frequency. Voltage and current graphs show the six times fluctuation in every 0.1 seconds. Times lengthen of the peak-wave for phases are equal. The three-phase balanced load formed the currents graph as below. The excitation current increases in a fraction of a second as the electrical load increase, demonstrating AVR efficiency.








Fundamental (60Hz) = 0.7218, THD = 0.52%

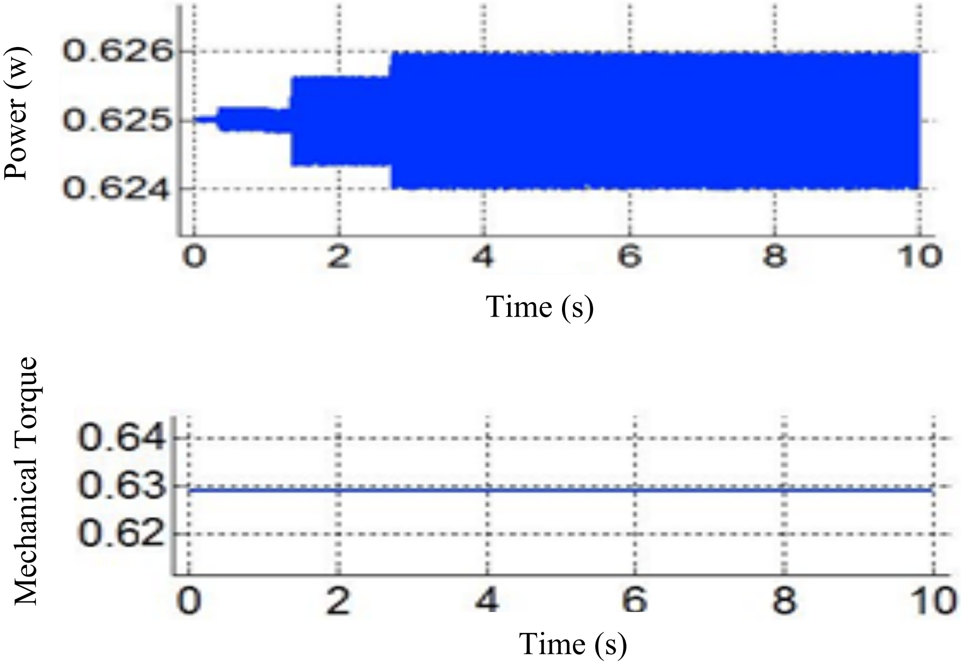
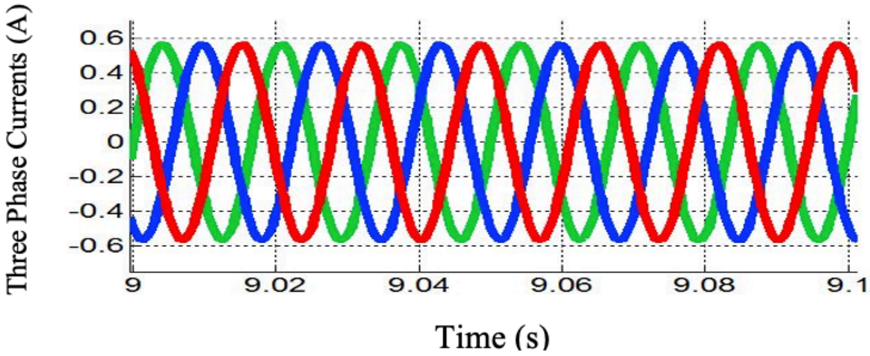
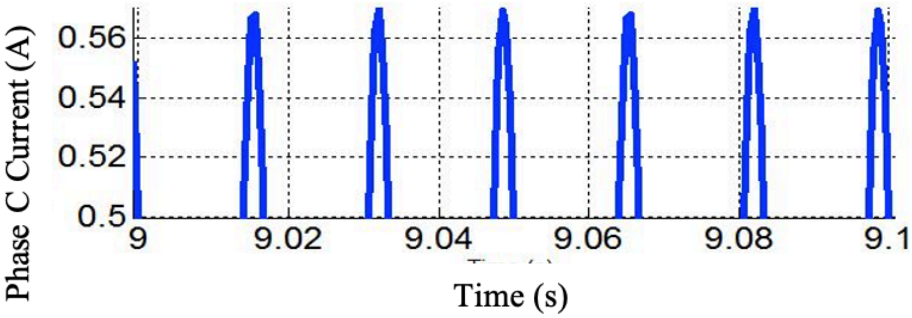
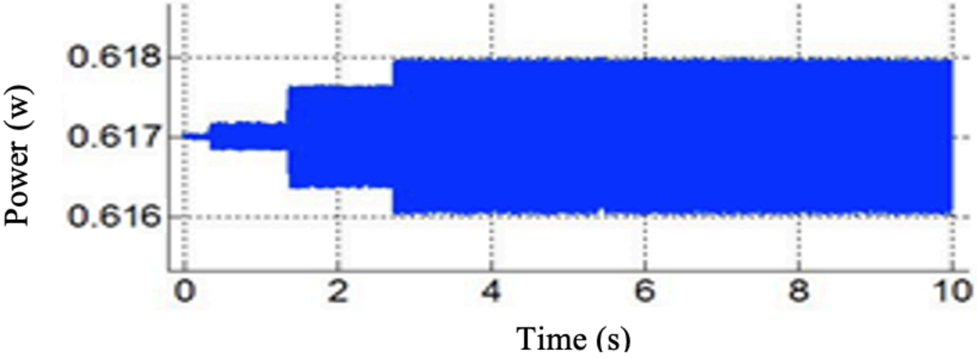


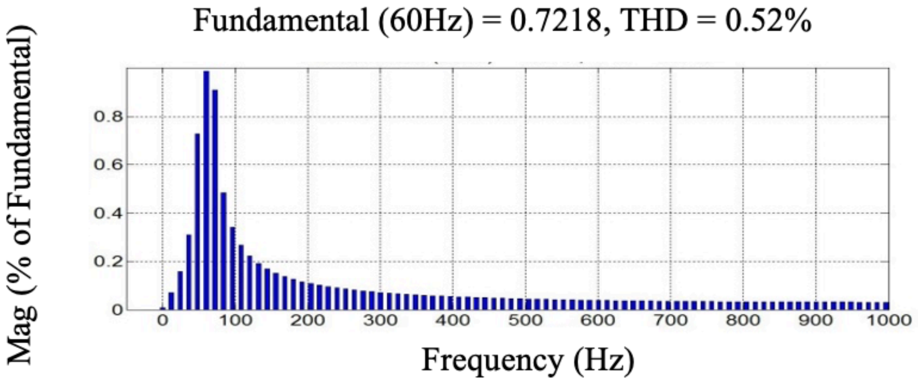
Figure 3-10. Compound speed control at 1800 rpm

Simulation of PMSG with developed governor accomplished using dq-projection. This projection reduces the three-phase complicated equation into dq0 rotating axis. These difficulties are due to the mutual inductances of Rotor-Stator and variation of inductances over time. MATLAB dq0 to abc block diagrams have been used to convert dq variables into three-phase voltages and currents. This model well represents PMSG performance, especially during balance load. (i_0) in dq0 matrix is placed for the unbalanced condition. Constant k_q, k_d and k_0 are valued as 2/3, 2/3, and 1/3 respectively to alleviate the numerical coefficient of dq0 matrix. This model controls the PMSG output using its internal excitation system. AVR system adapts the required magnetic field in the rotor field winding during load fluctuation. For the second part of this research, a 307 kW load has been connected to the PMSG (Figure 3-11). Rotor and stator speeds were kept constant at the same speed as the first scenario. The load current increased. However, it is important to mention that the voltage remains constant.








Fundamental (60Hz) = 0.7218, THD = 0.52%

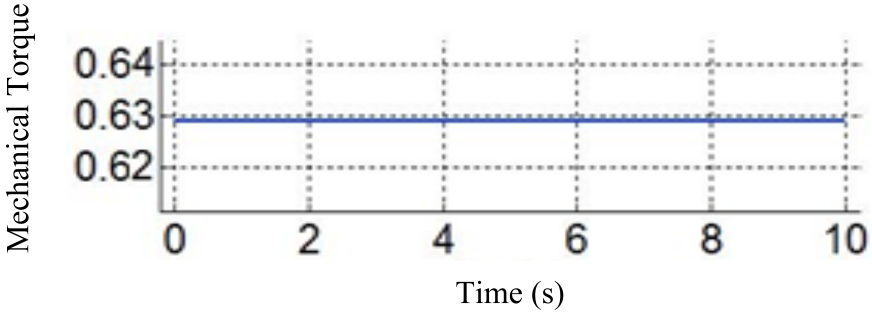


Figure 3-11. Developed PMSG connected to resistive/inductive loads

The full order model of the synchronous machine compensates the transient time of SG behavior by neglecting the effect of stator inductive current on itself. U_{ddd} and U_{qdd} are the stator damper winding voltages to repel the negative stator effect on itself and the effect of load variation on SG production. Figure 3-12 illustrates I_d and I_q while the damper windings are included or neglected.

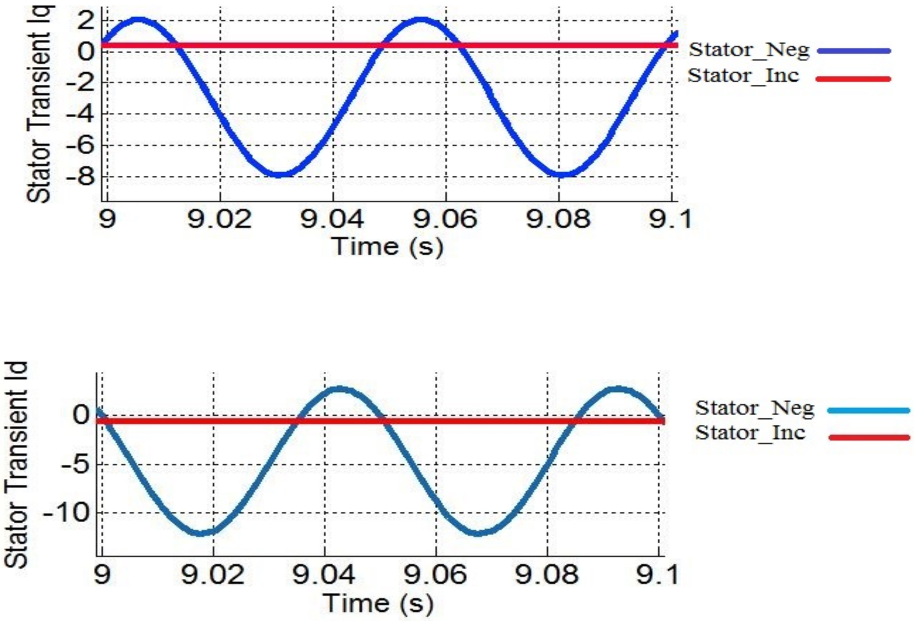


Figure 3-12. PMSG graphs parameters under 307 kW power

Figure 3-13 indicates the results using the control schematic diagram. In this simulation, CM runs after five seconds, and DE speed reduces to 1500 rpm. This fluctuation is transient, and voltage waveforms return to its sinusoidal form as fast as the total speed of the system reaches 1800 rpm. In continue, two different modes of DG illustrate for a specific phase. 50 Hz waveform indicates the performance of DE running at 1500 rpm while 60 Hz waveform shows the total system speed using CM.

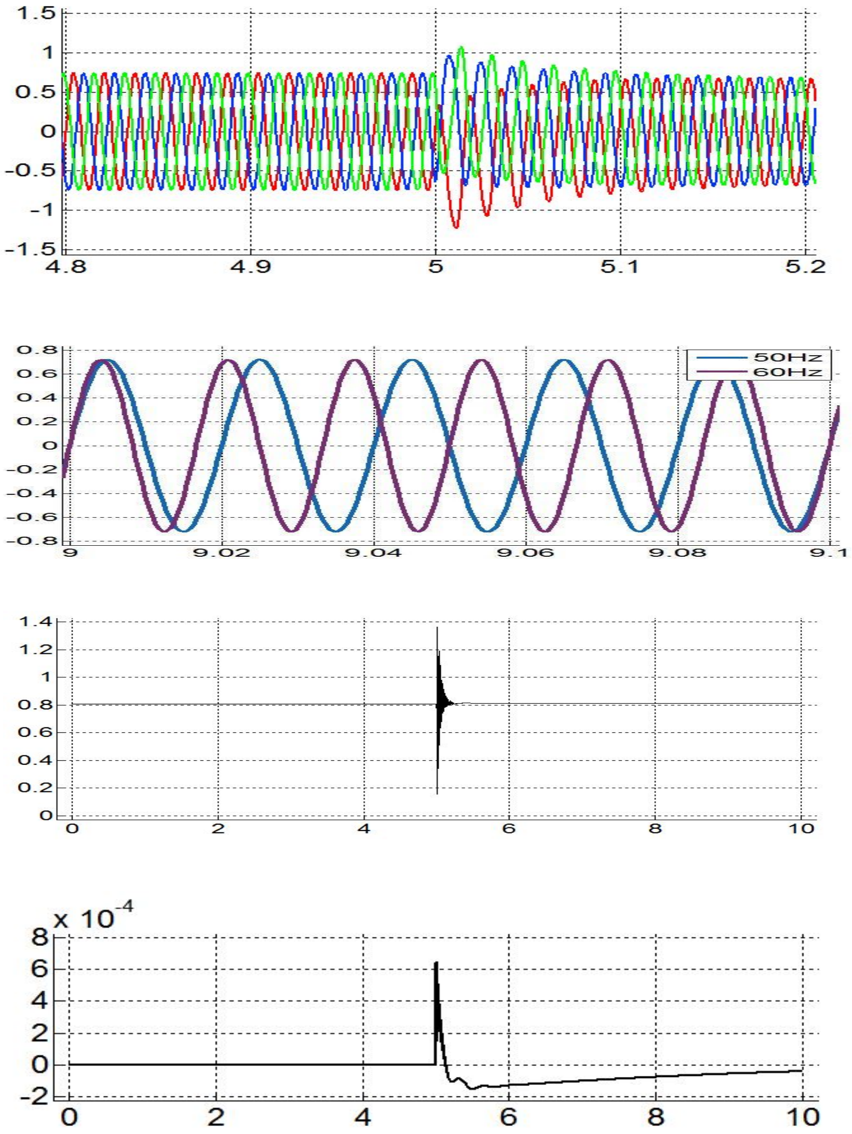


Figure 3-13. Rotating stator results using proposed control schema

3.4. PERFORMANCE EVALUATION FOR DEVELOPED GENSET

3.4.1. Experimental setup

This technology is tested using a 500 kW Caterpillar diesel generator, and all measurements are extracted from the precise three-phase electric instrument and electronic weighing scale. Table 3-2 released the genset data. This experiment has been repeated twice. First, the diesel engine runs at 1800 rpm without a compensator motor connection (Blocked synchronous motor). In this scenario, the goal is to track DE fuel consumption from the fuel tank by connecting SG into two different electric loads (196 and 307 kW).

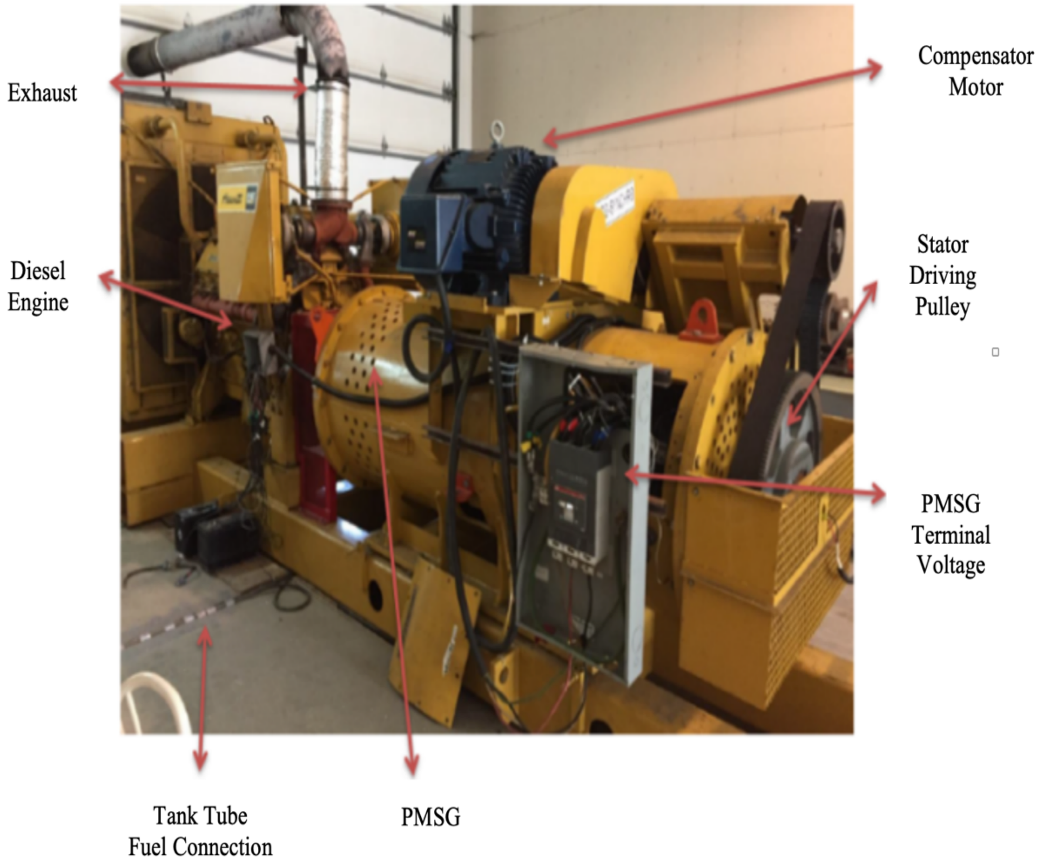


Figure 3-14. Developed Genset using compound speed

As for switching the DG operating mode from static stator to rotating stator mode, DE stopped completely and restarted to produce 50 Hz frequency. The reason behind this principle is that due to the lack of power converters, this method avoids any harmonic production while switching to the rotating mode. Moreover, CM can work in both 50 Hz and 60 Hz condition. As fast as the DE speed reached its steady-state condition, CM starts to rotate at its nominal speed. In terms of the second scenario, CM rotates the generator stator using a small gearbox. PMSM (CM) specification is given in detailed in appendix V.

Table 3-2. Parameters of diesel Genset

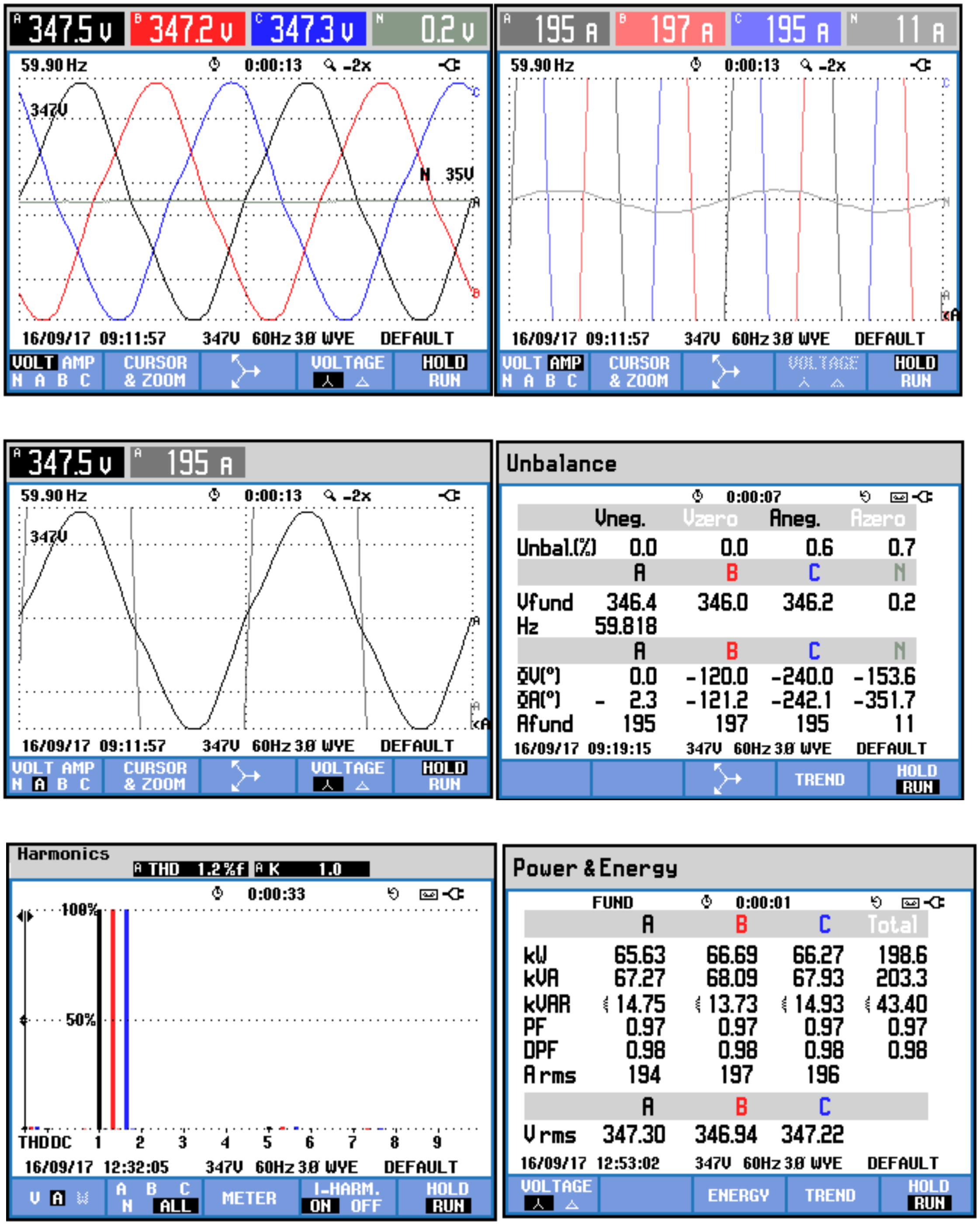
Variables	***Nominal Values***	***Variables***	***Nominal Values***
Diesel Engine		*Compensator Motor*	
Cooling	*Radiator Package*	*Stator Speed (Timing Belt)*	*255*
Fuel	*3 Stage Filter*	*Output HP*	*100HP*
Governor Type	Programmable Electronic Engine Control	*Frequency*	*50-60HZ*
Starting-Charging	*Battery Charger*	*Motor Speed*	*1785RPM*
Generator		*Number of Poles*	*4*
Excitation	*Self-Excitation*	*Starting Method*	*Inverter*
Number of Poles	*4*	*Power Termination*	*Bus Bar* *Circuit Breaker*
Frequency	*60HZ*	*Control Panel*	*Digital 0/I Module* *Load Share Module*
RPM	*1545*		
Over Speed Capability	*150*		
Alignment	*Pilot Shaft*		
Voltage Regulation	*½% Steady State* *1% (No-load to Full-load)*		
Voltage L-L	*480V*		
Power	*500KW*		

A small gearbox has been installed above the SG casing and connected to the stator of the 500 kW generator. The role of this gearbox is to provide an ideal speed for the synchronous stator. Thus, the stator starts to rotate to compensate for the necessary speed. Figure 3-14 demonstrates that the driving belt has been used to transfer the rotational torque from CM to the PMSG Stator. Experimental results produced using developed test bench and Genset specification are given in appendix III. The final speed which transfers to the stator has been measured by a tachometer at 255 rpm. Therefore, the crankshaft speed for the diesel engine has reduced to 1545 rpm. Results from these scenarios are shown below when SG is connected into two different 196-kW and 307 kW electric loads, respectively.

Results from these scenarios are shown below when SG is connected into two different 196-kW and 307 kW electric loads, respectively.

3.4.2. Experimental results

The results below are the PMSG electrical outputs while using a rotatory stator. This technology helps DE crankshaft to be more flexible during low electric load. DE speed decreased; however, PMSG outputs using rotatory stator are near to the conventional one. Three-phase Fluke multimeter power quality and analyzer devices have been used to measure PMSG outputs. This technology is tested, and results are indicating in Figure 3-15 and Figure 3-16 by connecting PMSG into 196-kW and 307 kW loads, respectively. It is important to mention that the compensator speed was kept constant during the experiment. No sophisticated gearbox or power converter has been used regarding electric outputs treatment. Figure 3-16 indicates the graphs and the parameters of developed PMSG while connecting to the 307 kW load. Frequency and harmonics have shown a very small change by comparing it with the 196 kW load. AVR system increases the internal excitation of the rotor winding to compensate for the load augmentation. Therefore, system voltage kept almost constant as the load increased.



Unbalance

	Vneg.	Vzero	Aneg.	Azero
Unbal.(%)	0.0	0.0	0.6	0.7

	A	B	C	N
Vfund	346.4	346.0	346.2	0.2
Hz	59.818			

	A	B	C	N
ΦV(°)	0.0	-120.0	-240.0	-153.6
ΦA(°)	- 2.3	-121.2	-242.1	-351.7
Afund	195	197	195	11

16/09/17 09:19:15 347V 60Hz 3Ø WYE DEFAULT

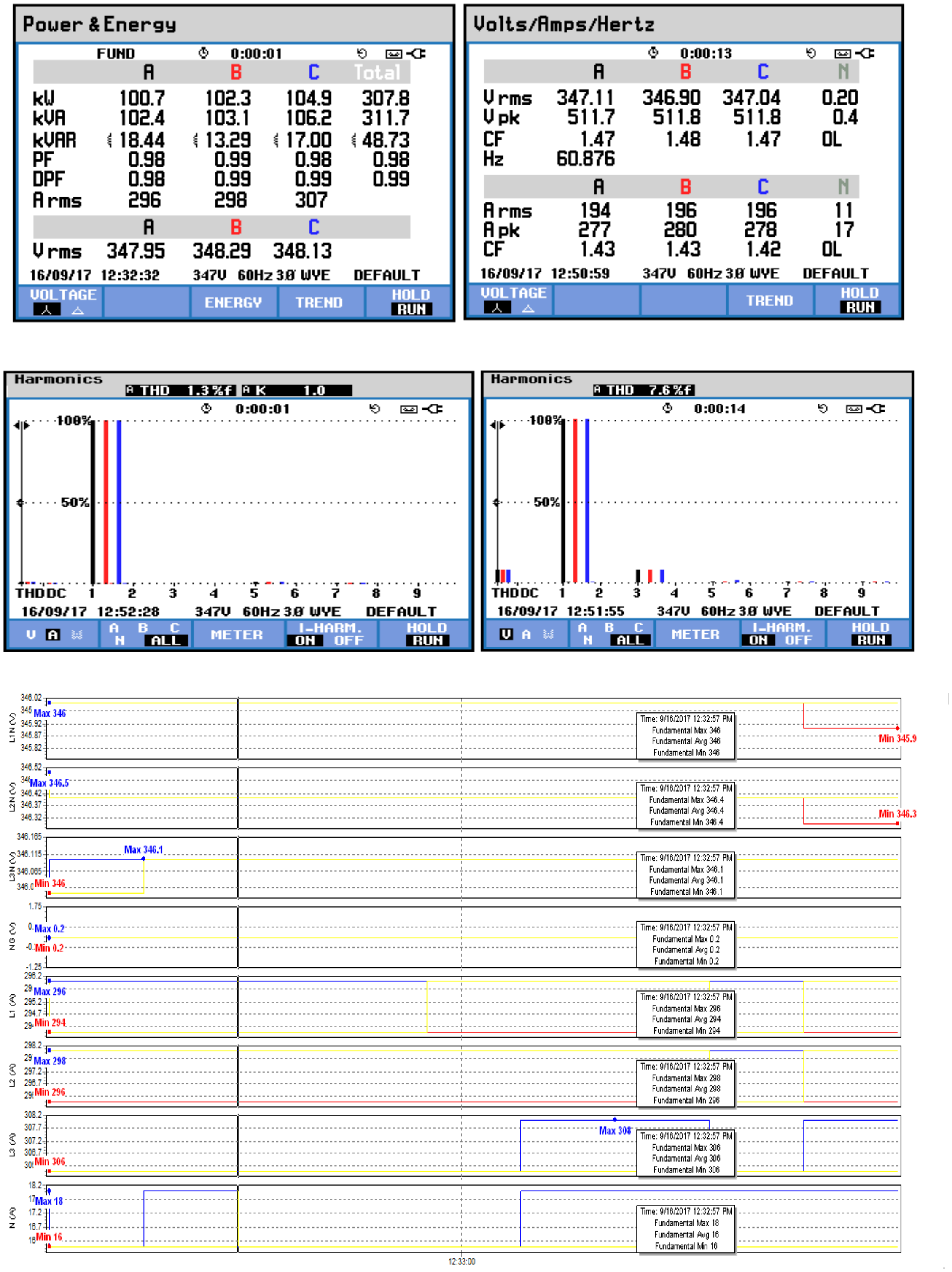
Power & Energy

	A	B	C	Total
kW	65.63	66.69	66.27	198.6
kVA	67.27	68.09	67.93	203.3
kVAR	14.75	13.73	14.93	43.40
PF	0.97	0.97	0.97	0.97
DPF	0.98	0.98	0.98	0.98
A rms	194	197	196	

	A	B	C
V rms	347.30	346.94	347.22

16/09/17 12:53:02 347V 60Hz 3Ø WYE DEFAULT

Figure 3-15. PMSG outputs with proposed structure connecting to 196 kW RL-load



Power & Energy

FUND 0:00:01

	A	B	C	Total
kW	100.7	102.3	104.9	307.8
kVA	102.4	103.1	106.2	311.7
kVAR	18.44	13.29	17.00	48.73
PF	0.98	0.99	0.98	0.98
DPF	0.98	0.99	0.99	0.99
A rms	296	298	307	

	A	B	C
V rms	347.95	348.29	348.13

16/09/17 12:32:32 347V 60Hz 3Ø WYE DEFAULT

Volts/Amps/Hertz

0:00:13

	A	B	C	N
V rms	347.11	346.90	347.04	0.20
V pk	511.7	511.8	511.8	0.4
CF	1.47	1.48	1.47	OL
Hz	60.876			

	A	B	C	N
A rms	194	196	196	11
A pk	277	280	278	17
CF	1.43	1.43	1.42	OL

16/09/17 12:50:59 347V 60Hz 3Ø WYE DEFAULT

Harmonics A THD 1.3 %f A K 1.0

0:00:01

16/09/17 12:52:28 347V 60Hz 3Ø WYE DEFAULT

Harmonics A THD 7.6 %f

0:00:14

16/09/17 12:51:55 347V 60Hz 3Ø WYE DEFAULT

Time: 9/16/2017 12:32:57 PM
Fundamental Max 346
Fundamental Avg 346
Fundamental Min 346

Time: 9/16/2017 12:32:57 PM
Fundamental Max 346.4
Fundamental Avg 346.4
Fundamental Min 346.4

Time: 9/16/2017 12:32:57 PM
Fundamental Max 346.1
Fundamental Avg 346.1
Fundamental Min 346.1

Time: 9/16/2017 12:32:57 PM
Fundamental Max 0.2
Fundamental Avg 0.2
Fundamental Min 0.2

Time: 9/16/2017 12:32:57 PM
Fundamental Max 296
Fundamental Avg 294
Fundamental Min 294

Time: 9/16/2017 12:32:57 PM
Fundamental Max 298
Fundamental Avg 298
Fundamental Min 296

Time: 9/16/2017 12:32:57 PM
Fundamental Max 306
Fundamental Avg 306
Fundamental Min 306

Time: 9/16/2017 12:32:57 PM
Fundamental Max 18
Fundamental Avg 16
Fundamental Min 16

Figure 3-16. PMSG results with the proposed structure connecting to 307 kW RL-Load

3.5. EXPERIMENTAL VALIDATION

The proposed section is the experimental validation using fixed and Non-static stator mode for PMSG. Modeling and experimental results are compared in Table 3-3. The goal of this part is to evaluate the impact of the non-static stator on the PMSG out-put. However, it is important to show the optimization of DE consumption using rotatory stator technology. This optimization has achieved while PMSG products, kept at its standard range.

