

**STABILITY AND CONTROL FOR GRID
CONNECTED RENEWABLE POWER
SYSTEMS**

BY

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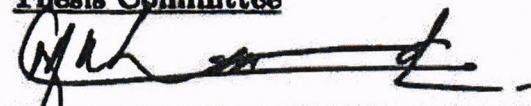
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