Table 3-3. Modeling vs. prototype validation

A=Analysis E=Experiment Load 307KW	***Fixed Stator 1800-RPM***		***Error***	***Rotating Stator (Rotor) 1545-RPM (Stator) 255-RPM***		***Error***
	A	**E**	**%**	**A**	**E**	**%**
Voltage Harmonic (%)	5.9	6.2	5.08	8.1	7.6	6.17
Current Harmonic (%)	1.41	1.5	6.38	1.27	1.3	2.36
Frequency (HZ)	60	59.8	0.3	60	60.87	1.45
P. F	0.96	0.98	2.08	0.96	0.98	2.08

Voltage, frequency, and other PMSG results are recorded while the prototype ran in its steady-state condition. The data collection gathered using power analyzer Fluke 435/003, Weightronix w1-130, and tachometer A13M2236B.

3.6. FUEL MEASUREMENT

The objective of this study brightly shines in this part as the fuel consumption illustrates significant improvement during low loads connection. Electric weight apparatus (Weigh-Tronix) is used to track fuel consumption from the fuel tank and its specifications are given in appendix IX. Figure 3-17 indicates the fuel optimization of developed GENSET. Fuel rates are considered in liter per hour. By comparing bar charts, the amount of fuel saved for the first load (196-kW) is larger than the second load (307-kW). However, a new stator concept has been used in both scenarios.

During load augmentation, more current is absorbed from the demand side. Thus, the AVR system applied more voltage in rotor winding to meet the energy demand. Whereas this condition put more stress on the DE crankshaft, the DE governor opens the fuel hatch more than before to increase the power. Finally, the DE crankshaft can rotate the generator rotor at the same speed as it rotates for the first load (mechanical torque increased).

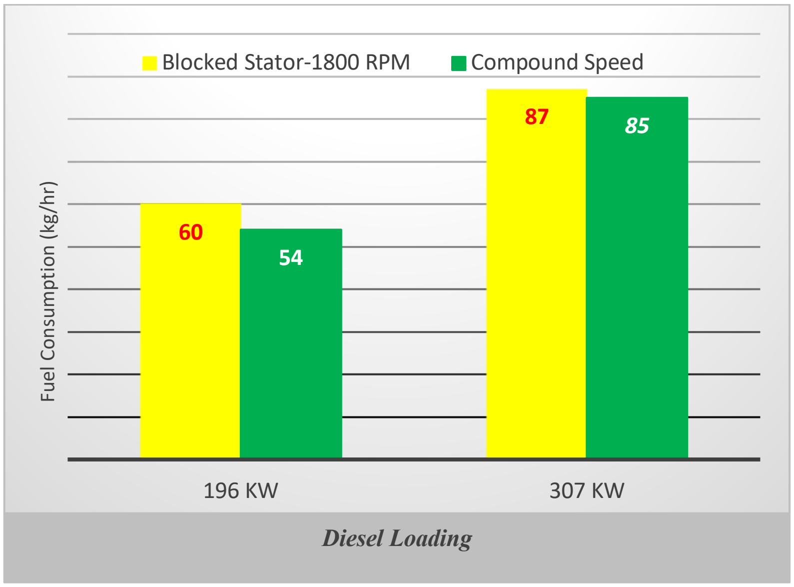


Figure 3-17. Fuel optimization using rotating stator

3.7. FUEL EFFICIENCY

This research has proved significant fuel saving by rotating DE at its most efficient speed during low loads connection. Figure 3-18 approximates the fuel consumption of 500-kW GENSET based on the electrical load at which the generator is connecting to. This experiment was repeated twice for a developed PMSG by connecting 196-kW and 307 kW RL-load into it. By the data released from Figure 3-17, the fuel-saving is more significant while developed PMSG is connected to the 196-kW-RL-Load. Therefore, the fuel-saving during low load connection for the 500-kW generator is achieved by decreasing mechanical torque on the DE crankshaft. It is important to mention that investigation on real fuel saving is always depending on the load impact for an application. This technology could also reduce fuel consumption in another way by replacing smaller diesel engines rather than high capacity DE for the same electric demand. The smaller diesel engine could apply for these kinds of applications due to the reduction of the mechanical load.

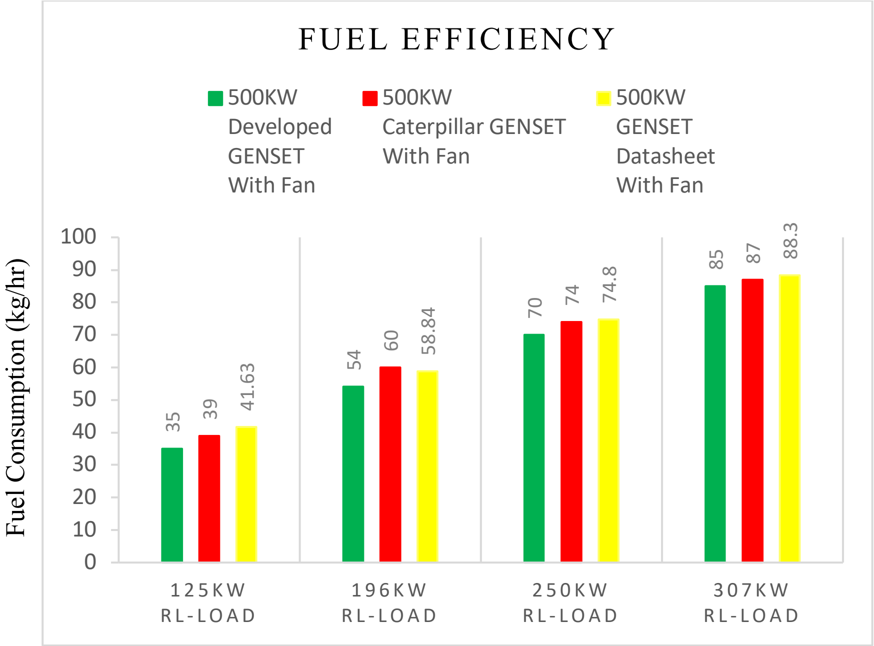


Figure 3-18. Approximate Genset consumption (kg/hr) compared with data sheets [24, 191]

CHAPTER 4
SPEED CONTROL OF DIESEL-DRIVEN GENERATOR SET USING POWER CONSUMPTION TRACKING STRATEGY

Résumé

Les génératrices à vitesse variable peuvent améliorer les performances globales du groupe électrogène en permettant au moteur diesel de réduire sa vitesse à des charges plus faibles. Dans ce chapitre, un générateur diesel à vitesse variable (VSDG) utilise un stator rotatif entraîné par un moteur compensateur. À des charges plus faibles, le stator tourne dans le sens opposé du rotor, un processus qui peut être utilisé à des fins telles que le maintien d'une vitesse relative fixe entre les deux composants d'un générateur. Cela permet au moteur diesel de tourner à une vitesse inférieure (identique à celle du rotor) et d'augmenter son efficacité. La présente recherche porte sur le contrôle du moteur compensateur entraînant le stator du générateur à l'aide d'un variateur de fréquence qui adapte la vitesse à sa valeur optimale en fonction de la charge. Les performances de la stratégie de contrôle proposée ont été testées à l'aide d'une carte microcontrôleur Freescale programmée en code C pour déterminer la tension appropriée pour le variateur de fréquence. L'algorithme de contrôle utilise une application en temps réel implémentée sur une carte processeur de signaux FDRM-KL25Z. Les performances de contrôle d'un moteur asynchrone de 2 kW (LabVolt EMS 8503-00 / 208 V / 3 ϕ / 60 (50) Hz) ont été démontrées expérimentalement dans différentes conditions de fonctionnement.

SPEED CONTROL OF DIESEL-DRIVEN GENERATOR SET USING POWER CONSUMPTION TRACKING STRATEGY

4.1. INTRODUCTION

Nowadays, several electric production applications, such as hybrid standalone or grid-connected, are still using DE. Despite the huge growth of renewable energy contribution in electric production, DE performance optimization is critical due to its important role in electric energy production.

This research focuses on DE optimization based on a new rotating stator technology for an electric generator. This section has divided into two parts to clearly discuss the existing technologies and their important criteria to have an efficient system.

4.1.1. Variable speed diesel generator

Conventional DG generally operate at fixed speeds, 1800 rpm or 1500 rpm, to produce 60 Hz or 50 Hz current, respectively. During operation, electric load varies and affects the operation regime of DG; for lower loads, while maintaining the fixed rotational speed, Genset efficiency drops, specific fuel consumption (fuel quantity required to produce a given amount of energy), and GHG emissions increase [176].

The reason is that at lower loads, the efficiency of the decreases as it operates at the constant speed required by the electrical generator to maintain power quality [161]. In this chapter, the control of a variable speed generator that allows the operation of the Genset at maximum efficiency by adapting the diesel engine speed to the load is presented. For higher loads, close to the nominal regime, the Genset operates at its nominal speed, either 1800 rpm or 1500 rpm, to produce 60 Hz or 50 Hz current respectively.

With a variable speed generator, when the load decreases, the speed of the diesel engine reduces, such as to operate at optimal efficiency. In this research, the constraints to increase diesel engine efficiency and maintain power quality, such as to reduce the complexity and the costs of the entire Genset are addressed.

Several solutions are available in the literature [46, 91] to adapt the DE speed to electric load variations to avoid excessive torque production. In Ref. [192] a variable-ratio transmission allows maintaining a constant generator speed while engine speed slows down at lower loads.

According to the authors, Continuous Variable Transmission (CVT) offers variable engine speed adapted to the load, simultaneously with constant mechanical torque for the power generator. This CVT consists of two toroidal traction discs connected with actuated rollers. This shiftless transmission allows the input to be variable within its operation range [108].

One way to drive DE at variable speed is to use power converters. They consist of different power devices such as power switches, inductors, and capacitors. Meanwhile, system efficiency augmentation, unwilling noise reduction, and precise output control are additional parameters that need to be considered. Therefore, researchers employ sophisticated control schemes using dq-projection to control the performance power devices for having ideal sinusoidal voltage and current [193].

Power converters connected with energy storage systems can also produce a constant voltage and frequency at the output point during different load conditions. Fault protection, protective relays, and high standard electric production are advantages of using power converters [35]. However, the Genset performance is always limited by the power converter; engine speed cannot decrease or increase beyond the power converter capacity.

In this chapter, a new VSDG technology that uses a rotating stator driven by a compensator motor is studied. The diesel engine shaft is solidarily fixed to the generator rotor and turns at the same speed.

The stator turns in the opposite direction of the rotor to maintain a fixed relative speed between the two components of the generator and allow diesel engine speed reduction at lower loads. As such, it is possible to maintain a constant current, voltage, and frequency and to lower DE speed (same as the rotor) to increase its efficiency.

A variable speed AC motor, feed directly from the generator, drive the stator at the required synchronized speed with the rotor. The control of this compensator motor driving the stator uses a variable-frequency drive that adapts the speed to its optimal value according to the load. The detailed description of this variable speed diesel generator is presented together with a review of the literature regarding the variable speed AC motor.

4.1.2. Variable speed AC motor

More than 60 percent of electric load consumption belongs to the AC motors in industrial and residential sectors [194]. Several control methods are available to adjust AC motor speed to meet different application conditions [194]. Vector control is an integrated control method for AC motors' speed based on their dynamic model. It integrates torque, magnetic flux, and rotor position elements.

The implementation of these space vector methods, which requires precise and fast mathematical calculations, increased significantly with the development of more powerful microcontrollers in the past decades, as detailed in [195, 196].

Vector control techniques are complex and expensive, but they can accurately control the speed of the motors in large intervals from zero to more than the rated speed. Generally, the proportional integral and derivative (PID) regulators in inner and outer control loops achieve a variable voltage and variable frequency regulation, simultaneously [197].

This strategy improves motor response time and decreases unreliable performance. The flux production of armature and stator magnetic field is of main interest. The magnitude of the rotating magnetic field is proportional to the fluctuation of both voltage and frequency. Therefore, the value of the rotating magnetic field keeps constant if the change of both voltage and frequency magnitude keep constant. As such, machine speed varies its speed without any disturbance [198, 199]. For instance, in ref. [200] a closed-loop space vector control method employs a hysteresis, current-controlled, voltage source inverter.

The author proposes an integral plus proportional controller, based on a sinusoidal pulse-width modulation (SPWM) inverter, as an effective method to achieve a fast dynamic response and linear performance of the AC motor. Another important parameter in motor speed control is the magnetic torque. Commonly, the treatment of the motor-phase current is an effective way to change the motor speed and its electric torque proportionally [201].

Finally, significant improvements to control the speed of AC motors are using vector control methods [202]. Power converters facilitate the control within a wide range of speeds and induction torque, specific to different applications. Industrial automation can rely on electric drives (EDs), leading to higher productivity and better efficiency. However, fast growth and a wide variety of EDs in industrial applications may impair the power quality and induce harmonic pollution into the power system.

4.2. DEVELOPED GENSET USING ROTATING STATOR

In this chapter, the diesel engine speed controlled to the load using a new generator concept based on a rotating stator. Unlike in other generators, here, the stator will rotate driven by a "compensator" AC motor is such a way to maintain a fixed relative speed between the stator and the rotor [106].

Therefore, the generator speed is not limited to the rotor speed anymore. Subsequently, synchronous speed is achieved using rotor speed, stator speed or a combination of both. Rotating-stator technology reduces the need for power electronics to maintain a constant voltage and frequency.

As such, the generator maintains its synchronous speed using stator rotation while the diesel engine can adapt its speed to operate at the maximum efficiency dictated by the operation conditions [27]. Based on the explanation above, the synchronous generator (SG) speed is the sum or difference between rotor and stator speed, respectively, if they turn in the opposite or same direction:

$$n_{synch\ (Total)} = n_{Rotor} \pm n_{Stator} \tag{4.1}$$

Consequently, at lower loads, the diesel engine slows down to avoid unnecessary torque production, and, simultaneously, the stator turns at the required speed to meet power quality standards. Rotating stator technology improves the performance and efficiency of VSDG applications by reducing the role of power converters and increasing the fuel saving-profile while the variable speed system is working under a low electric load regime [49].

No power converter is used from SG's end since the variable speed is achieved by controlling stator speed. This phenomenon reduces the risk of power capacitor shortage in the power converter and ameliorates system flexibility since DE speed is no longer limited on power converter capacity. However, adding a compensator motor introduces an additional maintenance process to the system [203].

Figure 4-1 illustrates the general operation of the proposed VSDG using a controlled compensator motor to drive the stator. The compensator motor starts automatically once the grid consumption drops under a threshold value. Based on the real-time load variation, a speed control algorithm has been developed for the induction motor (compensator motor). The compensator motor (CM) is connected to the stator of the synchronous generator (SG) using a small gearbox and is powered by the SG itself.

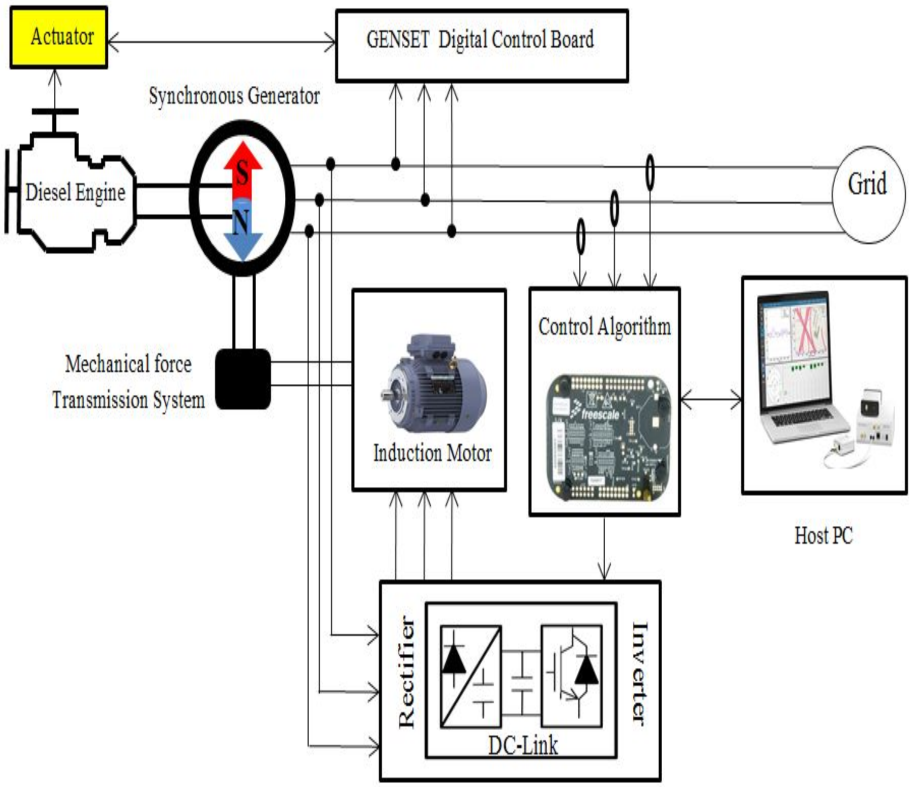


Figure 4-1. Configuration of the VSDG

The main objective of the application is to improve the efficiency of the VSDG at a low load regime. For instance, if at a given load, the optimal efficiency of the diesel engine is at 1500 rpm, it means that the generator rotor should also turn at 1500 rpm.

Consequently, CM runs to rotate the stator at 300 rpm in the opposite direction of the rotor. Synchronous generator speed reaches 1800 rpm while diesel engine speed stays at 1500 rpm as required by the optimal operation.

4.3. THE ARCHITECTURE OF THE VSDG WITH ROTATING STATOR

Figure 4-2 illustrates the architecture of the VSDG with a rotating stator and compensator motor. This new technology increases the overall performance of the VSDG by allowing the DE to operate at maximum efficiency speed. In a conventional Genset, the engine and generator speed are fixed.

Moreover, the SG needs to rotate at its synchronous speed to produce the required power quality when it operates either at low or full load. The engine shaft, coupled with the generator's rotor, rotates at SG's nominal speed at all regimes. Therefore, an oscillation of the DE speed affects power quality. Load oscillation is another factor that reduces system efficiency in fixed Gensets. These phenomena affect power quality and increase DE fuel consumption. Also, the DE is not able to follow these oscillations, and its poor performance is not independent of the fuel governor device [76].

The stator frame and the rotor shaft are also mounted in the generator housing on both sides using robust bearings. This modification allows both parts of the generator, the rotor, and stator, to rotate around the same axis. It is important to mention that the stator windings, core, and connections remain the same as for a conventional generator [204].

A pulley is coupled to the stator frame and mounted on the generator casing. By applying a mechanical force on the pulley itself, the stator starts to rotate at the desired speed and direction. A small-size compensator motor is fixed above the generator casing and is connected to the stator pulley using a timing belt. A small mechanical gearbox is installed on SG's housing and fixed with CM shaft.

The reason for having such a gearbox is to connect the CM shaft with the timing belt easily and adjust stator speed to the specific value. Moreover, in the above patent, the speed of the CM shaft converted to 250 rpm using a mechanical gearbox. However, based on motor rating (respecting optimum speed efficiency) and DE optimum regime, the mechanical gearbox may change [105].

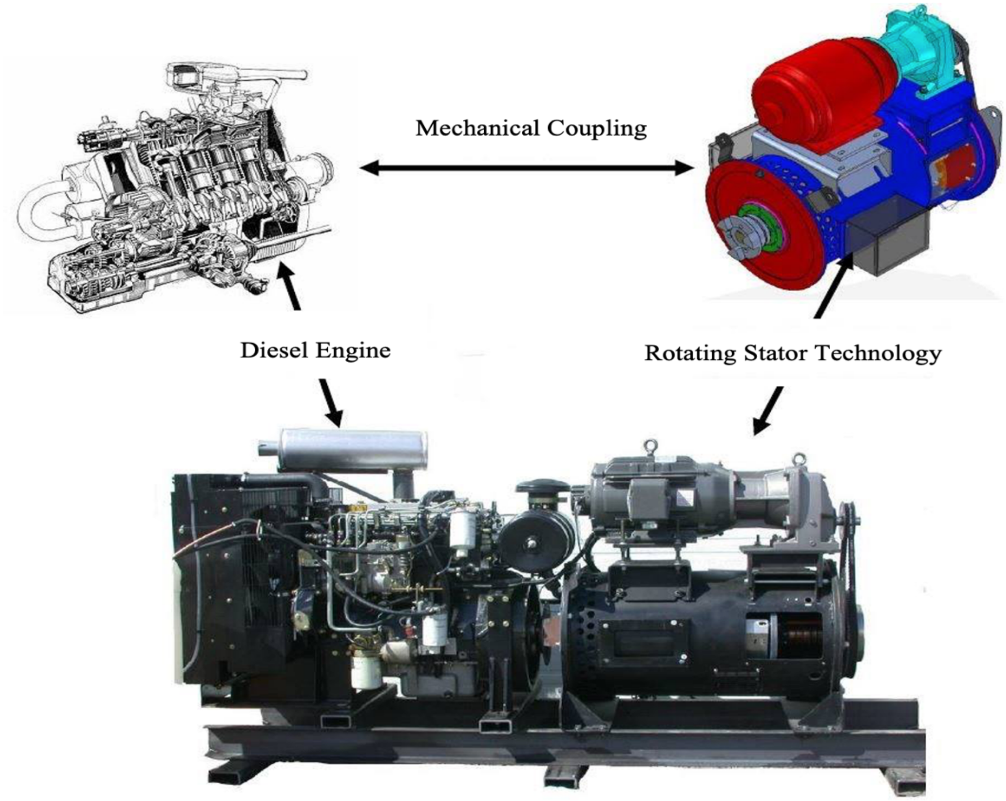


Figure 4-2. The architecture of the VSDG with the rotating stator

CM electricity is supplied by the Genset itself and is able to run at either 50 Hz or 60 Hz. During low load, DE speed decreases to save fuel, and the CM begins to rotate the stator at the appropriate speed and direction to keep the generator at synchronous speed. For instance, if engine speed falls to 1500 rpm for efficiency purposes, CM adjusts the stator speed at 300 rpm in the opposite direction of the rotor. The result is that the generator keeps its speed at 1800 rpm to support electric demand, whereas DE speed adjusts at its most efficient point.

The aim of this project is to control the CM speed with a reliable and robust method to achieve an efficient diesel-generator operation. This technology alleviates system complexity by eliminating power converters from the generators’ rotor and stator. A much smaller-scale electronic controller ensures the CM control and operation. This results in better fuel consumption profile, robust speed controller method and a vast range of variable speed without limitation by converter capacity [76].

4.4. SENSOR-LESS SPACE VECTOR MODULATION SPEED CONTROLLER BASED ON CONSTANT V/F

Frequency drives offer many advantages such as low harmonic distortion, bidirectional power flow, and fast dynamic response [205].

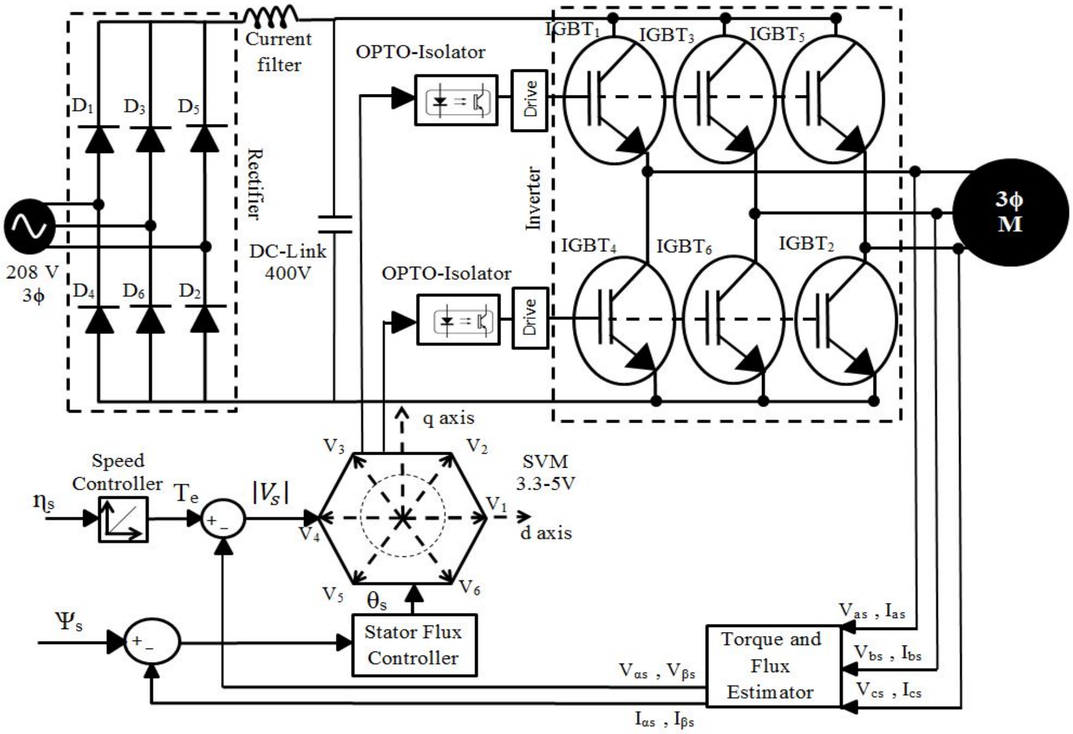


Figure 4-3. Direct Power Control of the Induction Motor (IM) based on sensor-less SVM applied to VSDG

In this section, a robust method connect a programmed microcontroller with the power drive using Direct Power Control and Space Vector Modulation (DPC-SVM) method.

Figure 4-3 shows the configuration of the Voltage Source Converter (VSC) based on a constant switching frequency operation. To eliminate high-switching frequency, we introduced a passive RC filter [206, 207]. However, in this structure, three-phase power is used as variable feedback for the PWM controller to mitigate low order harmonics in case of unbalanced loads.

In this configuration, L is an inductor to repel the current oscillations, the optoisolators are the filters to regulate the input signals, and the drives are transistors to precisely trigger the IGBTs. The DPC method makes it possible to send the appropriate signals by estimating the instantaneous position of the rotor. AC motors need the precise AC voltage signal to have the oscillations proportional to the frequency.

For this reason, Variable Frequency Drives (VFD) are always arranged in a way to regulate output V/F to a constant ratio and value [208]. VFDs create variable voltage and frequency to change AC motor speed. Accordingly, the speed of the AC motor varies with the change in frequency, and the higher the frequency applied to the motor, the faster the motor rotates [209].

The control principle of the VSC uses the SVM-PWM method by separating the voltage and current components. One of the reasons for connecting the feedback control loop in the SVM method is to adjust the instantaneous active power (P) toward its reference value. The second reason is to follow and evaluate the reactive power (Q) to regulate directly the DC-Link. The unit power factor can also be acquired by monitoring the reactive power. In this method, both P and Q are calculated in α and β reference frame using Clark's transformation as follows:

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} E_\alpha & E_\beta \\ E_\beta & -E_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{4.2}$$

where E_α , E_β and i_α , i_β represent components on α and β axes for the output voltage and current, respectively. DPC-SVM estimates the reference stator voltage to minimize the torque and current ripples.

Based on SVM modulates, PWM creates appropriate signals to generate reliable sinusoidal waveforms using constant switching frequency. v_s (Ideal motor speed) is a produced voltage signal coming from a microcontroller card. Power converter receives a treated voltage signal v_s, which is 0-10 V and creates the requested frequency at the output point to control the motor speed. In conclusion, for this part, VFD using DPC method receives treated v_s as input from the microcontroller and produces constant torque and variable speed using a constant ratio V/F strategy.

4.5. AC MOTOR SPEED CONTROL WITH MICROCONTROLLER

Microcontrollers are programmable, reusable, and cost-effective devices that create sine pulse width modulation signals for switching purposes [210]. In this research, we use a Freescale FRDM–KL25Z microcontroller card programmed with MCUXpresso software. After compiling the required code, FreeMASTER software was used as a Run-Time developer application to monitor the real-time experiment. This section aims to propose a simple control algorithm to achieve ideal speeds for an induction motor coupled with the stator of a VSDG. There are several objectives associated with this approach:

- High reliability achieved by a self-correction loop
- Ease of integration with Variable Frequency Drives (VFD)
- Fast processing speed and high accuracy
- High efficiency due to accurate switching command

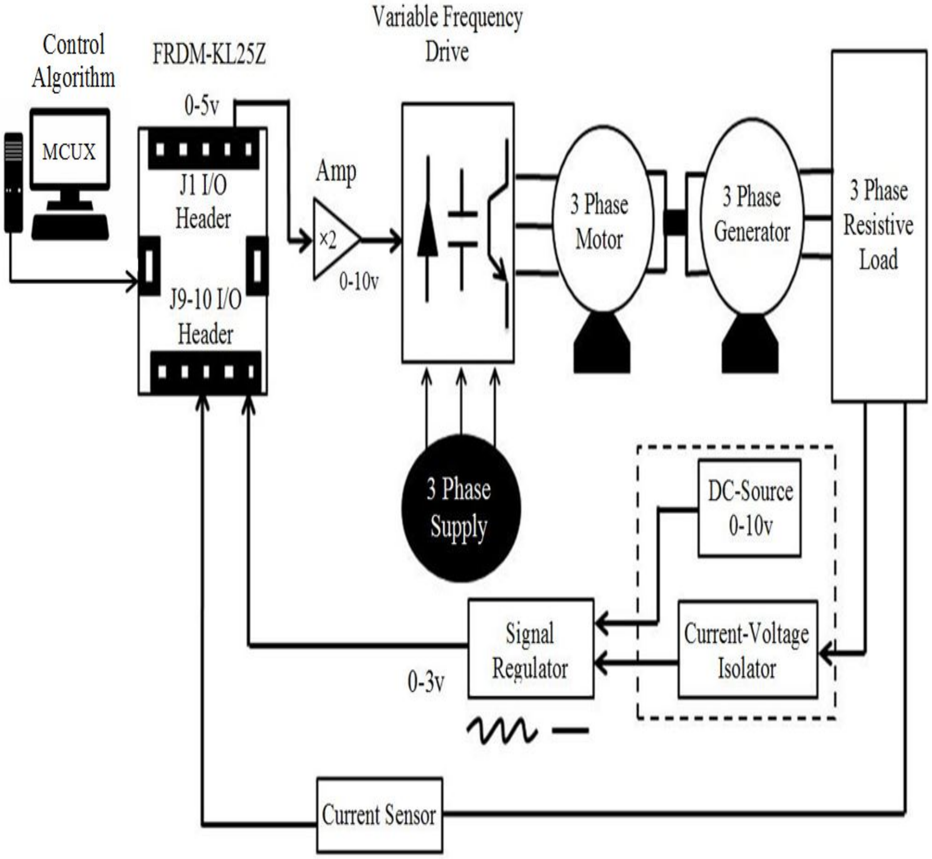


Figure 4-4. Closed-Loop Control Diagram of Variable Speed Motor Application

Figure 4-4 shows a complete diagram of a simple and robust application for controlling motor speed based on the load fluctuation. Several parameters must be set on the DSP controllers to create a sine wave simulator. The default mode of this controller is able to process only 12-bit DC signals and send the requested response to its output ports. In this application, we need a controlled 0-10 V AC voltage at the output port of the DSP card to trigger the VFD system.

To start encoding the analog-to-digital conversion board (ADC), we need to initialize some parameters, including the signal processing time and the number of samples per cycle. The FreeMASTER software can recognize the internal and external ports of the DSP for its control algorithm. However, the input and output port voltages are 0-3 V and 0-5 V, respectively. This board is capable of receiving DC current and voltage signals from its input and sending the appropriate voltage signal to the AC power converter. Therefore, additional devices are required to adapt the microcontroller card to the power converter and the measuring devices (sensors).

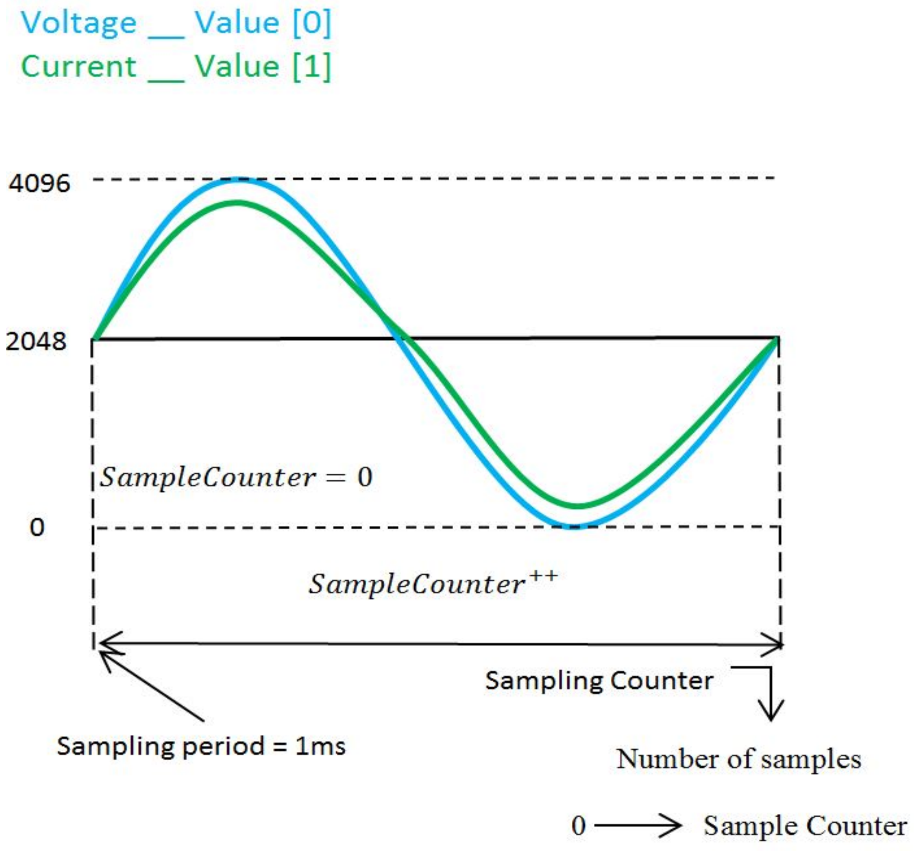


Figure 4-5. Domain and Frequency Definition of 12 Bits ADC

Figure 4-5 illustrates the complete bit space definition and its domain based on DSP card limits. The input values are converted into DC signals and inserted in the control algorithm based on specific current and voltage limits. Near to 250 sample signals have been embedded in each 1ms to create high-quality sinusoidal waveform and reduce graph discretization. Our objective is to regulate the AC motor speed based on the load oscillation.

Therefore, both feedbacks illustrated in Figure 4-4 are coming from the current and voltage measurement devices. They can track the load variation and send an appropriate signal to the DSP input ports.

4.6. DESIGN OF THE SPEED CONTROL ALGORITHM AND NUMERICAL SIMULATION

The objective of this section is to develop the control algorithm for the AC motor used as a compensator for the rotating stator VSDG. The AC motor drives the stator of the VSDG such as the diesel engine and the rotor reduce their speed to avoid producing unnecessary energy during low electric demand. Speed control coding which has been written to meet system needs based on load fluctuation and consumption is given in appendix VI.

Unlike numerous studies focusing on the generator's electric output treatment with a power converter, we vary the speed of the DG using a new technology based on a rotating stator. Thus, the AC motor shaft is coupled to the rotating stator and compensate the required speed of the electric generator to avoid harmonic distortion when the diesel engine slows down. As a result, the control algorithm regulates the speed of the compensator motor by tracking the electric load variation. Different loops and conditions in this algorithm ensure that motor performance is always within the intended area.

Figure 4-6 shows the structure of the control algorithm based on load power calculation. The three most important steps to define the control algorithm are as follows:

- **Workspace generation.** The first step to program every microcontroller is to provide an ideal environment with accurate classifications and specifications. The workspace may consist of several source code files that create a large environment. For this application, voltage and current sensors and a host computer are the external peripheral devices to be recognized by the software workspace and DSP ports. Workspace unfolds input signals every time the control algorithm requires them. Moreover, appropriate DSP ports found on the electric card's data sheet should be well recognized by the software parameters.

- **Speed control implementation.** Two main inputs are embedded in the controller coming from voltage and current measurement devices. These components are transformed into voltage signals, using limiters, before being processed by the algorithm. Both voltage and current parameters measured from the demand side are used in the equation below to determine the load power. The principle of the control algorithm is based on the instantaneous power formula. Accordingly, the control program runs by sending commands from the host computer to the microcontroller card. The control algorithm processes the input signals and produces appropriate signals for the power converter based on instantaneous electric grid consumption. One advantage of such a controller is the fast motor response and high electric torque production.

$$\text{Instantaneous Power} = \frac{\sum(Value\,[0] \times Value\,[1])}{Number\ of\ samples} \tag{4.3}$$

Real electric load varies asymptotically, and it consists of the active and reactive parts. Apparent power represents the total electric power value considering the angle between voltage and current.

As long as this project aims to synchronize the DE production with demanded mechanical torque applied on the DE shaft, the mathematical calculation of electric load active power is considered instead of calculating apparent power. However, the instantaneous calculation of active power reduces the complexity of the control algorithm resulting in a fast microcontroller response.

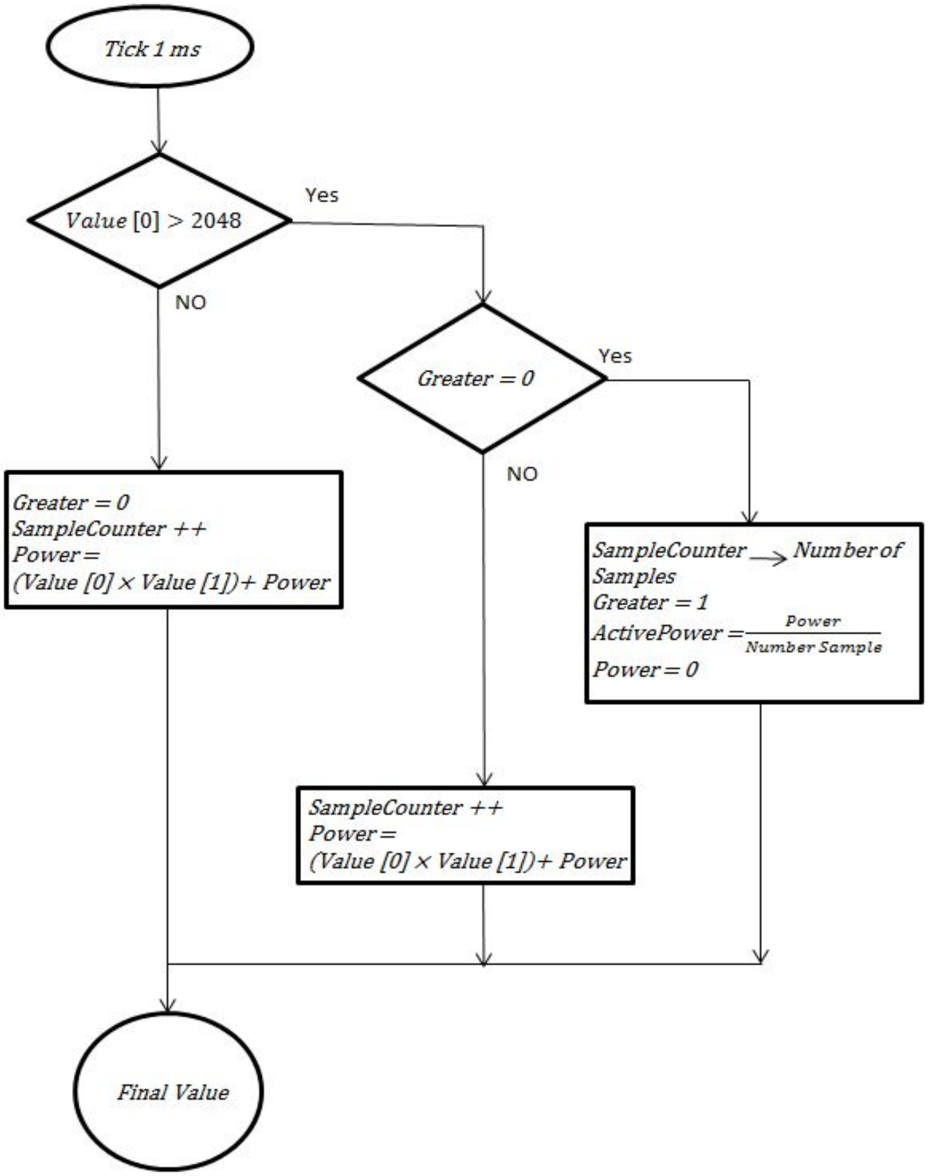


Figure 4-6. Autonomous AC Motor Speed Control Algorithm Based on Variable Input Surveillance

The proposed algorithm plan (Figure 4-6) is implemented in the microcontroller. Small ADC cards are integrated with motor peripherals to reduce application complexity and increase reliability. The motor terminals are connected with the microcontroller using VFD.

The algorithm shows a rapid time response by using high-sampling frequency and different control loops. Moreover, these control schemes reduce switching noise by giving a precise signal to the VFD.

- **Rules and conditions.** The final step before sending the voltage signal to the VFD input is to compare the load power with the predetermined thresholds. Three different load power intervals define the ideal speed condition into the control algorithm as follows. The goal of having such conditions is to adapt the main application (VSDG) with the load variation. Therefore, during a low electric load, the diesel engine slow down to avoid producing unnecessary mechanical torque. On the other hand, AC motor with the robust control algorithm starts compensating the required speed for the stator of the electrical generator.

600 W < Load Power (Per Phase) ≤ 1000 W-------------------Motor Speed = 1200 rpm

400 W < Load Power (Per Phase) ≤ 600 W--------------------Motor Speed = 1500 rpm

200 W < Load Power (Per Phase) ≤ 400 W--------------------Motor Speed = 1800 rpm

Figure 4-7 and Table 4-1 are reproducing the control algorithm response data using different pure resistive load values. These responses are from the motor speed and VFD output. I axis is a state-space model created in the workspace and the time axis is an indicator to demonstrate the sampling time on which motor reaction has been evaluated.

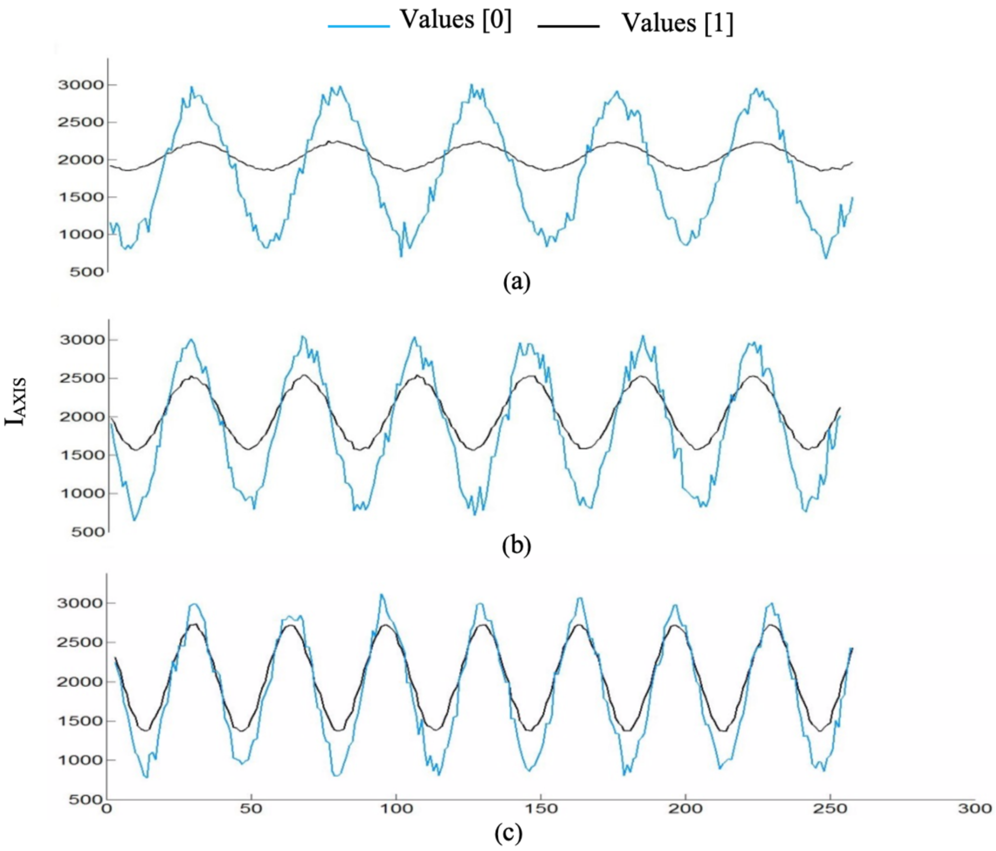
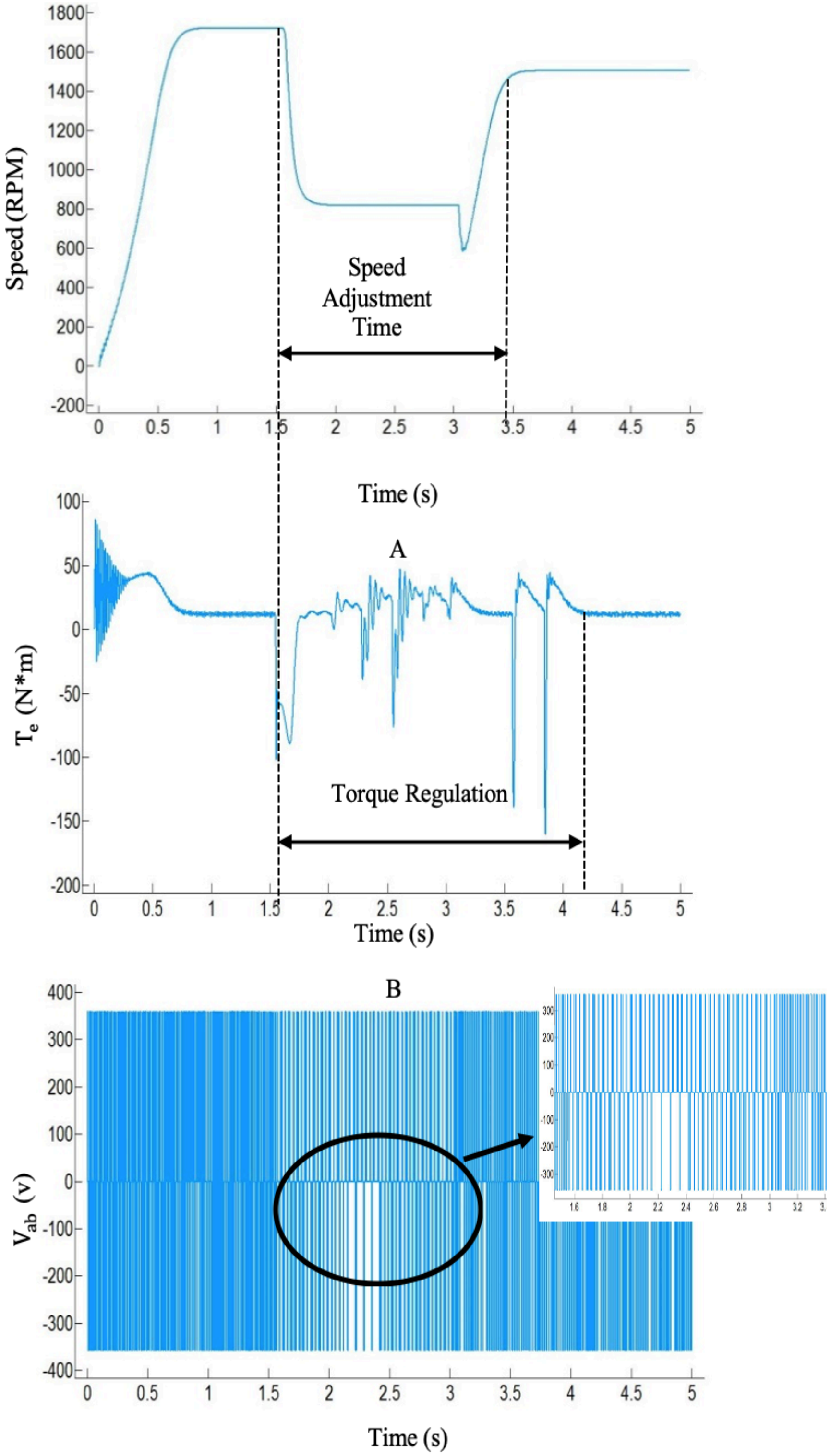


Figure 4-7. Received Signals from Motor Phase Terminal Voltages and Currents

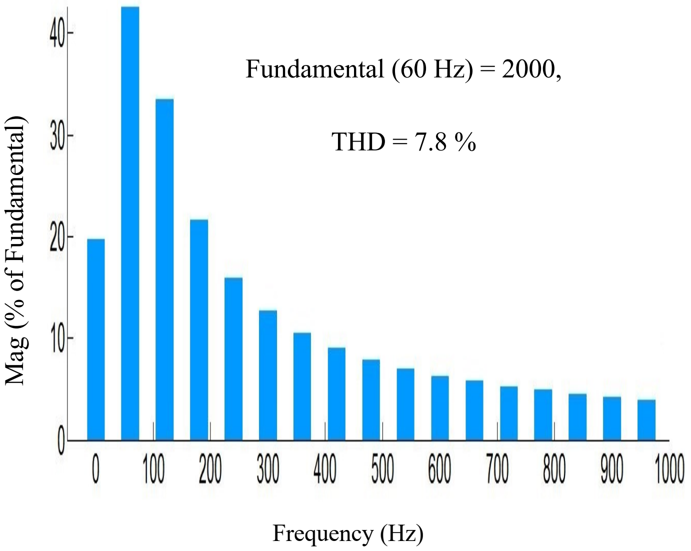
More precisely, Table 4-1 shows specific speed and active power of the electric load separately for every graph.

Table 4-1. Supplementary details of figure 7

RPM	**Sample Counter**	**Number Samples**	**Active Power**	**Frequency**	**Figure 7**
1200	126_{unit}	245_{DEC}	653.736_{W}	40.8163_{Hz}	*a*
1500	120_{unit}	197_{DEC}	485.672_{W}	50.7614_{Hz}	*b*
1800	118_{unit}	169_{DEC}	270.041_{W}	59.1716_{Hz}	*c*


Speed (RPM)
1800
1600
1400
1200
1000
800
600
400
200
0
-200
Speed
Adjustment
Time
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (s)
A
T_e (N*m)
100
50
0
-50
-100
-150
-200
Torque Regulation
Time (s)
B
V_{ab} (v)
400
300
200
100
0
-100
-200
-300
-400
Time (s)
1.6
1.8
2
2.2
2.4
2.6
2.8
3
3.2

C



D

Figure 4-8. Transient Effect of Load Variation on: (A) Motor Speed; (C) VFD Phase to Phase Output Voltage; (B) Motor Electric Torque; and (D) Current Harmonic Distortion Rate

Figure 4-8 focuses on the transient effect of the load variation on different parameters of the AC motor. In this scenario, the electric load increased one-step from 300 W to 500 W per each phase.

(a) Represents required time for the control application to regulate the motor speed based on the load variation.

(b) Indicates the VFD output voltage during the load fluctuation. The results show an appropriate sine PWM waveform for the induction motor. The fast-electromagnetic torque stabilization process appears in

(c). VFD using DPC and power correction loops programmed on the microcontroller achieves this.

(d) Illustrates THD of VFD output while motor is running at 1500 rpm.

4.7. IMPLEMENTATION AND EXPERIMENTS

The control algorithm operates on the FDRM-KL25Z signal processor board. Load power tracking control strategy and DPC-PWM are used in this application to achieve a fast and reliable response of motor speed. The experimental setup appears in Figure 4-9. System parameters are measured with Fluke 43B and its specifications are given in appendix VII. Table 4-2 gives more details of the motor speed control application.

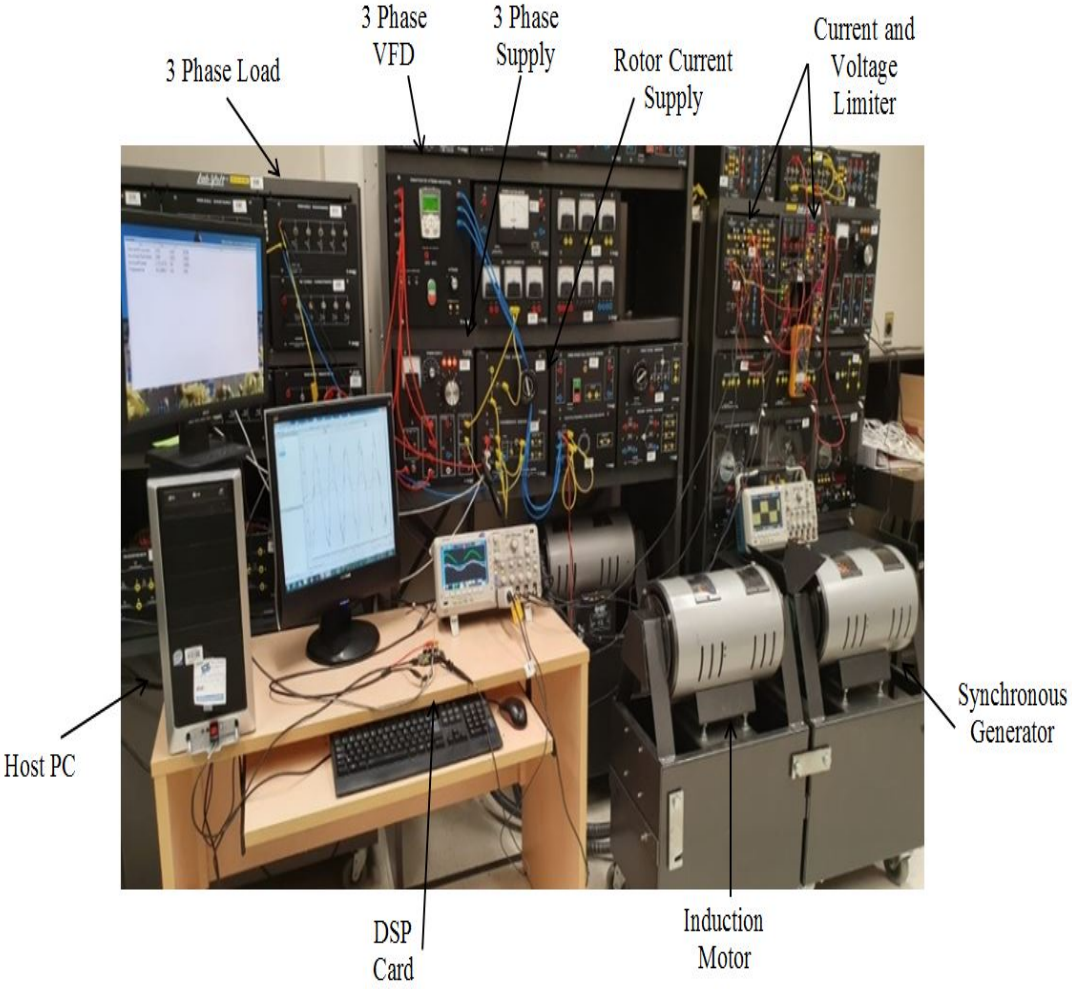


Figure 4-9. Hardware Implementation

Table 4-2. Parameters of variable speed induction motor

Application specification	**Quantity**
Squirrel-Cage Motor	*2-KW*
pole	*4*
Stator Winding	*Star or Delta*
Torque	*10.8 N.m*
Efficiency	*80%*
Microcontroller card	*FRDM-KL25Z*
Frequency	*48MHz*
Sensor	*MMA8451Q*
Connectivity	*MCU IMCU I/O*
Power Converter	*ABB ACS355-0 3E*
PN	*4 KW (5HP)*
U_1	*3-400 V/ 480 V*
I_1	*14 A /6.4 A*
f_1	*48….63 Hz*
Variable Resistance	*2 KW*
Resistance	*240/120/60/60/30 Ω*
Accuracy	*5%*
Nominal Voltage	*120 V – AC/DC*
Current/Voltage Isolator	*0.2 KW*
Maximum Continuous Current	*1/5 A*
Voltage Ranges	*30/300 V*

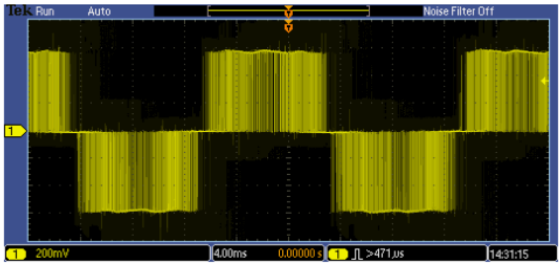
As the variable speed diesel generator uses an AC motor to rotate the generator's stator, we used a synchronous generator as a mechanical load for the induction motor instead of the rotating stator. The induction motor and the synchronous generator are coupled.

Consequently, the mechanical load applied on the AC motor shaft varies by changing the electrical load connected to the synchronous generator. The induction motor is equipped with rotor damper winding to limit induced voltage and increase motor torque. The controlled system supplies 208 V at 50/60 Hz and operates at three different rpm steps. In this experiment, electrical loads are changed manually to see the reaction of different components and simultaneously monitor the motor behavior and the control algorithm.

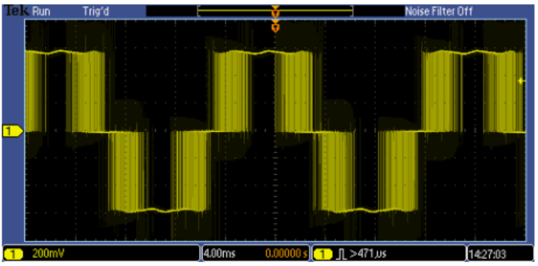
4.8. RESULTS AND DISCUSSION

The results below indicate the response of a 2-kiloWatt induction motor during the electric load step variation. Three-phase Fluke multimeter analyzer measured the power quality of VFD output and motor frequency. In Figure 4-10, we present the results for two different load power levels. For the first step, the 482 W electric load per phase is applied to the synchronous generator. Based on the conditions defined on the controller, the AC motor speed increased to 1497 rpm. This behavior proves that motor speed variation follows the control algorithm. While the experiment was running, the electric load is reduced to 295 W per phase manually. Consequently, the control program increases motor speed to 1798 rpm to meet the predetermined operating conditions.

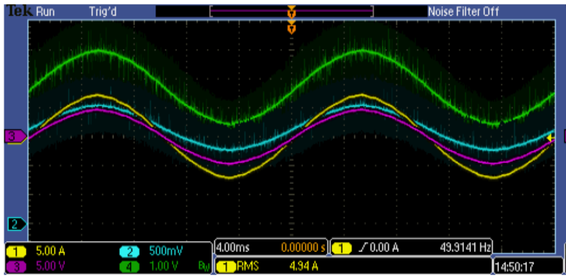
Therefore, during low load values, the VSDG speed control is able to compensate for the necessary rpm while the diesel engine slows down. Graphs (a_1, b_1) represent the motor frequency response as dictated by the control algorithm conditions. Green and blue graphs shown in (a_2, b_2) are voltage and current signals coming from signal limiters apparatuses. The pink graph indicates a reference signal produced by the microcontroller itself. The yellow graph shows the load current used by the microprocessor to calculate the instantaneous power. The three-phase current and its appropriate frequency for the two different loads appear in (a_3,b_3). The measured operational parameters of the induction motor and VFD output voltage harmonics are indicated in (a_4, b_4) and (a_5, b_5) respectively.



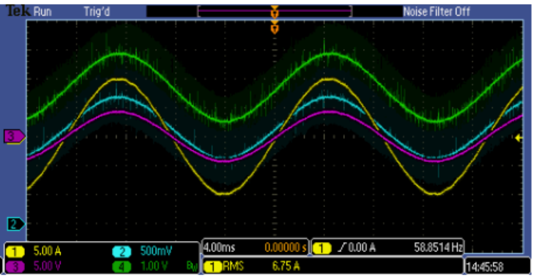
a_1



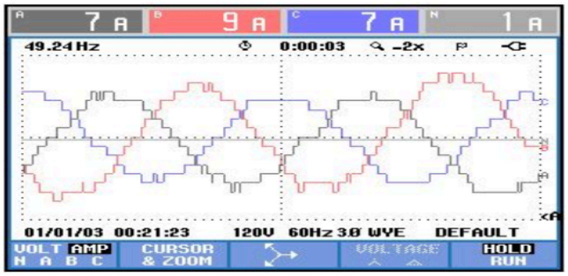
b_1



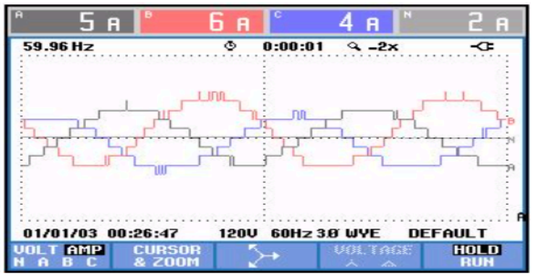
a_2



b_2



a_3



b_3

Power & Energy

FUND 0:00:05

	A	B	C	Total
kW	0.482	0.527	0.433	1.442
kVA	0.680	0.834	0.655	2.169
kVAR	0.479	0.646	0.492	1.617
PF	0.69	0.61	0.63	0.64
DPF	0.71	0.63	0.66	0.66
A rms	6	7	6	

	A	B	C
V rms	119.34	119.80	119.49

01/01/03 00:25:38 120V 60Hz 3Ø WYE DEFAULT

a_4

Power & Energy

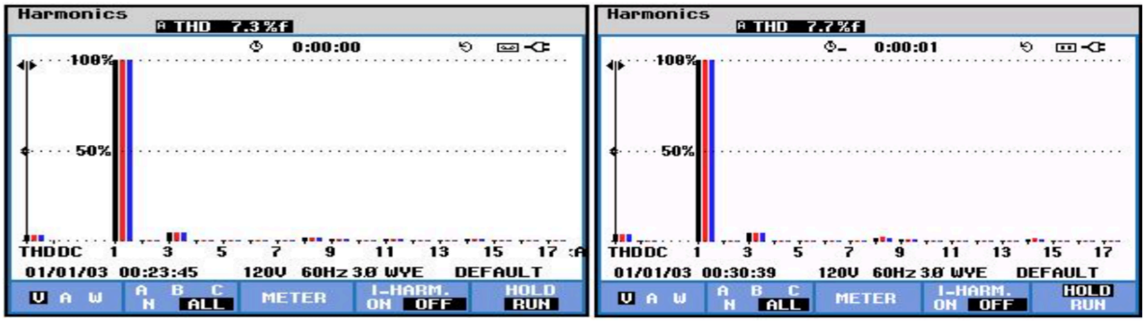
FUND 0:00:00

	A	B	C	Total
kW	0.295	0.276	0.292	0.663
kVA	0.497	0.663	0.482	1.643
kVAR	0.457	0.603	0.443	1.503
PF	0.38	0.41	0.37	0.39
DPF	0.39	0.42	0.40	0.40
A rms	4	6	4	

	A	B	C
V rms	121.34	121.78	122.24

01/01/03 00:27:17 120V 60Hz 3Ø WYE DEFAULT

b_4



a_5 b_5

Figure 4-10. Results for the 2-kiloWatt AC Motor Speed Control Application Using FDRM-KL25Z DSP Card

4.9. EXPERIMENTAL VALIDATION

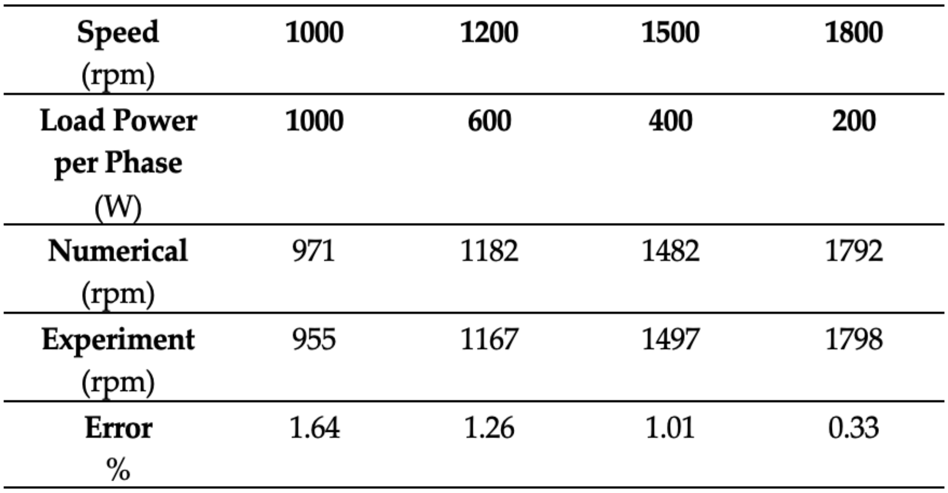
This section presents a comparison between the numerical and experimental simulations of the 2 kW induction motor speed control application. The numerical simulation uses MATLAB/Simulink environment following the algorithm described in Section 6.

In Table 4-3, the target speed values of the AC motor for each load and a comparison between the achieved values of the rpm using numerical and experimental approaches are presented. A tachometer device has used to track generator output frequency based on CM speed and to double-check the CM speed with the simulation modeling. The parameters of the tachometer are given in appendix VIII.

The comparative analysis of load vs. rpm shows the reliable performance of the control algorithm. During the operation of the test bench, the motor speed increases and decreases several times according to predetermined load variation. Each time, a steady-state condition is achieved within 1 to 3 seconds, which demonstrates good synchronicity between VFD and controlled program in producing electromagnetic torque. This response time shows that the

AC motor speed adjusts rapidly in the case of a sudden load change. Finally, the fast and robust response of the AC motor to the load variation results in minimum electric disturbances at VSDG output and motor shaft oscillations.

Table 4-3. Validation results



Speed (rpm)	**1000**	**1200**	**1500**	**1800**
Load Power per Phase (W)	**1000**	**600**	**400**	**200**
Numerical (rpm)	971	1182	1482	1792
Experiment (rpm)	955	1167	1497	1798
Error %	1.64	1.26	1.01	0.33

CHAPTER 5
CONCLUSION, RECOMMENDATIONS AND FUTURE WORKS

Résumé

Cette thèse a montré avec succès que la technologie de contrôle de vitesse variable peut être obtenue en éliminant le convertisseur de puissance de la sortie du générateur électrique. Cette réalisation est possible à l'aide d'un stator rotatif d'une génératrice à aimants permanents (PMSG) entraîné par un moteur compensateur. Le principe, la simulation et la structure d'un groupe électrogène de 500 kW sont décrits en détail dans les chapitres précédents. De plus, ce système n'a pas besoin de modifier le principe et la structure du moteur diesel. En outre, le groupe électrogène peut fonctionner avec le stator fixe au cas où le moteur du compensateur ne fonctionnerait pas (par exemple, problème de courroie de distribution, roulements défectueux, etc.). Par conséquent, la continuité du service d'électrification reste inchangée. Cette étude prouve une réduction de la consommation du carburant par le moteur diesel (DE) en utilisant une génératrice PMSG avec stator rotatif. Une économie de carburant significative de 5% a été observée pour les charges de forte puissance (80-85%). Cela permet au nouveau concept technologique de couvrir une large gamme d'applications industrielles et de concurrencer d'autres techniques conventionnelles telles que l'utilisation de variateurs électroniques de haute puissance. Ces économies de carburant donnent des retours sur investissement positifs pour différentes applications, ainsi que de faibles émissions de CO2. De plus, ces améliorations n'ont pas de conséquences négatives importantes sur la puissance électrique. Ce système présente une bonne durabilité dynamique grâce à l'utilisation d'une petite boîte de vitesses, une fiabilité élevée en éliminant les convertisseurs de puissance, une réduction des gaz à effet de serre en brûlant correctement et complètement le carburant et des performances élevées en régime permanent sur différentes plages de charge.

CONCLUSION, RECOMMENDATIONS AND FUTURE WORKS

5.1. DISCUSSION

In this thesis, many topology designs and control systems for variable speed energy production are studied. In these techniques, different system configurations, such as diesel-driven CVT, PMSG, DFIG, and WRIG, as well as various electrical and mechanical converter (e.g., full-electric power converter, RSC, SSC, and mechanical converter) are used. Besides, fixed and variable speed generator technologies are tested. Extensive simulation tests and experimental results for rotating stator application are provided.

Some of the major achievements of the thesis work are summarized as follows:

A diesel-driven variable speed permanent magnet synchronous generator using a rotating stator is proposed. First of all, this configuration was tested to confirm the accuracy of the concept. To do the confirmation, Genset starts to rotate at 1500 rpm so that the generator would be able to produce 50 Hz power. Then, the CM starts to rotate and drive the stator at the opposite direction of rotor speed. This phenomenon increases the relative speed (total speed) of the generator. Finally, the generator total speed has reached 60 Hz using a developed structure. The experiment results have shown good agreement with the simulation ones.

This project mathematically modeled a synchronous machine with a non-stationary stator using a d-q transformation. Different loads and speeds conditions have been applied to the numerical model, and the obtained results are compared with the experimental ones. This study proves that the rotating stator strategy is able to achieve high system efficiency in long-term projects since the idea is more efficient in the low load regimes.

High fuel-saving and low engine maintenance increase system efficiency as well as low GHG emission and less power shortage.

However, vibration and unpleasant noise may increase due to the malfunctioning of the timing belt during high CM speed. Also, this phenomenon may reduce generator output power quality and increase the risk of a power outage.

Regarding the Genset control system, this study proposed an efficient and robust but simple and cheap strategy to control DE speed during different loads conditions. The advanced speed control technique using a fast load power monitoring approach helps Genset to adapt rapidly to load variation. Unlike other speed control methods, this method is less expensive and needs a lower starting current. Moreover, a precise sensorless vector control technique increases the motor ability to ramp up or ramp down rapidly while connecting to the mechanical load. Accordingly, the load power tracking approach shows an effective solution to adapt the engine speed with an existing condition. This strategy increases system stability due to the availability of secured power during low or peak load and considering the ideal engine regime during unpredictable load conditions.

Below are important advantages of rotating-stator technology:

- Power converter elimination from the generator's output results in a less complicated system.
- We are improving the durability of the Genset application by eliminating the risk of power capacitor breakdown voltage.
- A vast range of variable speed operation since diesel engine speed is no longer dependent on power converter capacity.
- Reduce the risk of power shortage since electric load fluctuation is independent of power converter capacity.

- Rotating-stator technology reduces harmonic pollution in the power system produced by a high-rated power converter.

However, there are also some drawbacks:

- More maintenance is needed due to employing a compensator motor into the system.
- Power converters are expensive. However, this technology adds a compensator motor and its control system to the generator set.
- Malfunctioning of the gearbox may produce some vibrations.
- Gearbox may produce unwanted noises, and at high speed, it may produce harmonics.

5.2. CONCLUSION

This thesis has successfully shown that variable speed control technology is achieved by eliminating the power converter from electric generator output. This achievement is proposed by developing a PMSG stator using a compensator motor. The principle, simulation, and structure of a 500 kW Genset are discussed in detail in previous chapters.

This study proves DE fuel optimization by developing a PMSG structure based on a rotating-stator mode. Moreover, these improvements do not have significant negative consequences on the electrical output. This system shows good dynamic durability due to utilizing a small gearbox, high reliability by eliminating power converters, reducing greenhouse gases by correctly and completely burning fuel, and high steady-state performance throughout different load performance.

5.2.1. Diesel generator efficiency

One of the solutions to increase electricity production efficiency using gensets is to use VSDGs. A recently developed technology uses a rotating stator as a solution to allow the diesel engine to slow down and operate at better efficiency when electric load drops. An AC compensator motor drives the generator’s stator and adjusts its speed according to the VSDG electric load such that the stator speed increases when the VSDG electric load decreases.

In this project, a control algorithm has been developed for the AC compensator motor that follows the load variation. The numerical and experimental results demonstrated an efficient and robust control algorithm. The main advantages of introducing this control approach with the rotating stator VSDG technology are the increased efficiency operation and reduced fuel consumption and GHG emissions of the diesel engine. The fast time response of the AC motor ensures current quality without the use of complex power electronics.

5.2.2. Fuel consumption optimization

The amount of fuel consumed depends on the engine, the type of fuel used, the ambient condition, and the efficiency with which the output of the engine is transmitted to the electric generator. Diesel generators are a popular electricity source because of their low capital costs, but they can have high operating costs. This project has focused on the ambient temperature and condition and system efficiency to achieve fuel optimization.

This thesis presents a new technology based on the synchronous machine with a rotating stator concept improving the performance of a 500 kW diesel generator and aims to minimize the cost of electricity production. The experimental results have shown that significant fuel savings of 15% are obtained at low power loads, which are considered very attractive for remote areas where DGs frequently run at lower loads (<50%). In the first part of the project, we used static operation without a speed control system to ensure the stator speed adjustment. Then, we developed and demonstrated the functionality of a new generator structure system, allowing to adjust dynamically the stator speed of the alternator based on the applied load. This project has shown that it is possible to minimize the deviation from maximum speed when receiving a load on a 500 kW generator and meet the G2 performance classification of ISO 8528-part 5 using a speed controller.

Moreover, this system does not need to make modifications to the principle and structure of the diesel engine. Besides, Genset can operate with the fixed stator in case that the compensator motor failed to run (e.g., timing belt problem, defective bearings, etc.). Therefore, the continuity of the electrification service remains unchanged.

On the other hand, a significant fuel saving of 5% has been observed for high power loads (80-85%). This allows the new technology concept to cover a wide range of industrial applications and to compete with other conventional techniques such as the use of high power electronic variable speed drives. These fuel savings give positive economic returns on investment for different applications, as well as low CO2 emissions.

At the Raglan mine site, this study concludes that the rotating stator concept can offer reduced fuel consumption. The concept has been demonstrated as a reliable technology for electricity generation at remote mine sites, which offers fuel consumption and carbon emissions savings. Lessons learned at the Raglan Mine site are useful for other similar remote grids operating in Northern Canada and other sites. These sites include remote communities and industrial sites where all electricity needs are provided by diesel generators.

5.2.3. Diesel generator perspective and future goals

The diesel generator market is being pushed in different directions by a variety of conflicting drivers and global megatrends. While global power demand continues to increase and expand to off-grid locations, increasingly stringent environmental regulations and falling renewable/battery technology prices lead to a changing generator set landscape.

On the other hand, the use of diesel generator sets has increased over the past decade as the primary choice for reliable mobile, stationary, or temporary on-site power. Tightening emissions regulations, environmental concerns, and plummeting renewable energy costs are putting increased pressure on the diesel Genset industry. As manufacturers and suppliers of generator sets look to adapt to a changing energy system, there is a range of key technology developments that will play a crucial role in shaping future use.

Grid power quality, system stability, and production efficiency are three major challenges of every modern power system. They are turning to future energy production perspective, modern DEs operating to meet emergency conditions or, in worse cases, regulating system parameters (voltage, frequency). Synchronizing variable speed DG techniques with electric consumption is an important key factor to improve system efficiency.

This strategy helps especially the conventional power sources to reduce their fuel consumption and also minimize additional expenses. Among proposed production systems, some techniques are able to save more fuel and produce more reliable outputs. However, these methods are not suitable for all applications, specifically with sudden and large load oscillations. On the other hand, some techniques demonstrate reliable performance during load variation, even in remote areas but not too efficient for small communities as long as they need a high initial investment.

One important parameter in every project with Genset systems is Life Cycle Analysis (LCA). The goal is to identify whether hybrid diesel-wind has the potential to reduce the environmental impacts associated with the current diesel-generated electricity in remote communities. This could be achieved by comparing the LCA impacts of a hybrid diesel-wind turbine system with the current VSDG electricity system. Hybrid diesel-wind systems have been identified as a feasible option.

5.3. RECOMMENDATION AND FUTURE WORK

This thesis constitutes a complete theoretical basis regarding the various technologies allowing the optimization of the variable speed control and operational efficiency of Genset system. Although several experimental validations were carried out during this thesis, several further developments are necessary through the requirements of control and system security. In this thesis, the general proposed topologies and control algorithms were only simulated because of the non-availability of the equipment and the lack of space in the hardware Lab. It will be interesting to implement and validate them in real-life operations.

Regarding self-control variable speed diesel generator using rotating stator technology and although the novelty of the project, this thesis focused on some objectives and tried to improve several uncertain issues such as concept design, system modeling, and control unit. However, there are various questions to answer and projects to do. This project has a high potential capacity to be used in different power plants.

Regarding the electric alternator, it is strongly recommended to carry out a detailed analysis of the costs of modifications to be made on an existing electric machine (synchronous generator) according to its power. As long as the CM is supplied by the generator itself, a study is needed to adjust CM rating power based on generator capacity.

During high CM speed, alternator vibration may produce unwanted harmonics. Extensive research regarding different CM speeds unveils the dark side of the project.

In terms of the mechanical gearbox, vibration and noise may increase while CM is rotating at different speeds. Therefore, it is important to clarify the size of the gearbox for different genset capacities.

Real load varies instantaneously, and this phenomenon may produce harmonic pollution into the power system. Regarding system control and power quality, it is essential to apply different load types (e.g., dump loads, inductive, etc.) to the genset prototype and evaluate system reaction.

In terms of off-grid hybrid power plants, this technology could improve system efficiency during peak load regime when Genset system working in parallel with other sources of energy.

In terms of the wind turbine industry, a constant speed wind turbine is designed to obtain maximum efficiency at one wind speed that will give the optimum tip speed to wind speed ratio for the rotor blade. The variable speed machine can obtain the optimum tip speed to wind speed ratio at any wind speed by changing the machine speed as the wind speed changes. Replacement of power converter by rotating stator technology or a combination of both technologies could reduce the power system harmonics, increase wind energy absorption, and reduce power system instabilities. Figure 5-1 shows the conceptual schema of rotating stator technique into the variable speed wind turbine.

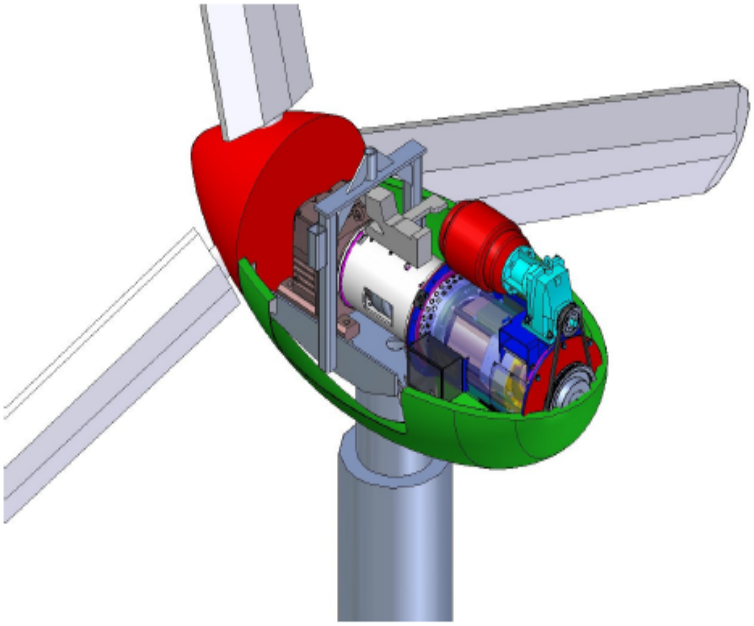


Figure 5-1. Integration of rotating stator technology with wind turbine

PUBLICATIONS

Performance Optimization of Diesel Generators Using Permanent Magnet Synchronous Generator with Rotating Stator,

- *Energy and Power Engineering, 2019,*

- ✓ Mohammadjavad Mobarra[a*], Mohamad Issa[a], Miloud Rezkallah[b], Adrian Ilinca[a]

Advanced Control of a Compensator Motor Driving a Variable Speed Diesel Generator with Rotating Stator,

- *MDPI, ENERGIES, 2020*

- ✓ Mohammadjavad Mobarra [a], Bruno Tremblay [b], Miloud Rezkallah[a] and Adrian Ilinca[1,*]

Variable Speed Diesel Generators: Performance and Characteristic Comparison,

- In progress…..

Mohammadjavad Mobarra[a*], Miloud Rezkallah[b], Adrian Ilinca[a]

Modeling and optimization of the energy production based on Eo-Synchro application

- *Journal of power engineer, IDGTE, 2018*

✓ Mohamad Issa, Mobarra.Mohammadjavad., Jean Fiset, Adrian Ilinca

Optimizing the performance of a 500 kW Diesel Generator: Impact of the Eo-Synchro concept on fuel consumption and greenhouse gases

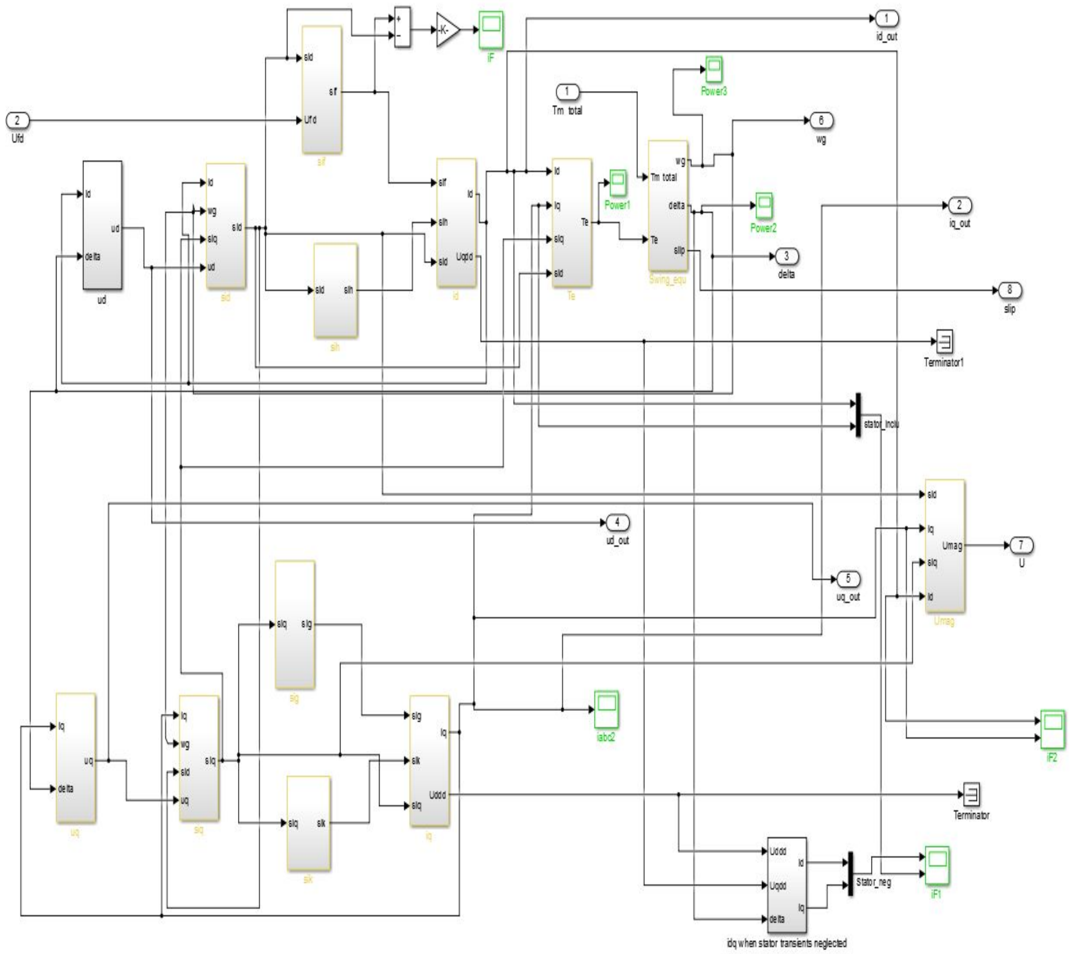
- *Journal of power engineer, IDGTE, 2018*

✓ Mohamad ISSA, Mohammadjavad MOBARRA, Jean FISET, Hussein IBRAHIM, Adrian ILINCA

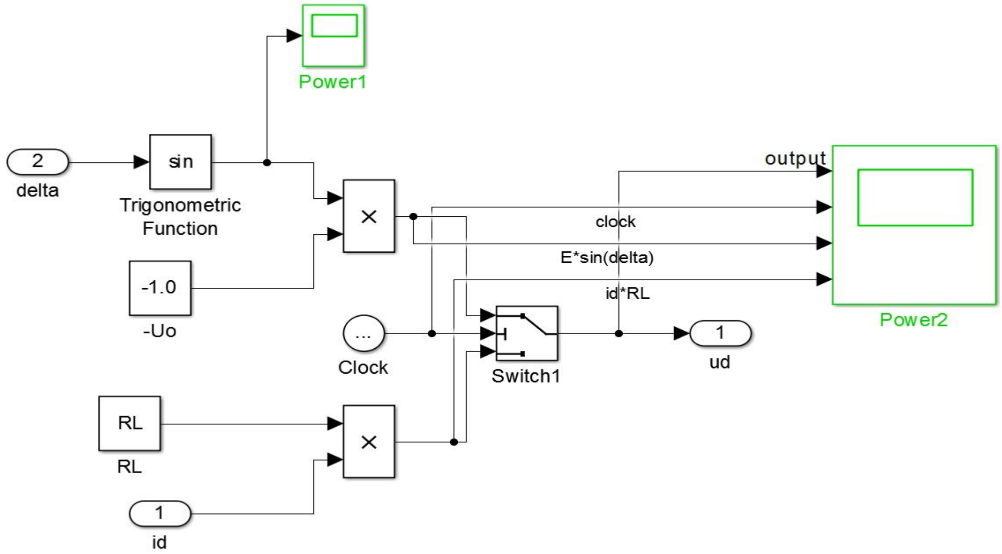
APPENDIX-I
NUMERICAL MODELING OF PMSG

Full order model of synchronous machine

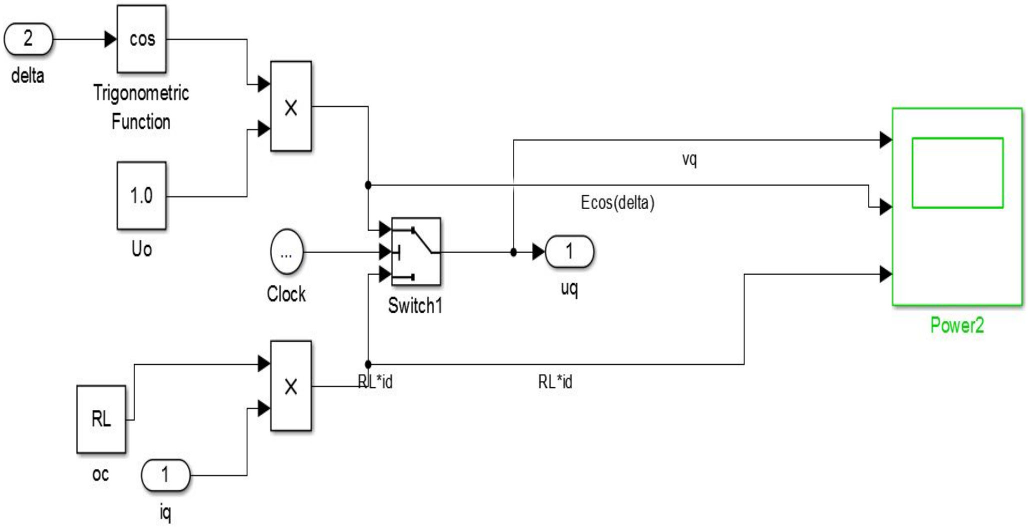
Reference: Power System Stability and Control by Prabha Kunder.



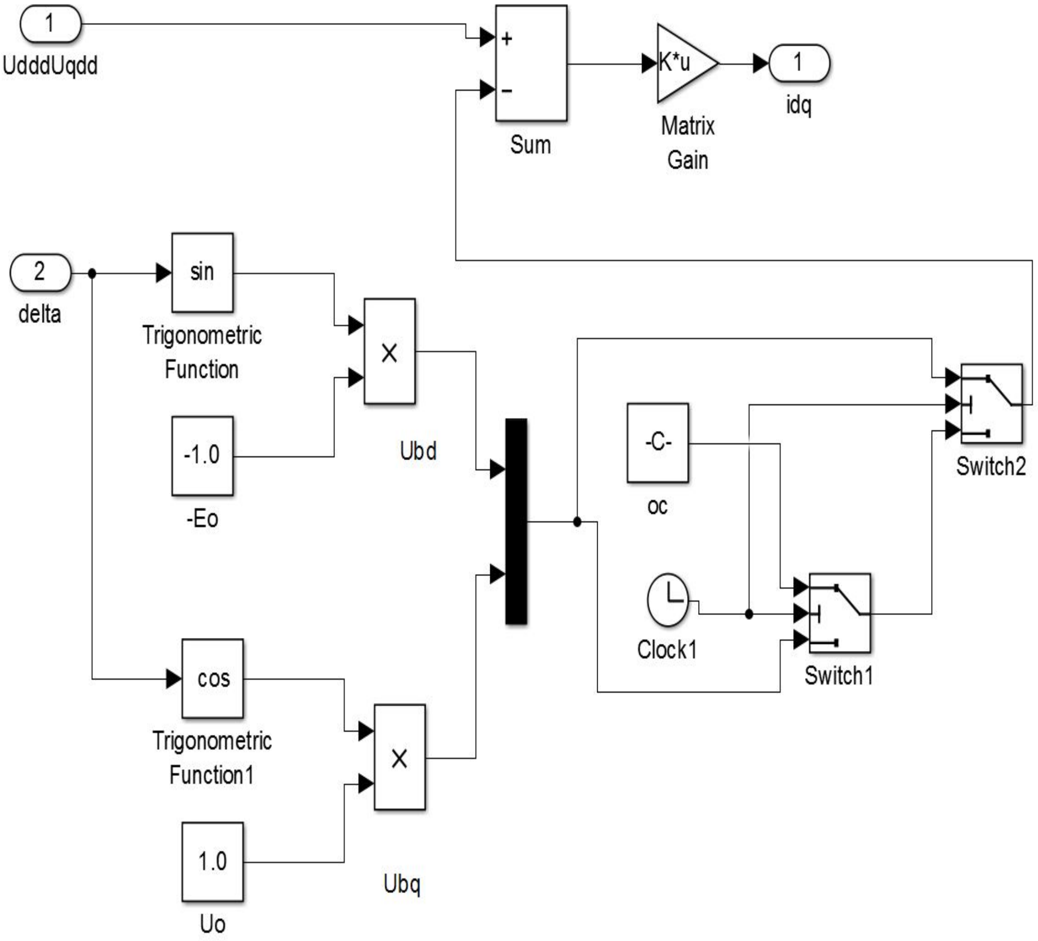
U_d-Vector Model



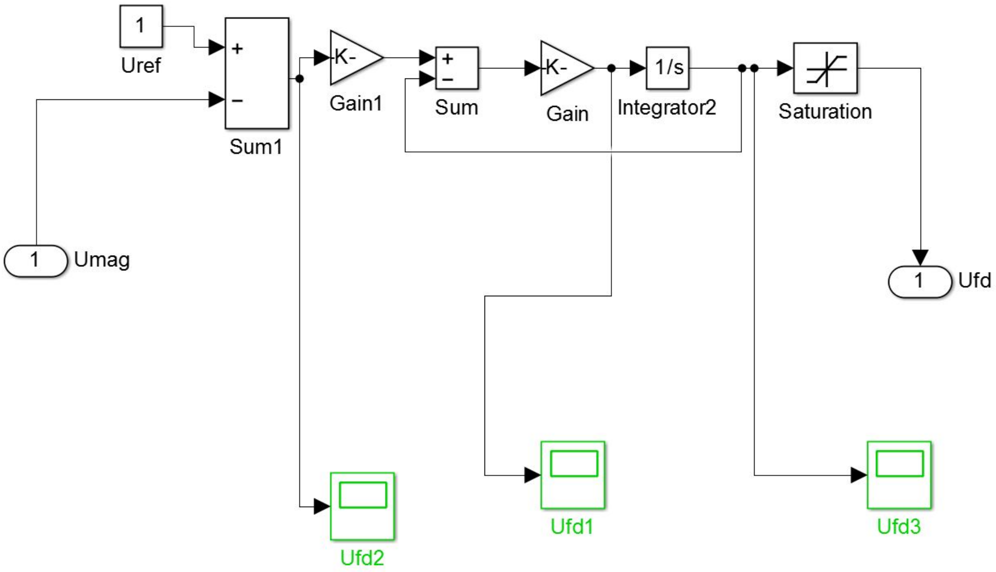
U_q-Vector Model



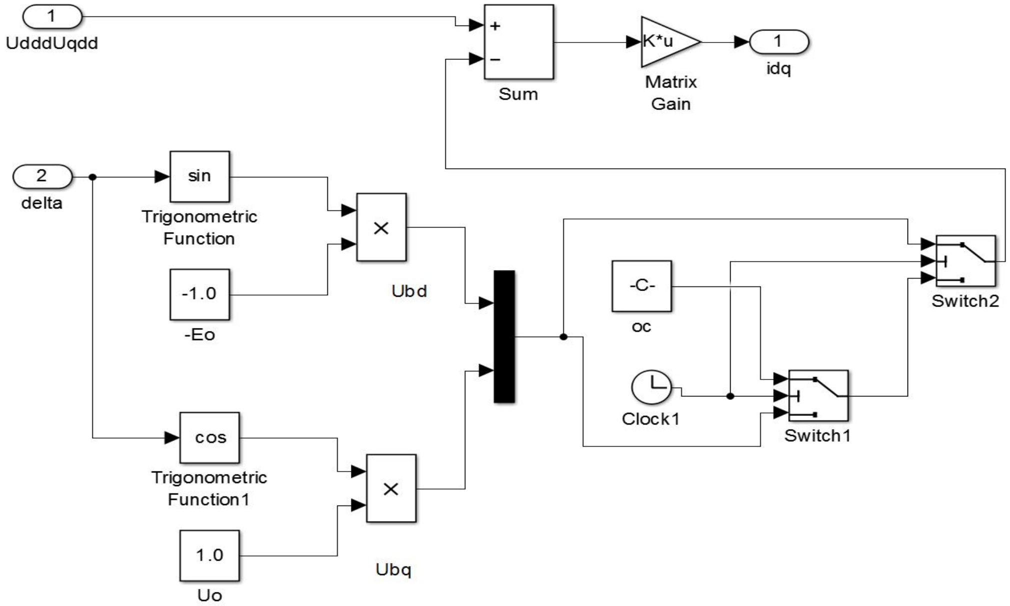
I_{dq}-Stator Transient Neglected



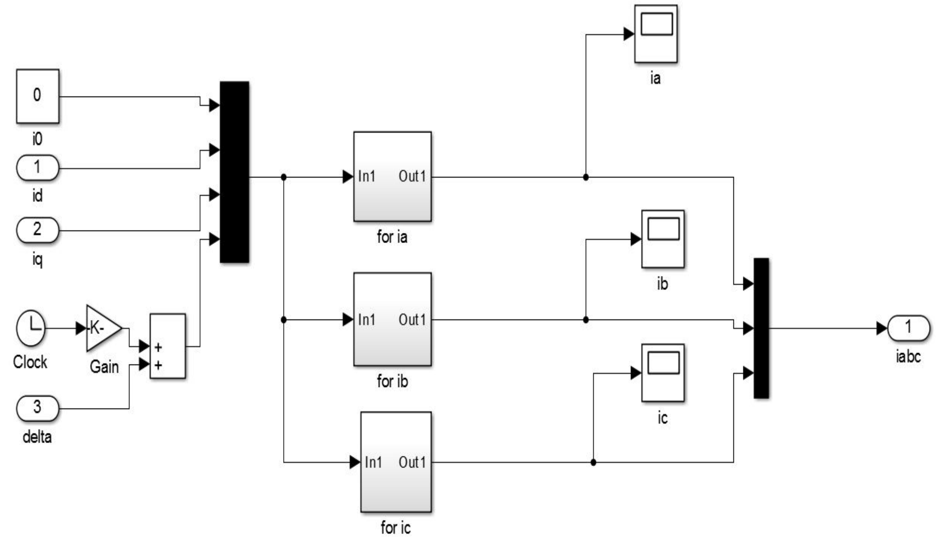
Automatic Voltage Regulation System



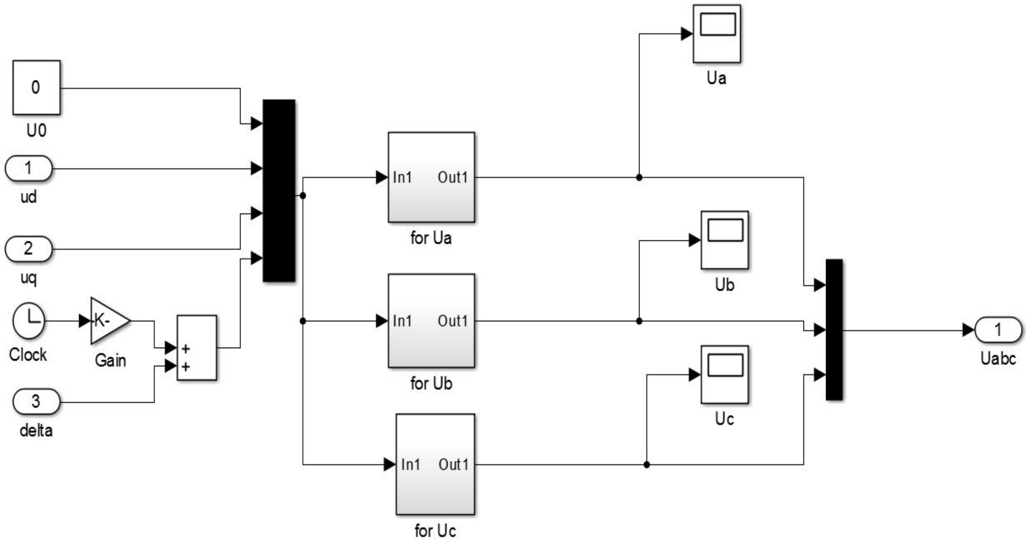
Synchronization System



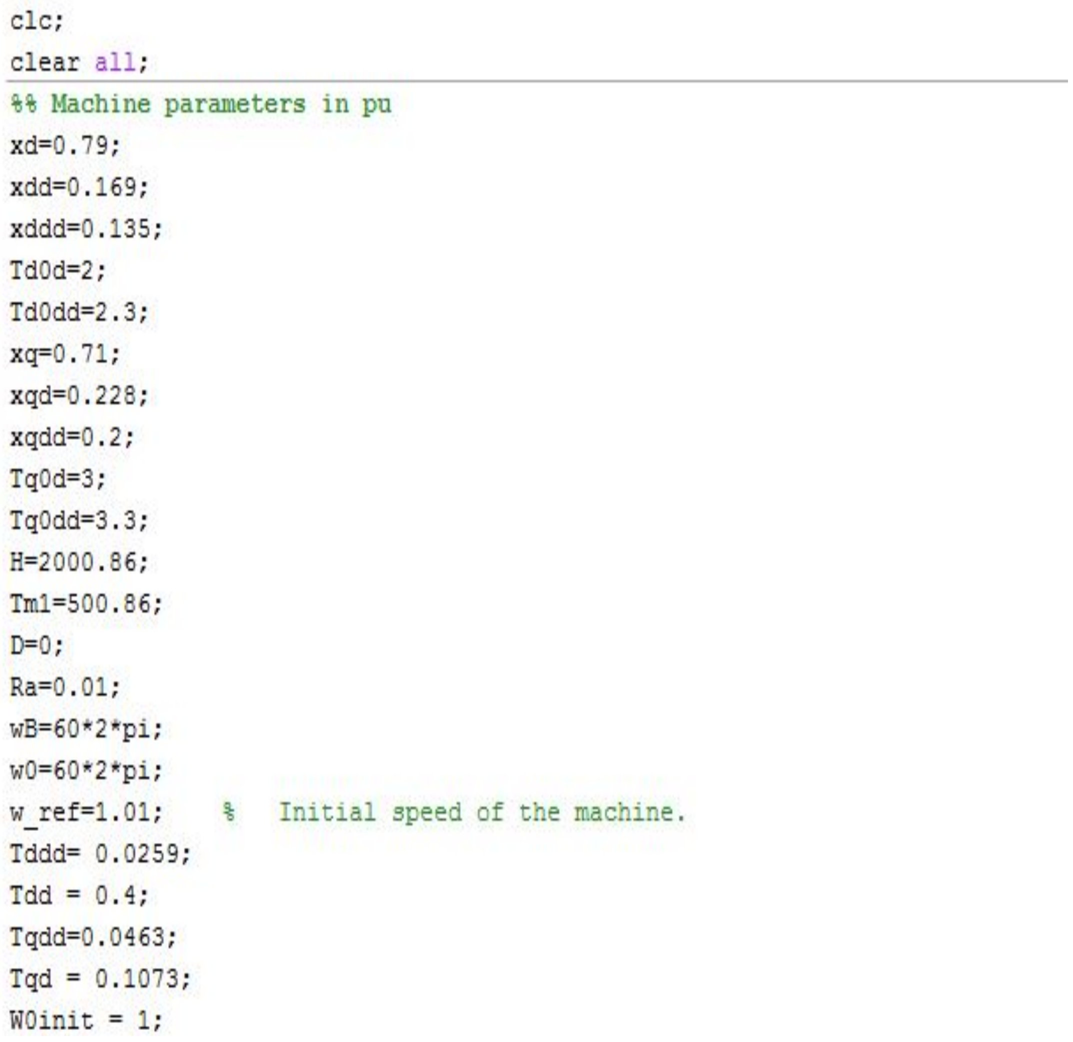
I_{0dq}-I_{abc} Transformation



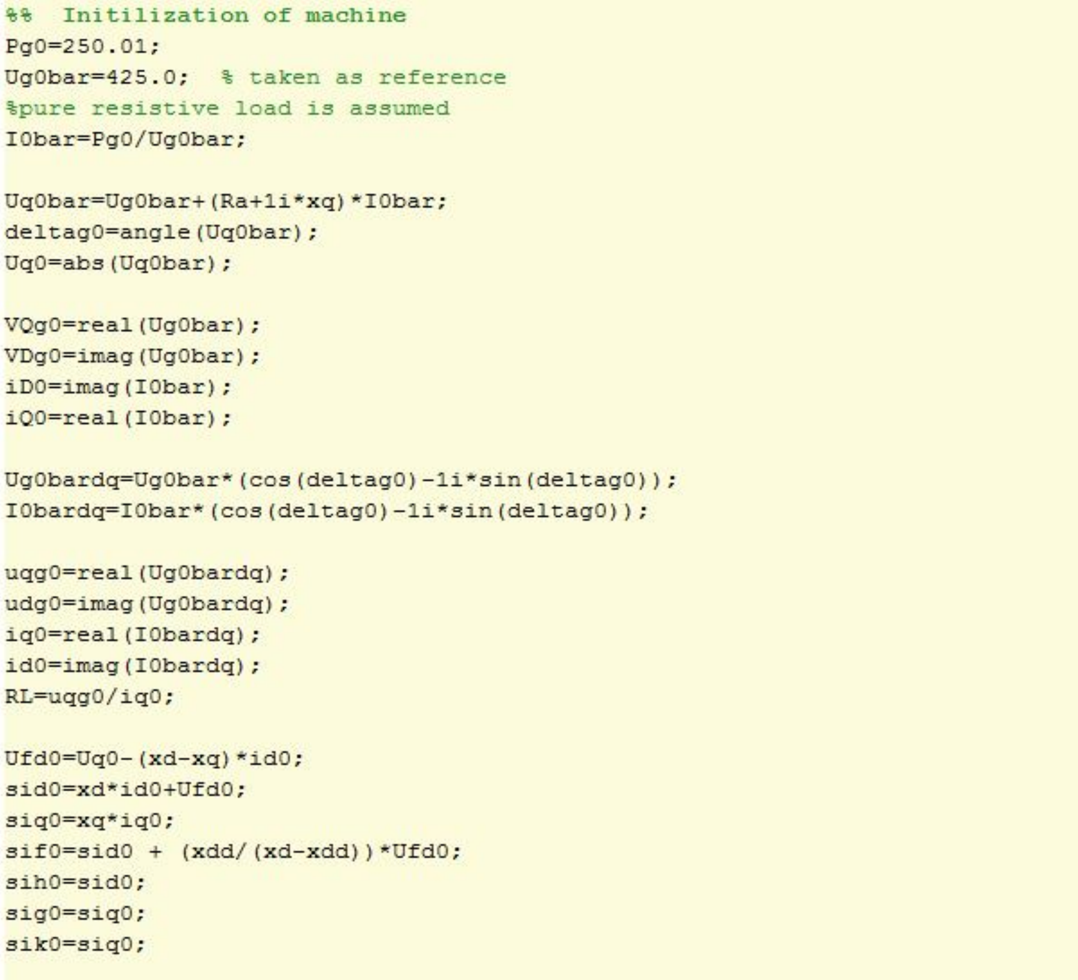
U_{0dq}-U_{abc} Transformation



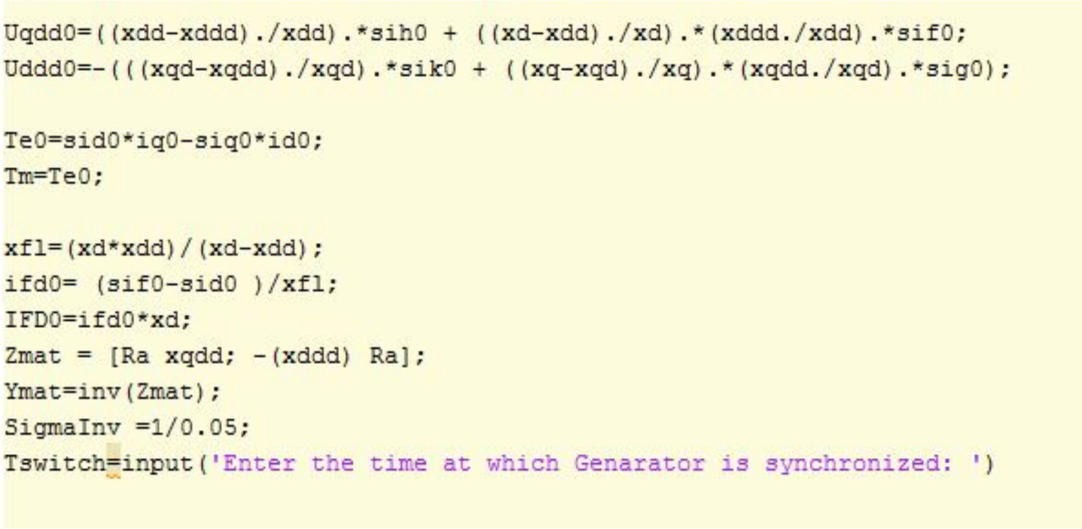
APPENDIX-II
PMSG SYNCHRONIZATION CODE



```
clc;
clear all;
%% Machine parameters in pu
xd=0.79;
xdd=0.169;
xddd=0.135;
Td0d=2;
Td0dd=2.3;
xq=0.71;
xqd=0.228;
xqdd=0.2;
Tq0d=3;
Tq0dd=3.3;
H=2000.86;
Tm1=500.86;
D=0;
Ra=0.01;
wB=60*2*pi;
w0=60*2*pi;
w_ref=1.01;    %   Initial speed of the machine.
Tddd= 0.0259;
Tdd = 0.4;
Tqdd=0.0463;
Tqd = 0.1073;
W0init = 1;
```



```
%%  Initilization of machine
Pg0=250.01;
Ug0bar=425.0;  % taken as reference
%pure resistive load is assumed
I0bar=Pg0/Ug0bar;

Uq0bar=Ug0bar+(Ra+1i*xq)*I0bar;
deltag0=angle(Uq0bar);
Uq0=abs(Uq0bar);

VQg0=real(Ug0bar);
VDg0=imag(Ug0bar);
iD0=imag(I0bar);
iQ0=real(I0bar);

Ug0bardq=Ug0bar*(cos(deltag0)-1i*sin(deltag0));
I0bardq=I0bar*(cos(deltag0)-1i*sin(deltag0));

uqg0=real(Ug0bardq);
udg0=imag(Ug0bardq);
iq0=real(I0bardq);
id0=imag(I0bardq);
RL=uqg0/iq0;

Ufd0=Uq0-(xd-xq)*id0;
sid0=xd*id0+Ufd0;
siq0=xq*iq0;
sif0=sid0 + (xdd/(xd-xdd))*Ufd0;
sih0=sid0;
sig0=siq0;
sik0=siq0;
```



```
Uqdd0=((xdd-xddd)./xdd).*sih0 + ((xd-xdd)./xd).*(xddd./xdd).*sif0;
Uddd0=-(((xqd-xqdd)./xqd).*sik0 + ((xq-xqd)./xq).*(xqdd./xqd).*sig0);

Te0=sid0*iq0-siq0*id0;
Tm=Te0;

xfl=(xd*xdd)/(xd-xdd);
ifd0= (sif0-sid0 )/xfl;
IFD0=ifd0*xd;
Zmat = [Ra xqdd; -(xddd) Ra];
Ymat=inv(Zmat);
SigmaInv =1/0.05;
Tswitch=input('Enter the time at which Genarator is synchronized: ')
```

APPENDIX-III
ROTATING-STATOR DIESEL GENERATOR SPECIFICATIONS

PRODUCT SPECIFICATIONS FOR C15 (60 HZ)

GENERATOR SET SPECIFICATIONS

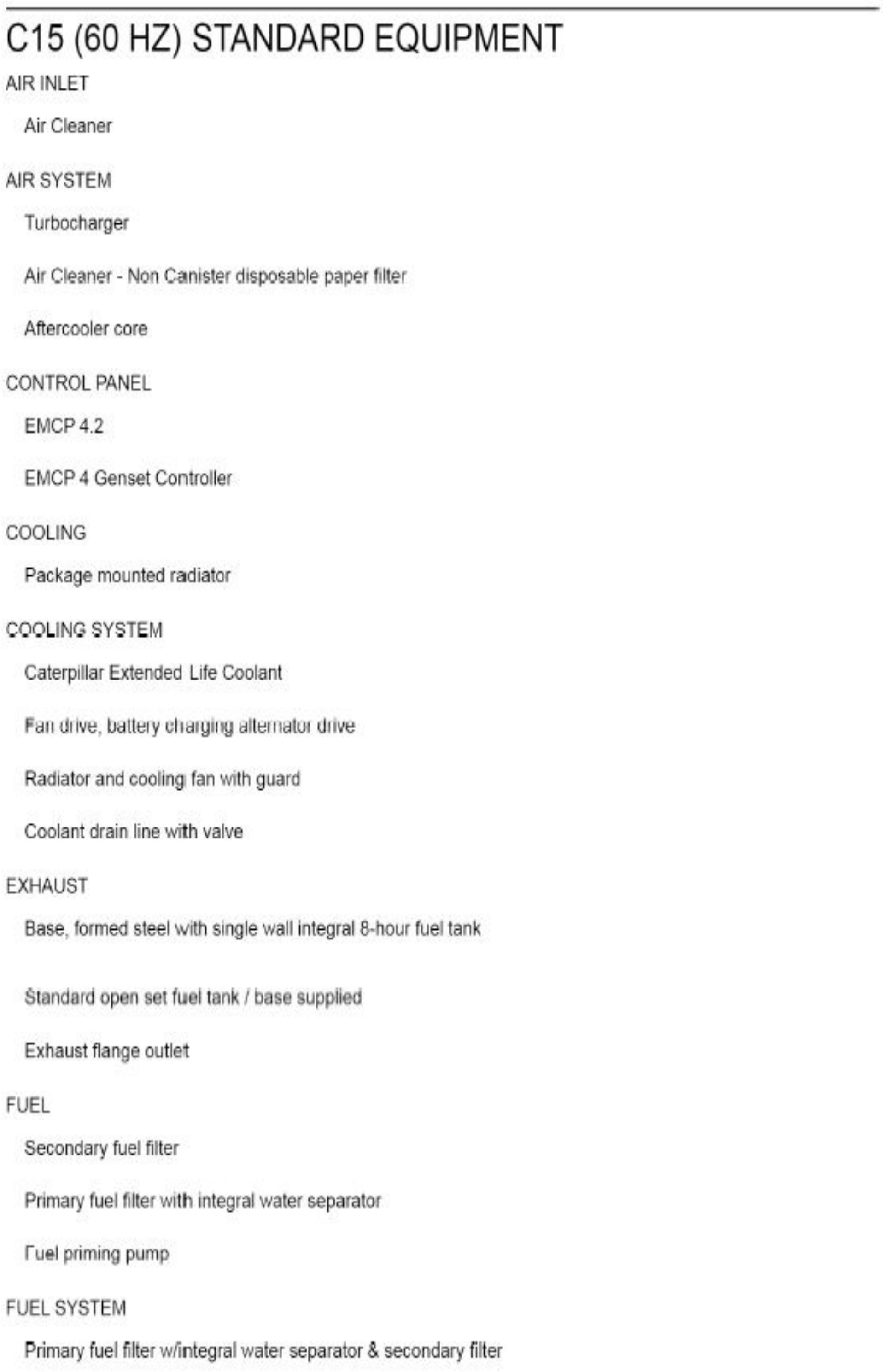
Minimum Rating	320 ekW
Maximum Rating	500 ekW
Emissions/Fuel Strategy	Low Fuel, Tier 2, Tier 3, EU Stage IIIA
Voltage	208 to 600 Volts
Frequency	60 Hz
Speed	1800 RPM
Duty Cycle	Standby, Prime

ENGINE SPECIFICATIONS

Engine Model	C15 ATAAC, I-6, 4-Stroke Water-Cooled Diesel
Bore	5.4 in
Stroke	6.75 in
Displacement	927.56 in^3
Compression Ratio	16.1:1
Aspiration	Air to Air Aftercooled
Fuel System	MEUI
Governor Type	Adem™A4

GENERATOR SET DIMENSIONS

Length - Maximum	168.2 in
Width - Maximum	81 in
Height - Maximum	82.4 in



C15 (60 HZ) STANDARD EQUIPMENT

AIR INLET

- Air Cleaner

AIR SYSTEM

- Turbocharger
- Air Cleaner - Non Canister disposable paper filter
- Aftercooler core

CONTROL PANEL

- EMCP 4.2
- EMCP 4 Genset Controller

COOLING

- Package mounted radiator

COOLING SYSTEM

- Caterpillar Extended Life Coolant
- Fan drive, battery charging alternator drive
- Radiator and cooling fan with guard
- Coolant drain line with valve

EXHAUST

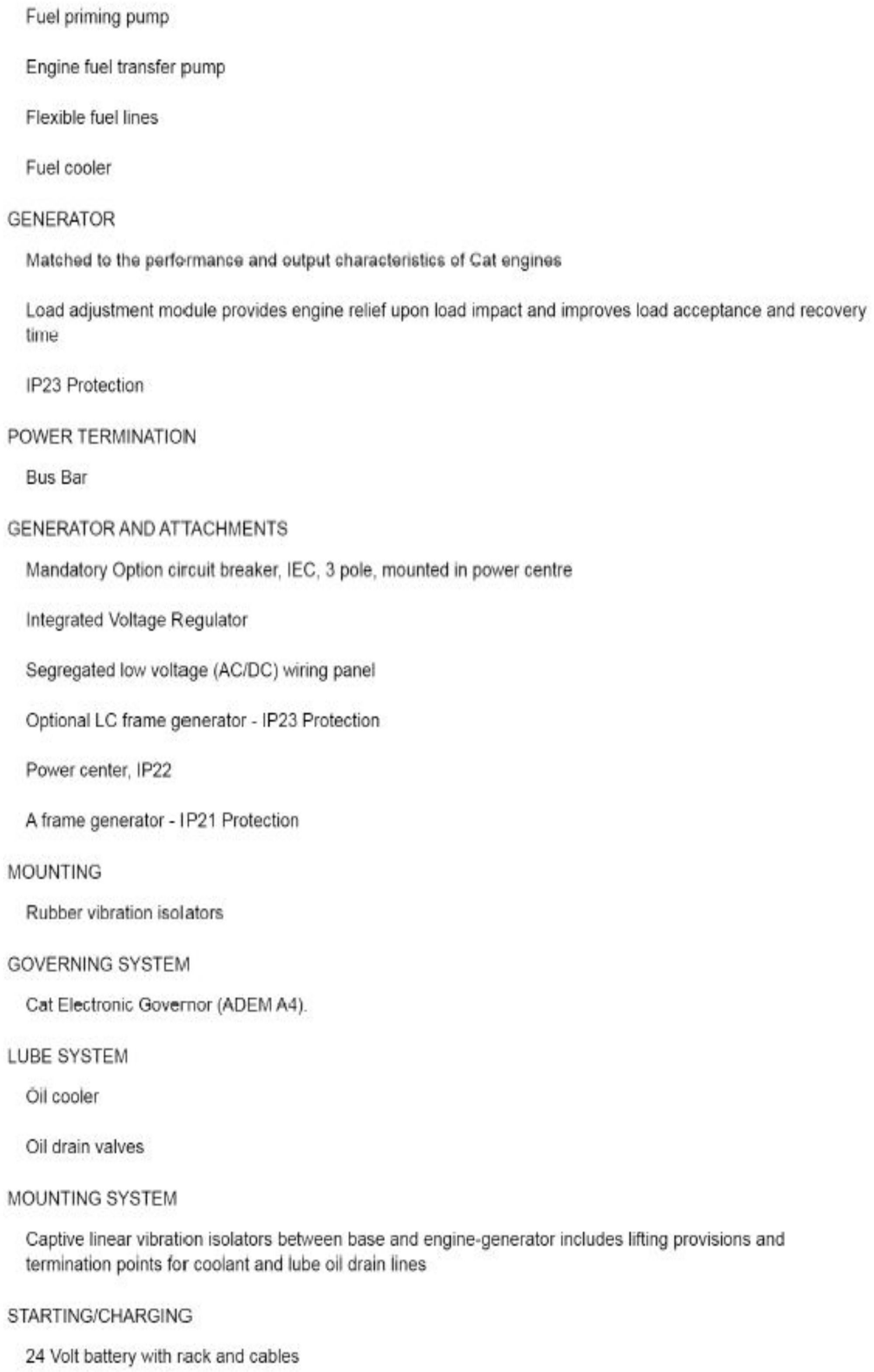
- Base, formed steel with single wall integral 8-hour fuel tank
- Standard open set fuel tank / base supplied
- Exhaust flange outlet

FUEL

- Secondary fuel filter
- Primary fuel filter with integral water separator
- Fuel priming pump

FUEL SYSTEM

- Primary fuel filter w/integral water separator & secondary filter



Fuel priming pump

Engine fuel transfer pump

Flexible fuel lines

Fuel cooler

GENERATOR

Matched to the performance and output characteristics of Cat engines

Load adjustment module provides engine relief upon load impact and improves load acceptance and recovery time

IP23 Protection

POWER TERMINATION

Bus Bar

GENERATOR AND ATTACHMENTS

Mandatory Option circuit breaker, IEC, 3 pole, mounted in power centre

Integrated Voltage Regulator

Segregated low voltage (AC/DC) wiring panel

Optional LC frame generator - IP23 Protection

Power center, IP22

A frame generator - IP21 Protection

MOUNTING

Rubber vibration isolators

GOVERNING SYSTEM

Cat Electronic Governor (ADEM A4).

LUBE SYSTEM

Oil cooler

Oil drain valves

MOUNTING SYSTEM

Captive linear vibration isolators between base and engine-generator includes lifting provisions and termination points for coolant and lube oil drain lines

STARTING/CHARGING

24 Volt battery with rack and cables

24 volt starting motor

Batteries

GENERAL

Engine and alternator pre paint, Caterpillar yellow

Paint - Caterpillar Yellow except rails and radiators gloss black

C15 (60 HZ) OPTIONAL EQUIPMENT

AIR INLET SYSTEM

Single element air cleaner

Dual element air cleaner

EXHAUST

Industrial, Residential, Critical Mufflers

CERTIFICATIONS

EU certificate of conformance

Global certification for CIS

CIRCUIT BREAKERS

Shunt trip for IEC circuit breaker

Pad-lockable circuit breaker device

4 Pole (IEC-100% rated) circuit breakers - Motorised

Auxiliary contacts, circuit breaker

3 Pole (IEC-100% rated) circuit breakers - Motorised

3 Pole (IEC-100% rated) circuit breakers - Package mounted

4 Pole (IEC-100% rated) circuit breakers - Package mounted

Power terminal strip

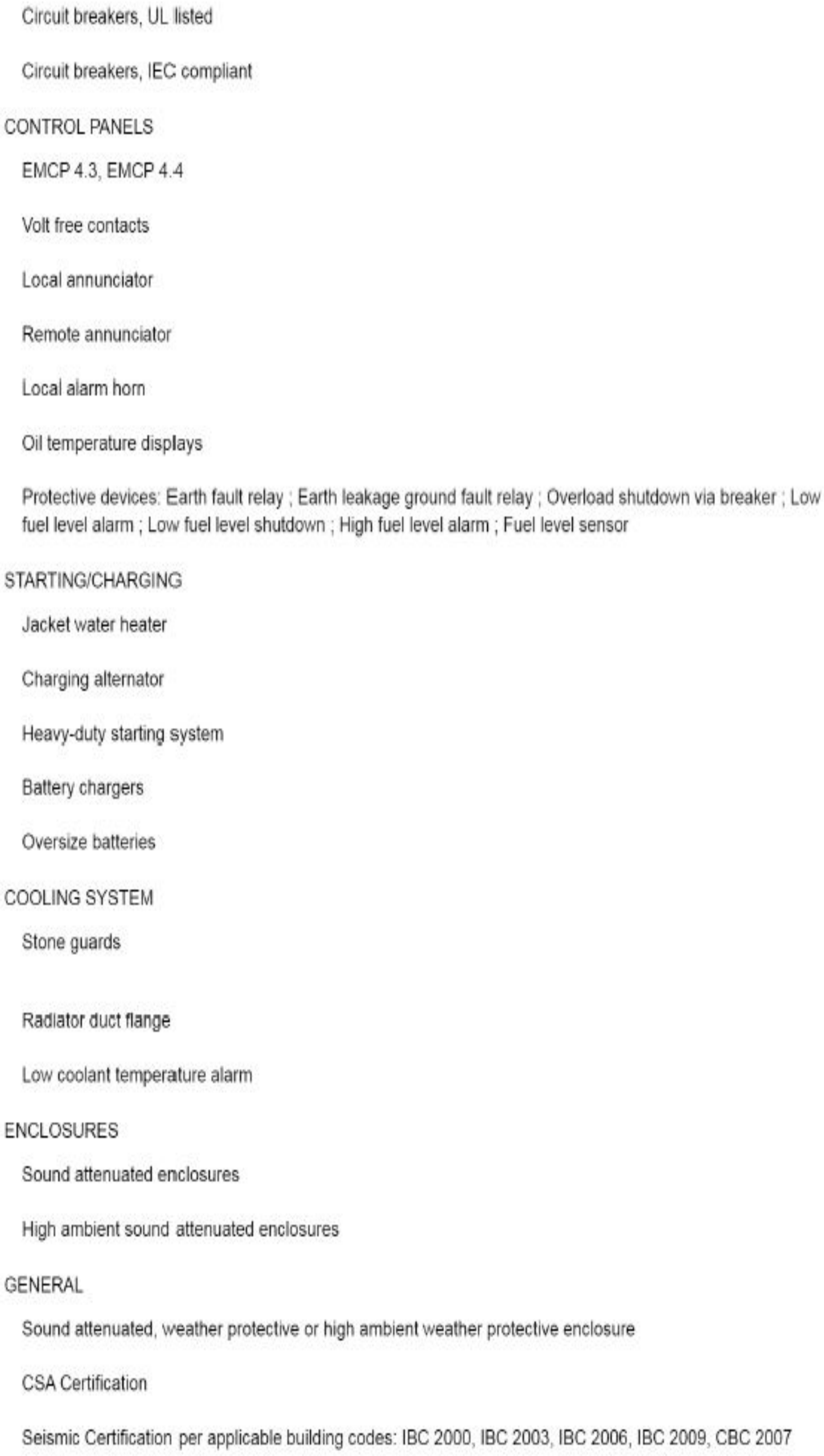
GENERATOR

Oversize and premium generators

Anti-condensation heater

Excitation: [ ]Permanent Magnet Excited (PM) [ ]Internally Excited (IE)

POWER TERMINATION



Circuit breakers, UL listed

Circuit breakers, IEC compliant

CONTROL PANELS

EMCP 4.3, EMCP 4.4

Volt free contacts

Local annunciator

Remote annunciator

Local alarm horn

Oil temperature displays

Protective devices: Earth fault relay ; Earth leakage ground fault relay ; Overload shutdown via breaker ; Low fuel level alarm ; Low fuel level shutdown ; High fuel level alarm ; Fuel level sensor

STARTING/CHARGING

Jacket water heater

Charging alternator

Heavy-duty starting system

Battery chargers

Oversize batteries

COOLING SYSTEM

Stone guards

Radiator duct flange

Low coolant temperature alarm

ENCLOSURES

Sound attenuated enclosures

High ambient sound attenuated enclosures

GENERAL

Sound attenuated, weather protective or high ambient weather protective enclosure

CSA Certification

Seismic Certification per applicable building codes: IBC 2000, IBC 2003, IBC 2006, IBC 2009, CBC 2007

- EEC Declaration of Conformity
- Integral & sub-base UL listed dual wall fuel tanks
- Automatic transfer switches (ATS)
- Single or dual wall sub-base fuel tanks
- The following options are based on regional and product configuration:
- EU Certificate of Conformance (CE)
- Single or dual wall integral fuel tanks
- Narrow, Wide or Skid Base
- UL 2200 package

EXHAUST SYSTEM

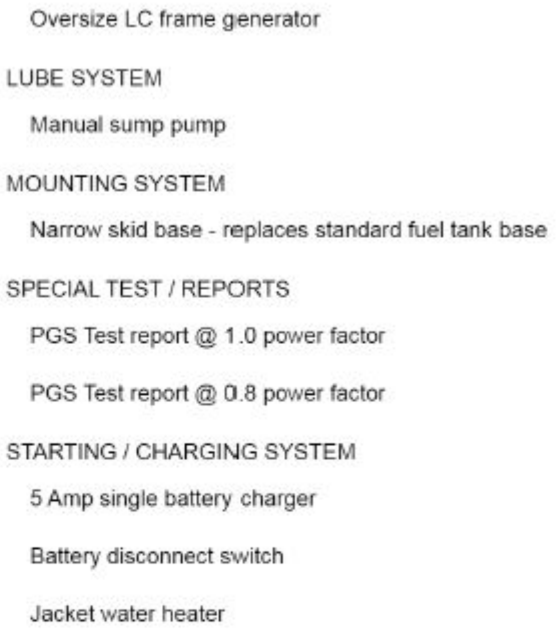
- Engine mounted muffler
- End in / End out mufflers - 10, 25 and 35 dBA attenuation
- 6 and 8 inch elbow kit
- Manifold and turbocharger guard
- Flexible exhaust fittings
- 6 and 8 inch flange GP

FUEL SYSTEM

- Manual fuel transfer pump
- Dual wall fuel tank base
- Fuel transfer system controls

GENERATOR AND ATTACHMENTS

- Space heaters
- Permanent magnet generator
- Ingress protection
- LC frame generator
- Oversize A frame generator
- LC frame CIP generator
- CIP a frame generator



Oversize LC frame generator

LUBE SYSTEM

Manual sump pump

MOUNTING SYSTEM

Narrow skid base - replaces standard fuel tank base

SPECIAL TEST / REPORTS

PGS Test report @ 1.0 power factor

PGS Test report @ 0.8 power factor

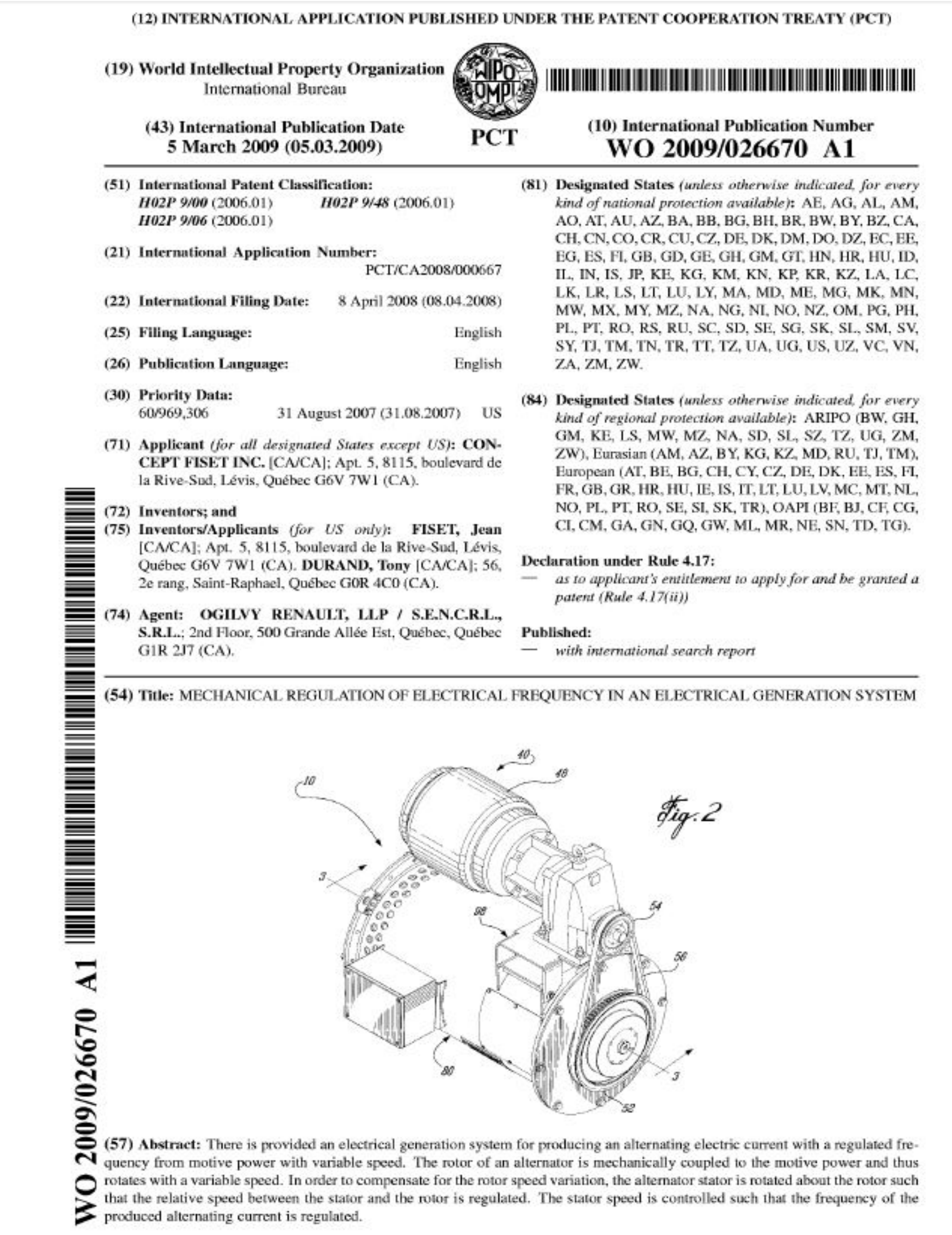
STARTING / CHARGING SYSTEM

5 Amp single battery charger

Battery disconnect switch

Jacket water heater

APPENDIX-IV
ROTATING-STATOR PATENT



(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
5 March 2009 (05.03.2009)

PCT

(10) International Publication Number
WO 2009/026670 A1

(51) International Patent Classification:
H02P 9/00 (2006.01) ***H02P 9/48*** (2006.01)
H02P 9/06 (2006.01)

(21) International Application Number: PCT/CA2008/000667

(22) International Filing Date: 8 April 2008 (08.04.2008)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/969,306 31 August 2007 (31.08.2007) US

(71) Applicant *(for all designated States except US)*: **CONCEPT FISET INC.** [CA/CA]; Apt. 5, 8115, boulevard de la Rive-Sud, Lévis, Québec G6V 7W1 (CA).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: **FISET, Jean** [CA/CA]; Apt. 5, 8115, boulevard de la Rive-Sud, Lévis, Québec G6V 7W1 (CA). **DURAND, Tony** [CA/CA]; 56, 2e rang, Saint-Raphael, Québec G0R 4C0 (CA).

(74) Agent: OGILVY RENAULT, LLP / S.E.N.C.R.L., S.R.L.; 2nd Floor, 500 Grande Allée Est, Québec, Québec G1R 2J7 (CA).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MT, NL, NO, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

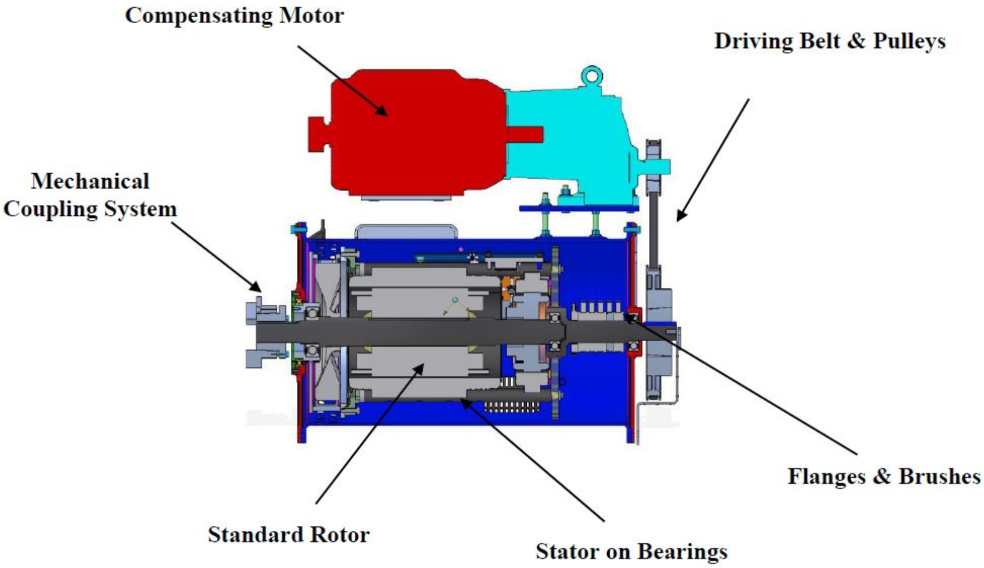
Declaration under Rule 4.17:
— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

Published:
— *with international search report*

(54) Title: MECHANICAL REGULATION OF ELECTRICAL FREQUENCY IN AN ELECTRICAL GENERATION SYSTEM

(57) Abstract: There is provided an electrical generation system for producing an alternating electric current with a regulated frequency from motive power with variable speed. The rotor of an alternator is mechanically coupled to the motive power and thus rotates with a variable speed. In order to compensate for the rotor speed variation, the alternator stator is rotated about the rotor such that the relative speed between the stator and the rotor is regulated. The stator speed is controlled such that the frequency of the produced alternating current is regulated.

WO 2009/026670 A1


Compensating Motor
Driving Belt & Pulleys
Mechanical Coupling System
Flanges & Brushes
Standard Rotor
Stator on Bearings

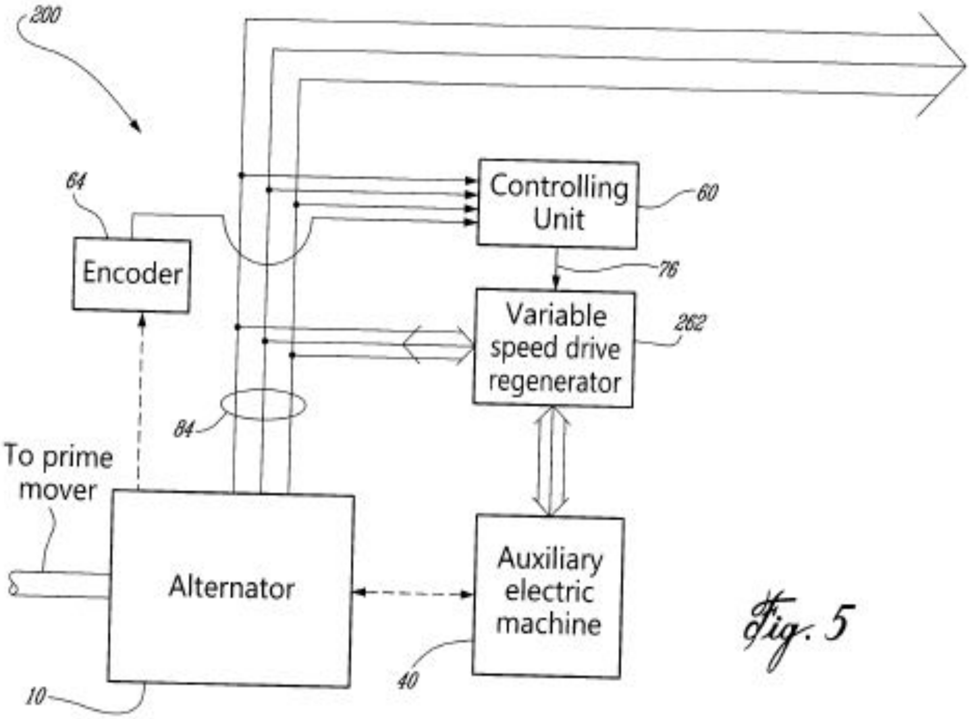
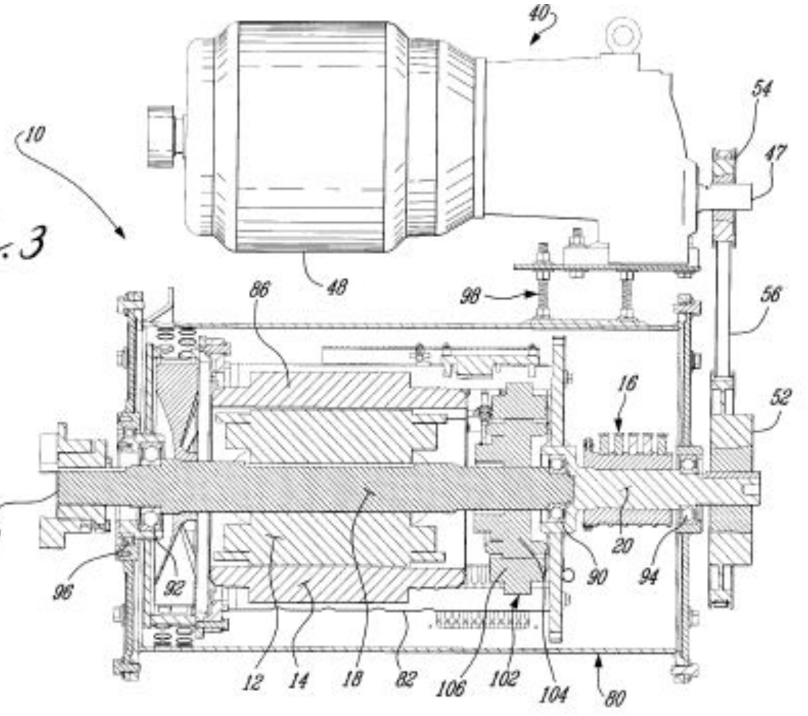

200
64
Encoder
Controlling Unit
60
76
Variable speed drive regenerator
262
84
To prime mover
Alternator
10
Auxiliary electric machine
40

Fig. 5


40
54
47
10
48
98
86
56
16
52
19
20
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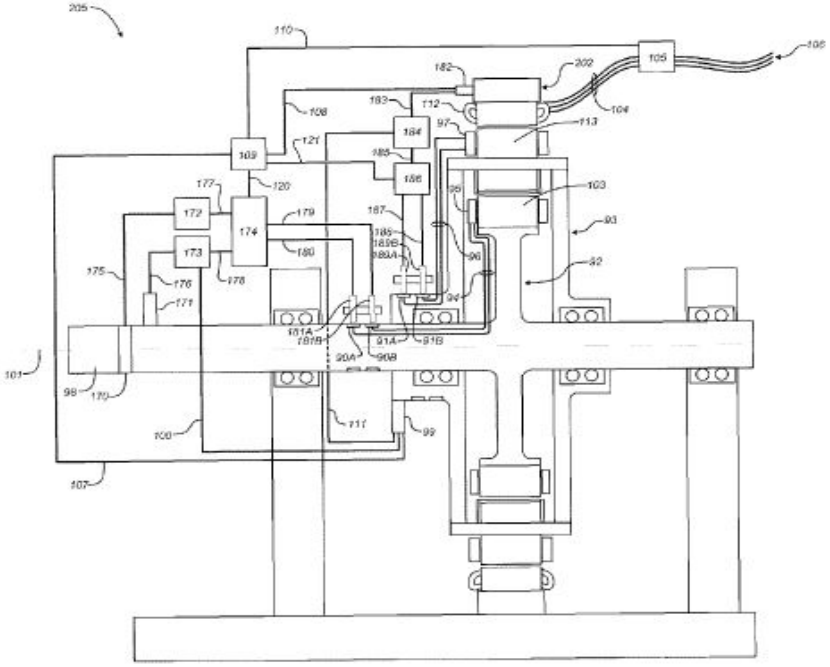
92
90
94
12
14
18
82
106
102
104
80

Fig. 3


205
110
106
105
202
182
183
108
104
112
97
113
184
109
121
185
186
120
177
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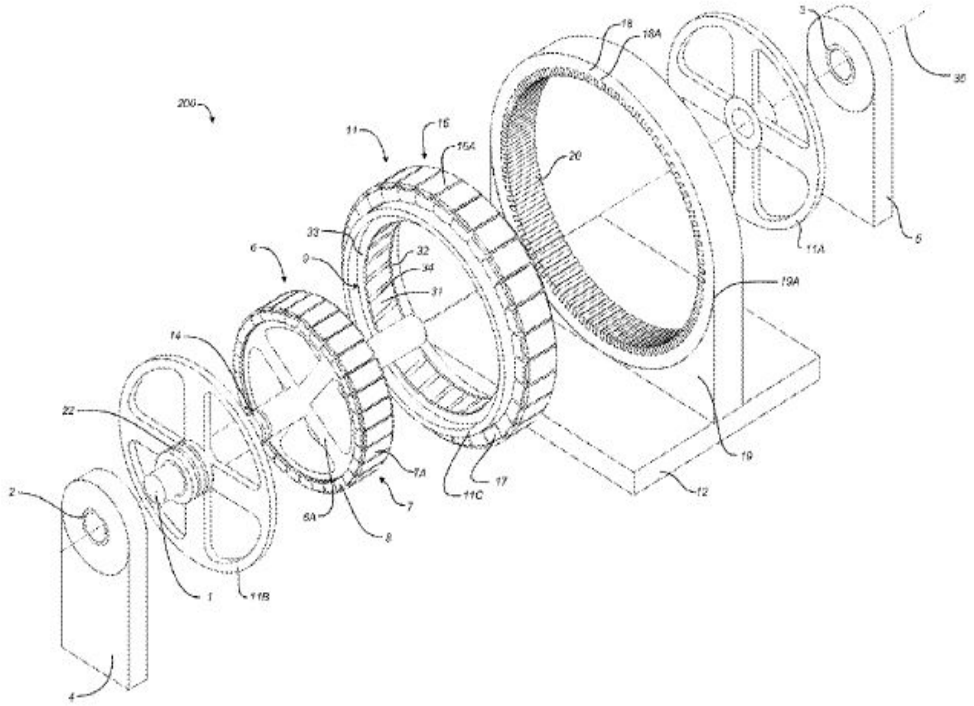
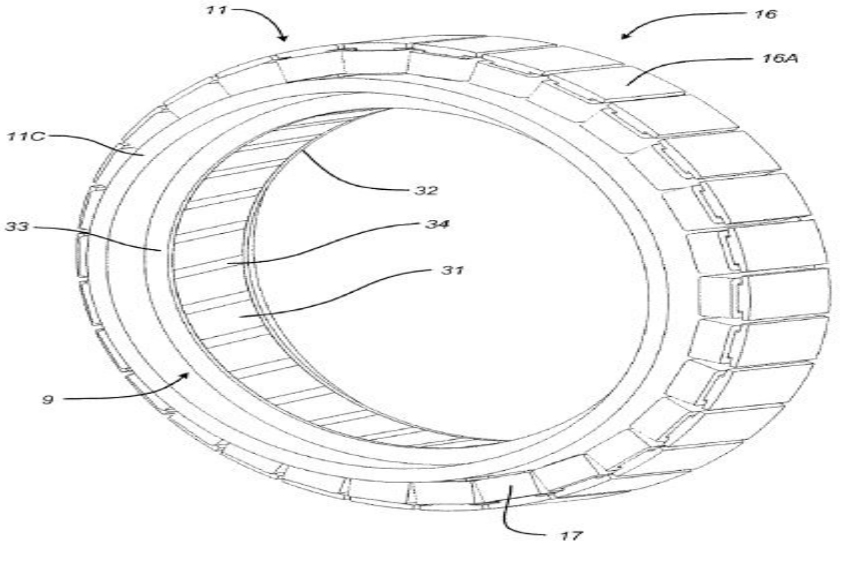
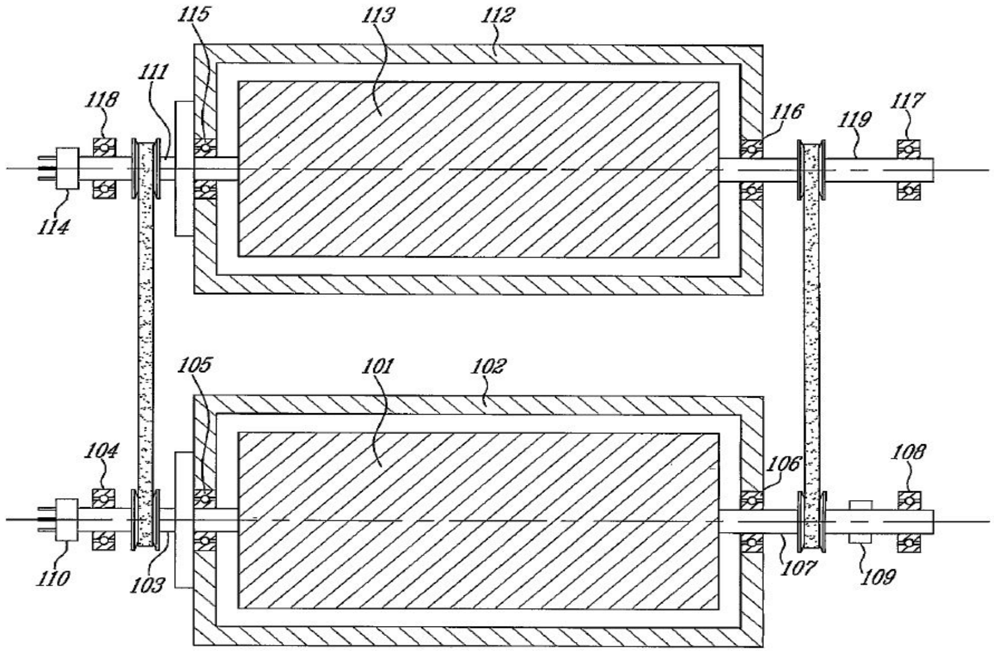
174
179
173
180
176
178
175
171
187
185
189B
189A
95
103
93
92
96
94
181A
181B
91A
91B
90A
90B
101
98
170
100
111
99
107


200
11
16
16A
18
18A
3
35
20
33
6
9
32
34
31
14
22
2
1
11B
6A
8
7A
7
11C
17
12
19
19A
11A
5
4


11
16
16A
11C
32
33
34
31
9
17


115
113
112
111
118
116
119
117
114
105
101
102
104
106
108
110
103
107
109

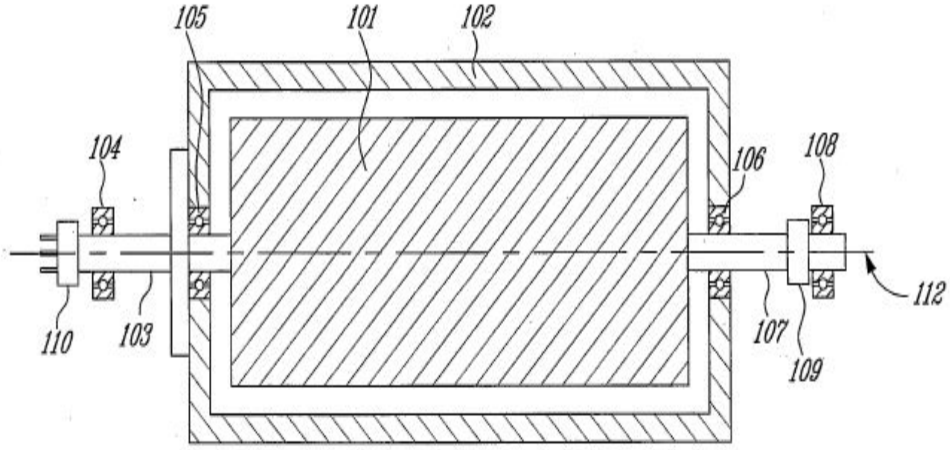
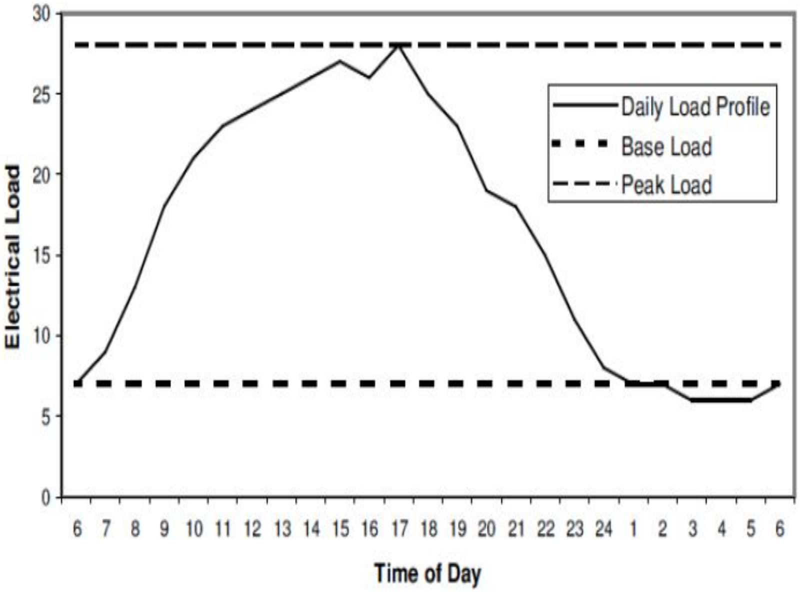
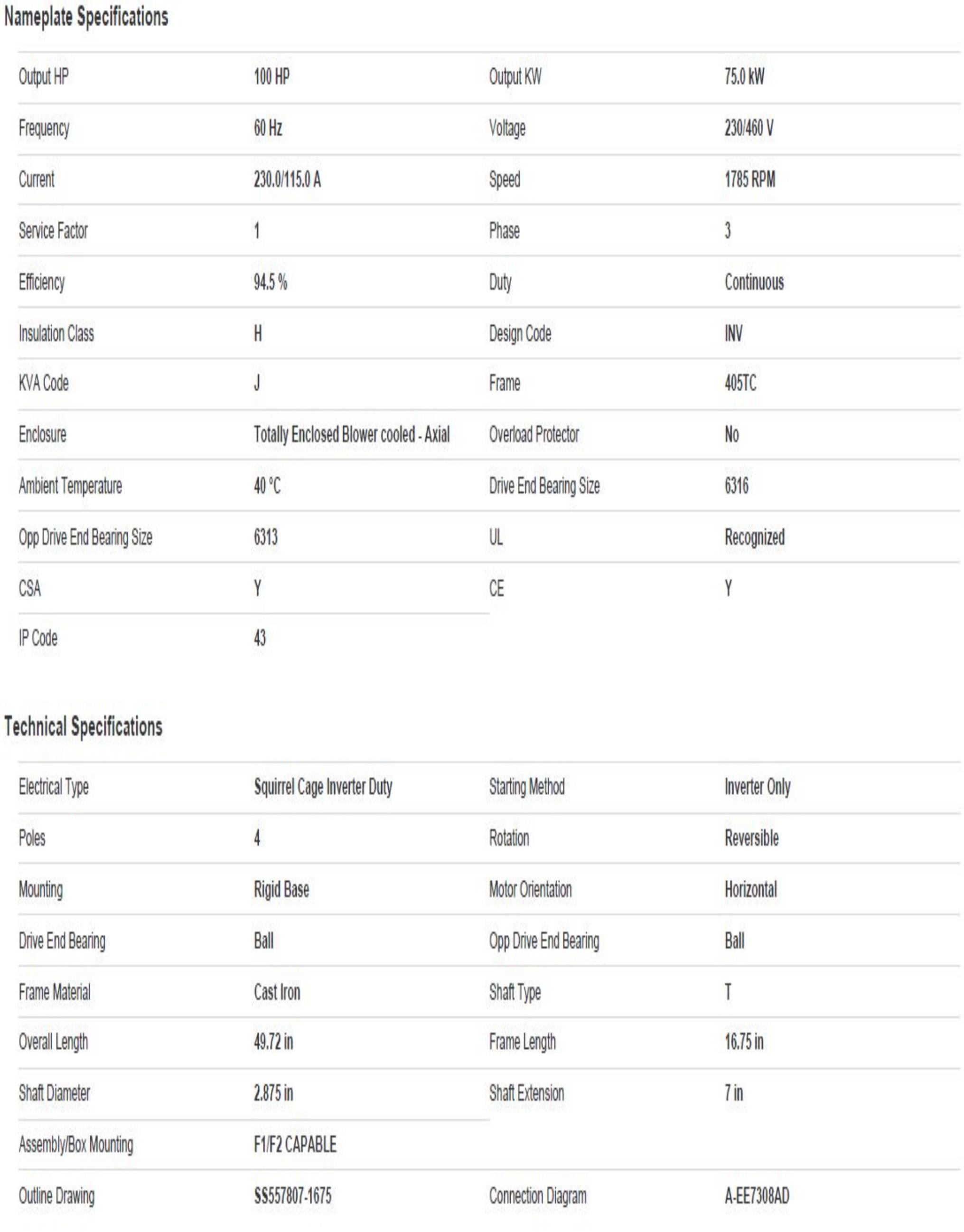

105
101
102
104
106
108
110
103
107
109
112

FIG. 1


30
25
20
15
10
5
0
Electrical Load
6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 1 2 3 4 5 6
Time of Day
Daily Load Profile
Base Load
Peak Load

APPENDIX-V
PMSM 100HP SPECIFICATION

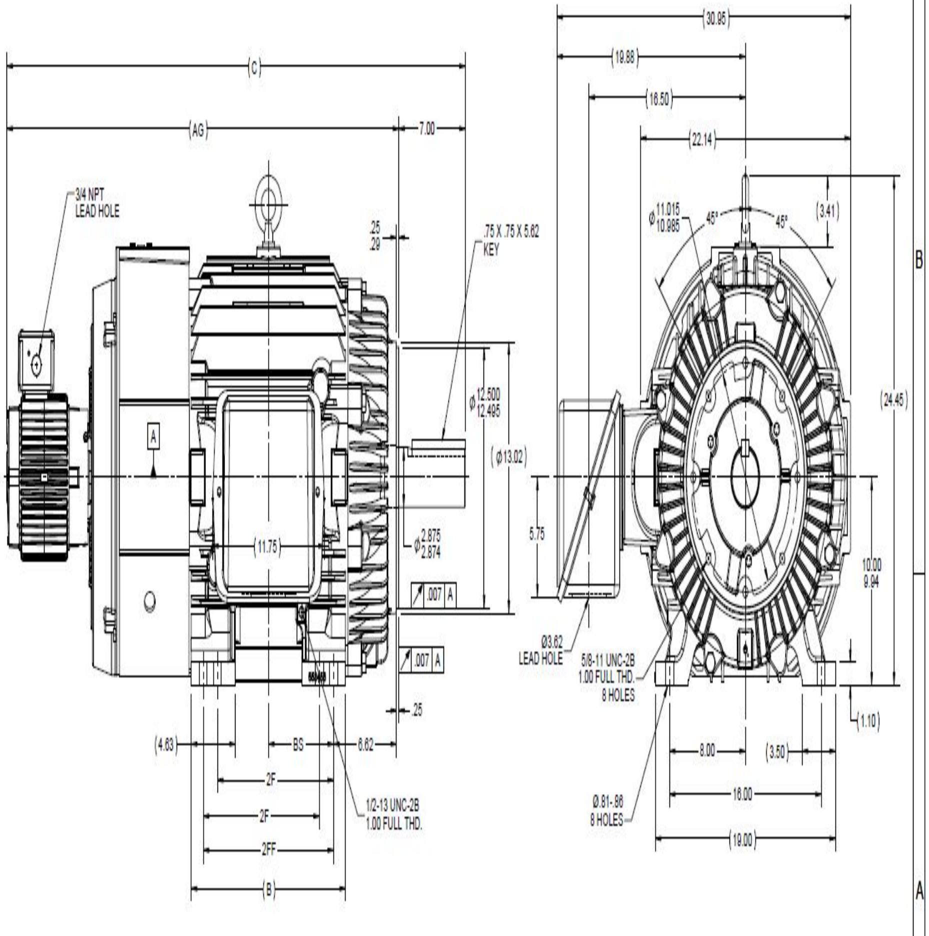


Nameplate Specifications

Output HP	100 HP	Output KW	75.0 kW
Frequency	60 Hz	Voltage	230/460 V
Current	230.0/115.0 A	Speed	1785 RPM
Service Factor	1	Phase	3
Efficiency	94.5 %	Duty	Continuous
Insulation Class	H	Design Code	INV
KVA Code	J	Frame	405TC
Enclosure	Totally Enclosed Blower cooled - Axial	Overload Protector	No
Ambient Temperature	40 °C	Drive End Bearing Size	6316
Opp Drive End Bearing Size	6313	UL	Recognized
CSA	Y	CE	Y
IP Code	43		

Technical Specifications

Electrical Type	Squirrel Cage Inverter Duty	Starting Method	Inverter Only
Poles	4	Rotation	Reversible
Mounting	Rigid Base	Motor Orientation	Horizontal
Drive End Bearing	Ball	Opp Drive End Bearing	Ball
Frame Material	Cast Iron	Shaft Type	T
Overall Length	49.72 in	Frame Length	16.75 in
Shaft Diameter	2.875 in	Shaft Extension	7 in
Assembly/Box Mounting	F1/F2 CAPABLE		
Outline Drawing	SS557807-1675	Connection Diagram	A-EE7308AD



NOTES:

1. CONDUIT BOX CAN BE ROTATED IN 90° STEPS.
2. CONDUIT BOX CAN BE MOUNTED ON OPPOSITE SIDE BY REMOVING BRACKETS AND TURNING FRAME 180°.
3. NAMEPLATES TO BE READ FROM CONDUIT BOX SIDE OF MOTOR.

DASH	FRAME	B	C	AG	2F	2FF	BS
1675	405TC	16.25	48.46	41.47	12.25	13.75	6.88

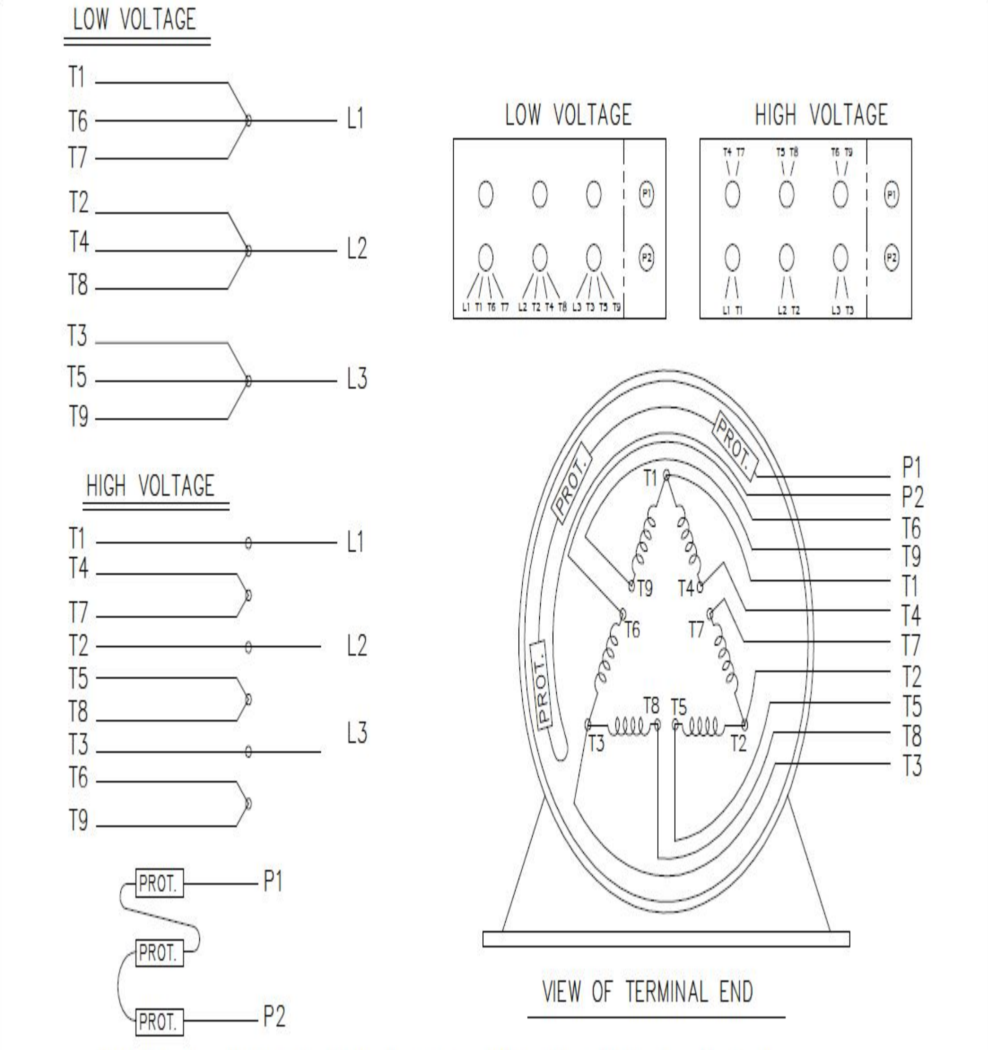
DRAWING REVISION A	REVISION BY W. JOERGER	DATE 02-27-2019
ECO ECO-0162532	APPROVED BY C. OHRMUNDT	DATE 02-27-2019
ECO DESCRIPTION RELEASED FOR PRODUCTION		

TOLERANCES UNLESS OTHERWISE SPECIFIED:

DEC.	INCH	mm	ANGLE
.X	±0.1	[±2.5]	±7' 30"
.XX	±0.03	[±0.76]	
.XXX	±0.005	[±0.127]	
.XXXX	±0.0005	[±0.0127]	

REMOVE BURRS & BREAK SHARP EDGES: .003/.015 [.076/.381] X 45°
CORNER FILLETS: R.02 [.51]
MACHINED SURFACES: 200/ INCH √ 5.1/ mm √
mm SHOWN IN [BRACKETS]

DRAWN BY W. JOERGER	Regal Beloit America, Inc.
DATE 02-27-2019	
APPROVED BY C. OHRMUNDT	DESCRIPTION OUTLINE 405TC FR - TEBC - C'FACE - AXIAL BLOWER
DATE 02-27-2019	
REFERENCE	MATERIAL / PROCESS/FINISH
THIRD ANGLE PROJECTION	SIZE B / DRAWING NUMBER SS557807 / SHEET 1 OF 1



WHEN MORE THAN ONE PROT. IS USED; PROT. ARE CONNECTED IN SERIES

DRAWING REVISION L
REVISION BY JP
REV DATE/© DATE 06-21-2019
ECO ECO-0168744
APPROVED BY MH
DATE 06-21-2019
ECO DESCRIPTION UPDATED TO CURRENT STANDARDS

TOLERANCES (EXCEPT AS NOTED):

DEC.	INCH	mm	ANGLE
.X	±0.1	[±3]	±7' 30"
.XX	±0.02	[±0.5]	
.XXX	±0.005	[±0.13]	
.XXXX	±0.0005	[±0.013]	

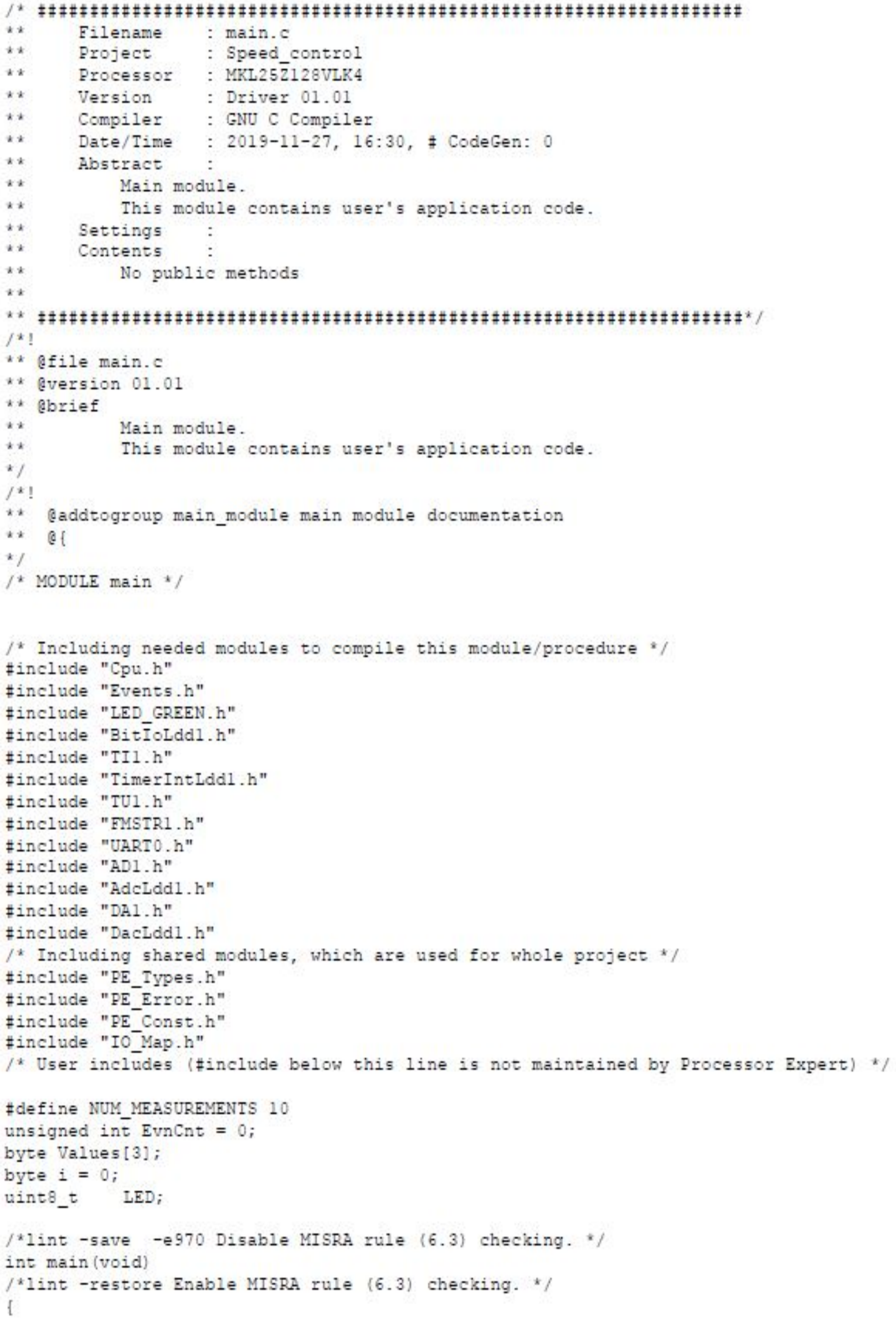
REMOVE BURRS & BREAK SHARP EDGES: .003/.015 [.08/.38] X 45 °
CORNER FILLETS: R.02 [.5]
MACHINED SURFACES: 200/ INCH √ 5.1/ mm √
mm DIMENSIONS IN [BRACKETS] ARE FOR REFERENCE ONLY

DRAWN BY MJD
DATE 12-19-1997
APPROVED BY GK
DATE 01-07-1998
REFERENCE
THIRD ANGLE PROJECTION

REGAL® Regal Beloit America, Inc.

DESCRIPTION CONN DIAGRAM-EXTERNAL
MATERIAL
PROCESS/FINISH
SIZE A
DRAWING NUMBER EE7308AD
SHEET 1 OF 1

APPENDIX-VI
SPEED CONTROL CODE



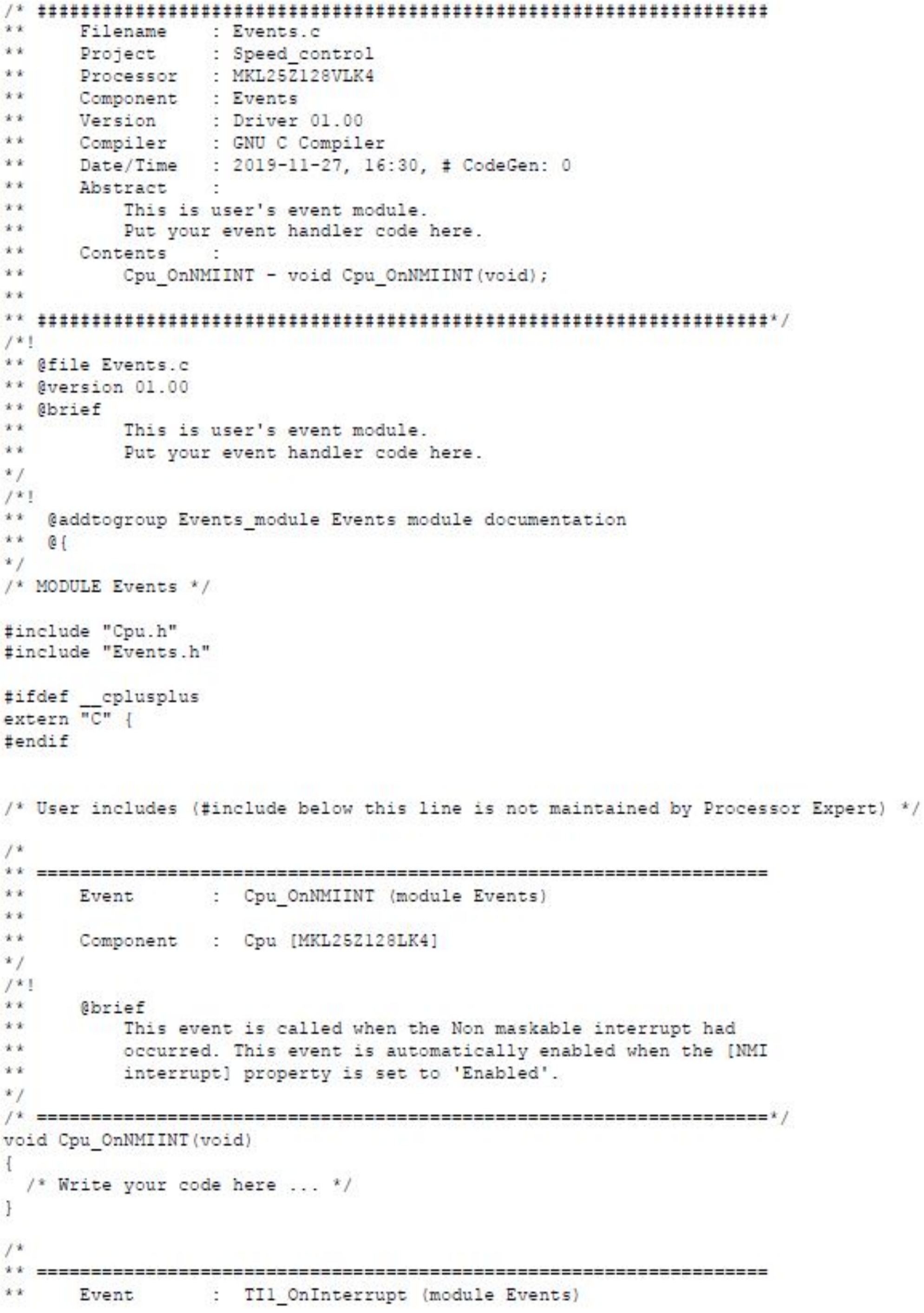
```
/* ###################################################################
**     Filename    : main.c
**     Project     : Speed_control
**     Processor   : MKL25Z128VLK4
**     Version     : Driver 01.01
**     Compiler    : GNU C Compiler
**     Date/Time   : 2019-11-27, 16:30, # CodeGen: 0
**     Abstract    :
**         Main module.
**         This module contains user's application code.
**     Settings    :
**     Contents    :
**         No public methods
**
** ###################################################################*/
/*!
** @file main.c
** @version 01.01
** @brief
**         Main module.
**         This module contains user's application code.
*/
/*!
**  @addtogroup main_module main module documentation
**  @{
*/
/* MODULE main */


/* Including needed modules to compile this module/procedure */
#include "Cpu.h"
#include "Events.h"
#include "LED_GREEN.h"
#include "BitIoLdd1.h"
#include "TI1.h"
#include "TimerIntLdd1.h"
#include "TU1.h"
#include "FMSTR1.h"
#include "UART0.h"
#include "AD1.h"
#include "AdcLdd1.h"
#include "DA1.h"
#include "DacLdd1.h"
/* Including shared modules, which are used for whole project */
#include "PE_Types.h"
#include "PE_Error.h"
#include "PE_Const.h"
#include "IO_Map.h"
/* User includes (#include below this line is not maintained by Processor Expert) */

#define NUM_MEASUREMENTS 10
unsigned int EvnCnt = 0;
byte Values[3];
byte i = 0;
uint8_t    LED;

/*lint -save  -e970 Disable MISRA rule (6.3) checking. */
int main(void)
/*lint -restore Enable MISRA rule (6.3) checking. */
{
```

```
  /* Write your local variable definition here */

  /*** Processor Expert internal initialization. DON'T REMOVE THIS CODE!!! ***/
  PE_low_level_init();
  /*** End of Processor Expert internal initialization.                    ***/
  AD1_Start();        // Run measurements
  DA1_Enable();                 /* Enable DAC component */

  //measured data are processed in the events this cycle waits for end

  /* Write your code here */
  /* For example: for(;;) { } */
  for(;;)
  {
        LED = LED_GREEN_GetVal();
        FMSTR1_Poll();
        if (EvnCnt == NUM_MEASUREMENTS) {
              //after 10 cycles the conversion is stopped
              AD1_Stop();
              EvnCnt = 0;
              AD1_Start();
        }
      //if (i==255) {               /* Set new value of the counter */
      //  i=0;
      //} else {
      //  i++;
      //}
        DA1_SetValue(&i);
  }
  /*** Don't write any code pass this line, or it will be deleted during code
generation. ***/
  /*** RTOS startup code. Macro PEX_RTOS_START is defined by the RTOS component.
DON'T MODIFY THIS CODE!!! ***/
  #ifdef PEX_RTOS_START
    PEX_RTOS_START();                  /* Startup of the selected RTOS. Macro is
defined by the RTOS component. */
  #endif
  /*** End of RTOS startup code.  ***/
  /*** Processor Expert end of main routine. DON'T MODIFY THIS CODE!!! ***/
  for(;;){}
  /*** Processor Expert end of main routine. DON'T WRITE CODE BELOW!!! ***/
} /*** End of main routine. DO NOT MODIFY THIS TEXT!!! ***/

/* END main */
/*!
** @}
*/
/*
** ###################################################################
**
**     This file was created by Processor Expert 10.5 [05.21]
**     for the Freescale Kinetis series of microcontrollers.
**
** ###################################################################
*/
```

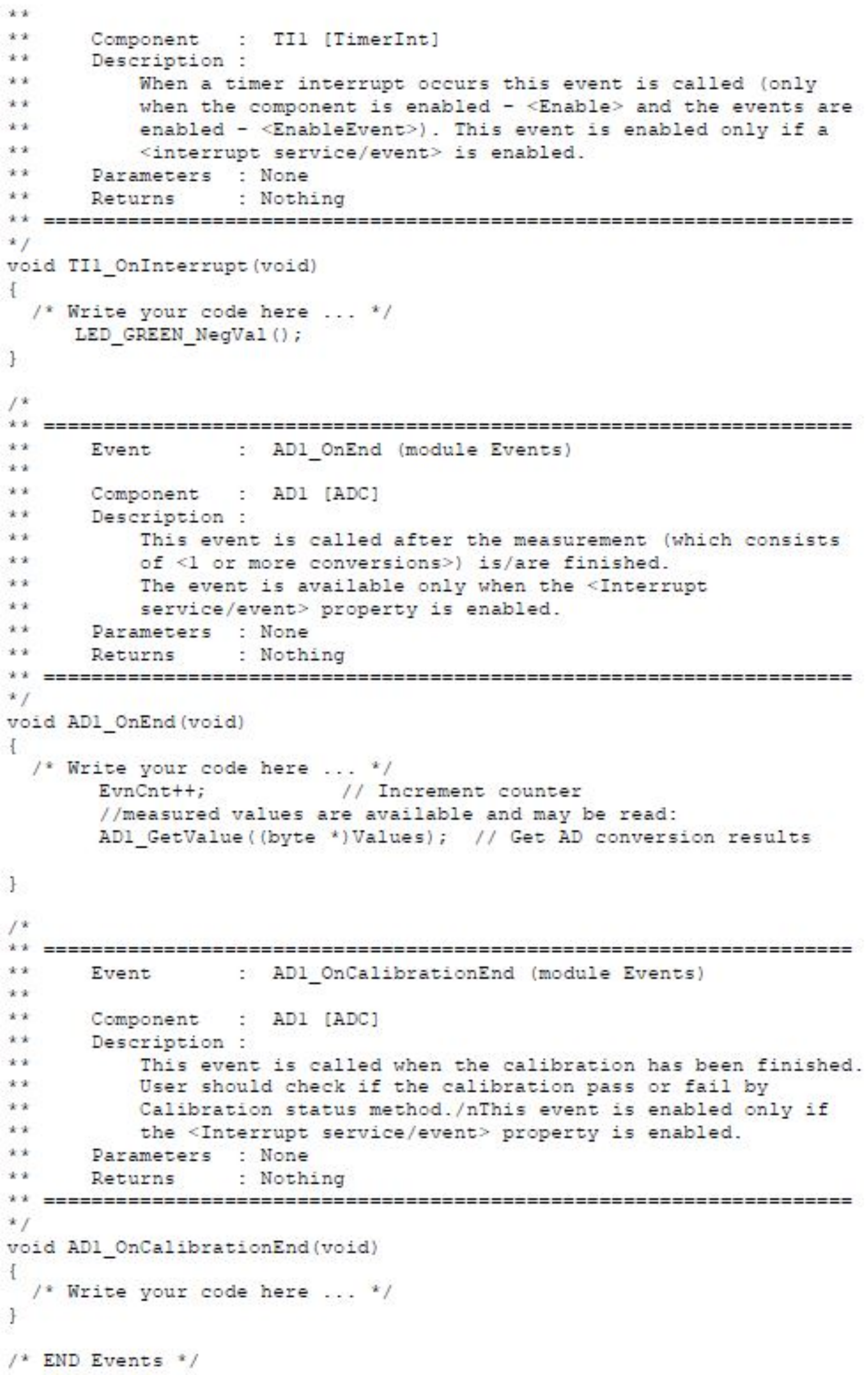
```
/* ###################################################################
**     Filename    : Events.h
**     Project     : Speed_control
**     Processor   : MKL25Z128VLK4
**     Component   : Events
**     Version     : Driver 01.00
**     Compiler    : GNU C Compiler
**     Date/Time   : 2019-11-27, 16:30, # CodeGen: 0
**     Abstract    :
**         This is user's event module.
**         Put your event handler code here.
**     Contents    :
**         Cpu_OnNMIINT - void Cpu_OnNMIINT(void);
**
** ###################################################################*/
/*!
** @file Events.h
** @version 01.00
** @brief
**         This is user's event module.
**         Put your event handler code here.
*/
/*!
**  @addtogroup Events_module Events module documentation
**  @{
*/

#ifndef __Events_H
#define __Events_H
/* MODULE Events */

#include "PE_Types.h"
#include "PE_Error.h"
#include "PE_Const.h"
#include "IO_Map.h"
#include "LED_GREEN.h"
#include "BitIoLdd1.h"
#include "TI1.h"
#include "TimerIntLdd1.h"
#include "TU1.h"
#include "FMSTR1.h"
#include "UART0.h"
#include "AD1.h"
#include "AdcLdd1.h"
#include "DA1.h"
#include "DacLdd1.h"

#ifdef __cplusplus
extern "C" {
#endif

extern unsigned int EvnCnt;
extern byte Values[3];


/*
** ===================================================================
**     Event       :  Cpu_OnNMIINT (module Events)
**
```

```
**     Component   :  Cpu [MKL25Z128LK4]
*/
/*!
**     @brief
**         This event is called when the Non maskable interrupt had
**         occurred. This event is automatically enabled when the [NMI
**         interrupt] property is set to 'Enabled'.
*/
/* ===================================================================*/
void Cpu_OnNMIINT(void);


/*
** ===================================================================
**     Event       :  TI1_OnInterrupt (module Events)
**
**     Component   :  TI1 [TimerInt]
**     Description :
**         When a timer interrupt occurs this event is called (only
**         when the component is enabled - <Enable> and the events are
**         enabled - <EnableEvent>). This event is enabled only if a
**         <interrupt service/event> is enabled.
**     Parameters  : None
**     Returns     : Nothing
** ===================================================================
*/
void TI1_OnInterrupt(void);

void AD1_OnEnd(void);
/*
** ===================================================================
**     Event       :  AD1_OnEnd (module Events)
**
**     Component   :  AD1 [ADC]
**     Description :
**         This event is called after the measurement (which consists
**         of <1 or more conversions>) is/are finished.
**         The event is available only when the <Interrupt
**         service/event> property is enabled.
**     Parameters  : None
**     Returns     : Nothing
** ===================================================================
*/

void AD1_OnCalibrationEnd(void);
/*
** ===================================================================
**     Event       :  AD1_OnCalibrationEnd (module Events)
**
**     Component   :  AD1 [ADC]
**     Description :
**         This event is called when the calibration has been finished.
**         User should check if the calibration pass or fail by
**         Calibration status method./nThis event is enabled only if
**         the <Interrupt service/event> property is enabled.
**     Parameters  : None
**     Returns     : Nothing
** ===================================================================
*/
```

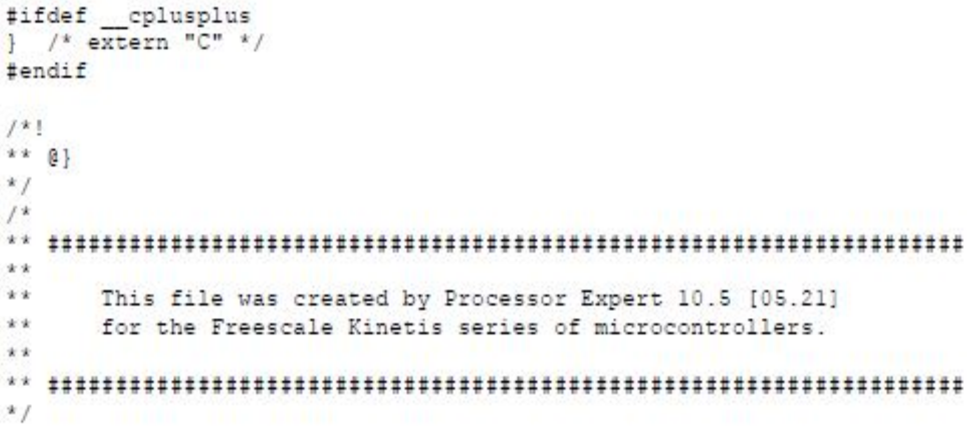
```
/* END Events */

#ifdef __cplusplus
}  /* extern "C" */
#endif

#endif
/* ifndef __Events_H*/
/*!
** @}
*/
/*
** ###################################################################
**
**     This file was created by Processor Expert 10.5 [05.21]
**     for the Freescale Kinetis series of microcontrollers.
**
** ###################################################################
*/
```



```
/* ###################################################################
**     Filename    : Events.c
**     Project     : Speed_control
**     Processor   : MKL25Z128VLK4
**     Component   : Events
**     Version     : Driver 01.00
**     Compiler    : GNU C Compiler
**     Date/Time   : 2019-11-27, 16:30, # CodeGen: 0
**     Abstract    :
**         This is user's event module.
**         Put your event handler code here.
**     Contents    :
**         Cpu_OnNMIINT - void Cpu_OnNMIINT(void);
**
** ###################################################################*/
/*!
** @file Events.c
** @version 01.00
** @brief
**         This is user's event module.
**         Put your event handler code here.
*/
/*!
**  @addtogroup Events_module Events module documentation
**  @{
*/
/* MODULE Events */

#include "Cpu.h"
#include "Events.h"

#ifdef __cplusplus
extern "C" {
#endif


/* User includes (#include below this line is not maintained by Processor Expert) */

/*
** ===================================================================
**     Event       :  Cpu_OnNMIINT (module Events)
**
**     Component   :  Cpu [MKL25Z128LK4]
*/
/*!
**     @brief
**         This event is called when the Non maskable interrupt had
**         occurred. This event is automatically enabled when the [NMI
**         interrupt] property is set to 'Enabled'.
*/
/* ===================================================================*/
void Cpu_OnNMIINT(void)
{
  /* Write your code here ... */
}

/*
** ===================================================================
**     Event       :  TI1_OnInterrupt (module Events)
```



```
**
**     Component   :  TI1 [TimerInt]
**     Description :
**         When a timer interrupt occurs this event is called (only
**         when the component is enabled - <Enable> and the events are
**         enabled - <EnableEvent>). This event is enabled only if a
**         <interrupt service/event> is enabled.
**     Parameters  : None
**     Returns     : Nothing
** ===================================================================
*/
void TI1_OnInterrupt(void)
{
  /* Write your code here ... */
     LED_GREEN_NegVal();
}

/*
** ===================================================================
**     Event       :  AD1_OnEnd (module Events)
**
**     Component   :  AD1 [ADC]
**     Description :
**         This event is called after the measurement (which consists
**         of <1 or more conversions>) is/are finished.
**         The event is available only when the <Interrupt
**         service/event> property is enabled.
**     Parameters  : None
**     Returns     : Nothing
** ===================================================================
*/
void AD1_OnEnd(void)
{
  /* Write your code here ... */
       EvnCnt++;          // Increment counter
       //measured values are available and may be read:
       AD1_GetValue((byte *)Values);  // Get AD conversion results

}

/*
** ===================================================================
**     Event       :  AD1_OnCalibrationEnd (module Events)
**
**     Component   :  AD1 [ADC]
**     Description :
**         This event is called when the calibration has been finished.
**         User should check if the calibration pass or fail by
**         Calibration status method./nThis event is enabled only if
**         the <Interrupt service/event> property is enabled.
**     Parameters  : None
**     Returns     : Nothing
** ===================================================================
*/
void AD1_OnCalibrationEnd(void)
{
  /* Write your code here ... */
}

/* END Events */
```



```
#ifdef __cplusplus
}  /* extern "C" */
#endif

/*!
** @}
*/
/*
** ###################################################################
**
**     This file was created by Processor Expert 10.5 [05.21]
**     for the Freescale Kinetis series of microcontrollers.
**
** ###################################################################
*/
```

APPENDIX-VII
FLUKE 43B

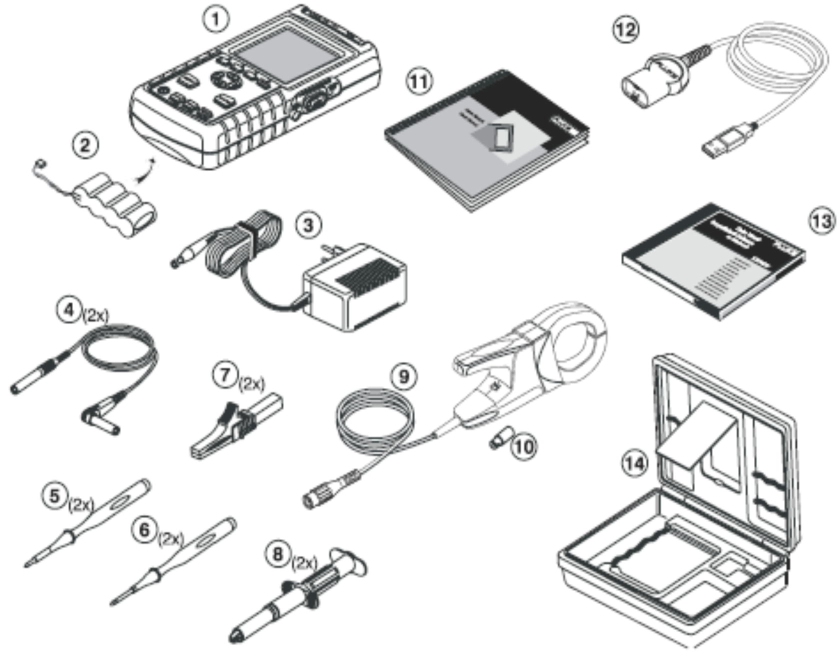
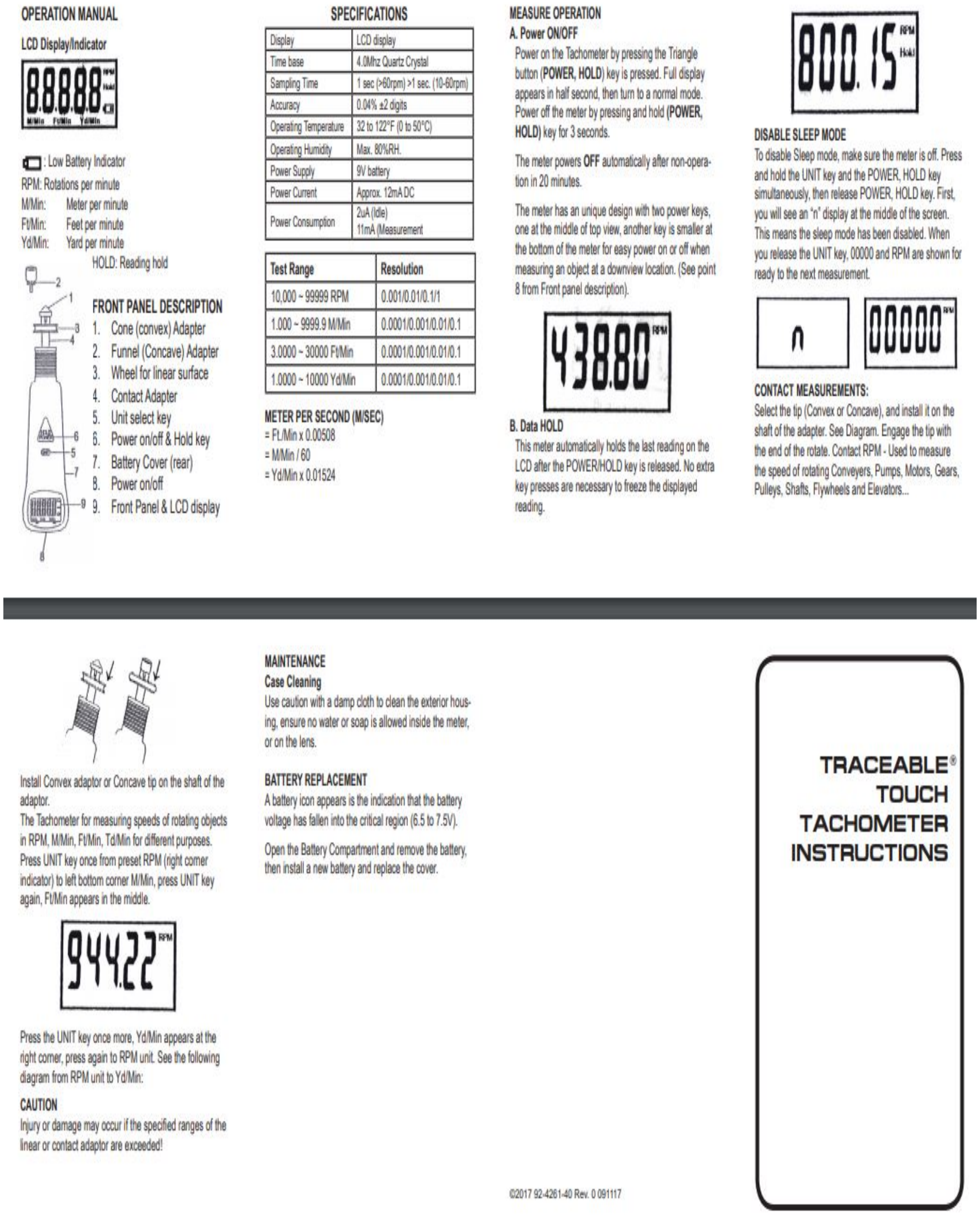


Figure 1. Carrying Case Contents

1	Fluke 43B	Power Quality Analyzer
2	BP120MH	Ni-MH Battery Pack (installed)
3	PM8907/8xx	Power Adapter/Battery Charger
4	TL24	Test Leads, red and black
5	TP1	Flat blade Test Pins, red and black
6	TP4	4mm Test Pins, red and black
7	AC85A	Large Jaw Alligator Clips for Banana Plugs, red and black
8	AC20	Industrial Alligator Clips for Banana Plugs, red and black
9	i400s	Clamp-on AC Current Probe
10	BB120	Shielded Banana-to-BNC Adapter Plugs (1x black)
11		Getting Started Manual incl. User / Application Manual CD
12	OC4USB	Optically Isolated USB Adapter/Cable
13	SW43W	FlukeView® Power Quality Analyzer software
14	C120	Hard Carrying Case

APPENDIX-VIII
TACHOMETER



OPERATION MANUAL

LCD Display/Indicator

▭ : Low Battery Indicator
RPM: Rotations per minute

M/Min:	Meter per minute
Ft/Min:	Feet per minute
Yd/Min:	Yard per minute

HOLD: Reading hold

FRONT PANEL DESCRIPTION

1. Cone (convex) Adapter
2. Funnel (Concave) Adapter
3. Wheel for linear surface
4. Contact Adapter
5. Unit select key
6. Power on/off & Hold key
7. Battery Cover (rear)
8. Power on/off
9. Front Panel & LCD display

SPECIFICATIONS

Display	LCD display
Time base	4.0Mhz Quartz Crystal
Sampling Time	1 sec (>60rpm) >1 sec. (10-60rpm)
Accuracy	0.04% ±2 digits
Operating Temperature	32 to 122°F (0 to 50°C)
Operating Humidity	Max. 80%RH.
Power Supply	9V battery
Power Current	Approx. 12mA DC
Power Consumption	2uA (Idle) 11mA (Measurement

Test Range	Resolution
10,000 ~ 99999 RPM	0.001/0.01/0.1/1
1.000 ~ 9999.9 M/Min	0.0001/0.001/0.01/0.1
3.0000 ~ 30000 Ft/Min	0.0001/0.001/0.01/0.1
1.0000 ~ 10000 Yd/Min	0.0001/0.001/0.01/0.1

METER PER SECOND (M/SEC)

= Ft./Min x 0.00508
= M/Min / 60
= Yd/Min x 0.01524

MEASURE OPERATION

A. Power ON/OFF

Power on the Tachometer by pressing the Triangle button (**POWER, HOLD**) key is pressed. Full display appears in half second, then turn to a normal mode. Power off the meter by pressing and hold **(POWER, HOLD)** key for 3 seconds.

The meter powers **OFF** automatically after non-operation in 20 minutes.

The meter has an unique design with two power keys, one at the middle of top view, another key is smaller at the bottom of the meter for easy power on or off when measuring an object at a downview location. (See point 8 from Front panel description).

B. Data HOLD

This meter automatically holds the last reading on the LCD after the POWER/HOLD key is released. No extra key presses are necessary to freeze the displayed reading.

DISABLE SLEEP MODE

To disable Sleep mode, make sure the meter is off. Press and hold the UNIT key and the POWER, HOLD key simultaneously, then release POWER, HOLD key. First, you will see an "n" display at the middle of the screen. This means the sleep mode has been disabled. When you release the UNIT key, 00000 and RPM are shown for ready to the next measurement.

CONTACT MEASUREMENTS:

Select the tip (Convex or Concave), and install it on the shaft of the adapter. See Diagram. Engage the tip with the end of the rotate. Contact RPM - Used to measure the speed of rotating Conveyers, Pumps, Motors, Gears, Pulleys, Shafts, Flywheels and Elevators...

Install Convex adaptor or Concave tip on the shaft of the adaptor.
The Tachometer for measuring speeds of rotating objects in RPM, M/Min, Ft/Min, Td/Min for different purposes. Press UNIT key once from preset RPM (right corner indicator) to left bottom corner M/Min, press UNIT key again, Ft/Min appears in the middle.

Press the UNIT key once more, Yd/Min appears at the right corner, press again to RPM unit. See the following diagram from RPM unit to Yd/Min:

CAUTION

Injury or damage may occur if the specified ranges of the linear or contact adaptor are exceeded!

MAINTENANCE

Case Cleaning

Use caution with a damp cloth to clean the exterior housing, ensure no water or soap is allowed inside the meter, or on the lens.

BATTERY REPLACEMENT

A battery icon appears is the indication that the battery voltage has fallen into the critical region (6.5 to 7.5V).

Open the Battery Compartment and remove the battery, then install a new battery and replace the cover.

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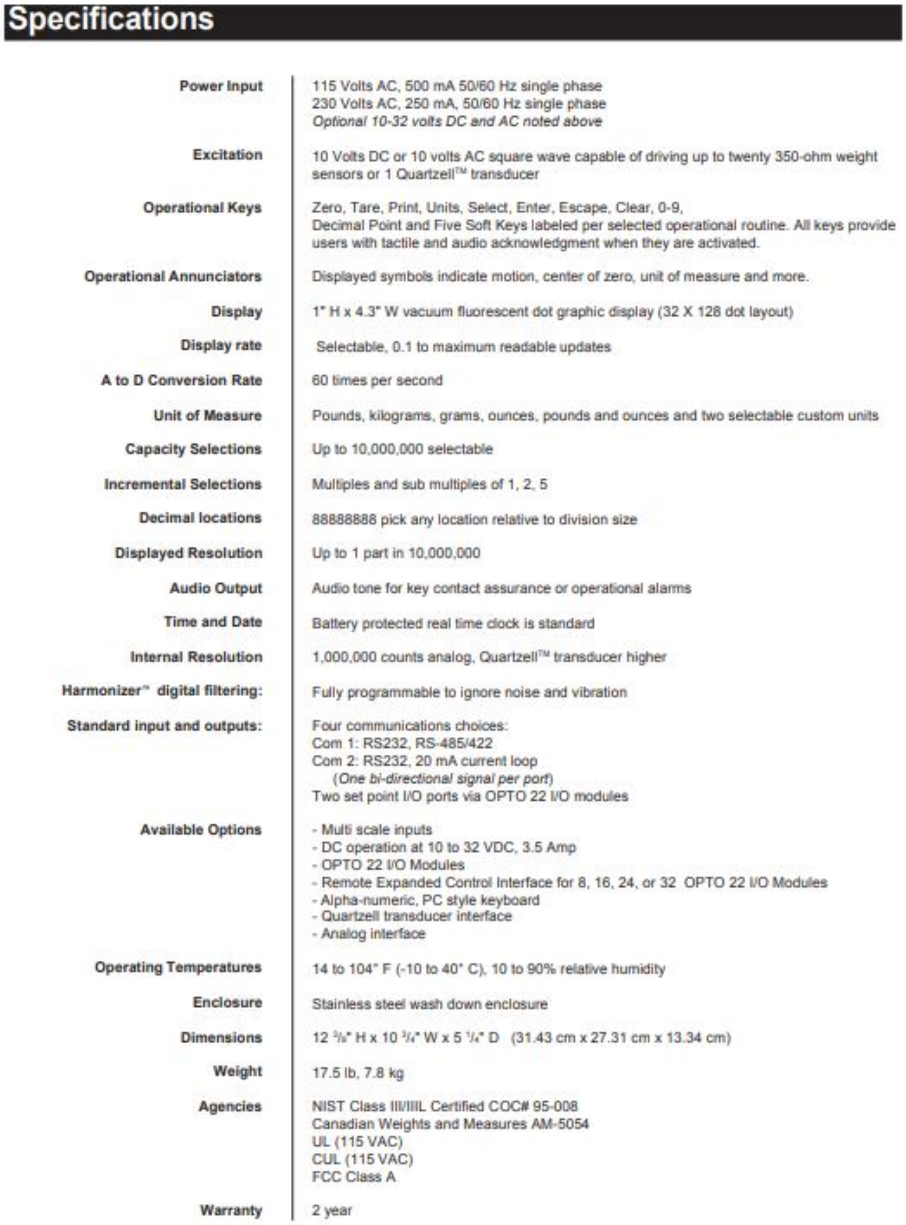
TRACEABLE®
TOUCH
TACHOMETER
INSTRUCTIONS

APPENDIX-IX
WEIGH-TRONIX



Specifications

Power Input	115 Volts AC, 500 mA 50/60 Hz single phase 230 Volts AC, 250 mA, 50/60 Hz single phase *Optional 10-32 volts DC and AC noted above*
Excitation	10 Volts DC or 10 volts AC square wave capable of driving up to twenty 350-ohm weight sensors or 1 Quartzell™ transducer
Operational Keys	Zero, Tare, Print, Units, Select, Enter, Escape, Clear, 0-9, Decimal Point and Five Soft Keys labeled per selected operational routine. All keys provide users with tactile and audio acknowledgment when they are activated.
Operational Annunciators	Displayed symbols indicate motion, center of zero, unit of measure and more.
Display	1" H x 4.3" W vacuum fluorescent dot graphic display (32 X 128 dot layout)
Display rate	Selectable, 0.1 to maximum readable updates
A to D Conversion Rate	60 times per second
Unit of Measure	Pounds, kilograms, grams, ounces, pounds and ounces and two selectable custom units
Capacity Selections	Up to 10,000,000 selectable
Incremental Selections	Multiples and sub multiples of 1, 2, 5
Decimal locations	88888888 pick any location relative to division size
Displayed Resolution	Up to 1 part in 10,000,000
Audio Output	Audio tone for key contact assurance or operational alarms
Time and Date	Battery protected real time clock is standard
Internal Resolution	1,000,000 counts analog, Quartzell™ transducer higher
Harmonizer™ digital filtering:	Fully programmable to ignore noise and vibration
Standard input and outputs:	Four communications choices: Com 1: RS232, RS-485/422 Com 2: RS232, 20 mA current loop (*One bi-directional signal per port*) Two set point I/O ports via OPTO 22 I/O modules
Available Options	- Multi scale inputs - DC operation at 10 to 32 VDC, 3.5 Amp - OPTO 22 I/O Modules - Remote Expanded Control Interface for 8, 16, 24, or 32 OPTO 22 I/O Modules - Alpha-numeric, PC style keyboard - Quartzell transducer interface - Analog interface
Operating Temperatures	14 to 104° F (-10 to 40° C), 10 to 90% relative humidity
Enclosure	Stainless steel wash down enclosure
Dimensions	12 3/8" H x 10 3/4" W x 5 1/4" D (31.43 cm x 27.31 cm x 13.34 cm)
Weight	17.5 lb, 7.8 kg
Agencies	NIST Class III/IIIL Certified COC# 95-008 Canadian Weights and Measures AM-5054 UL (115 VAC) CUL (115 VAC) FCC Class A
Warranty	2 year

WI-130 WDAC

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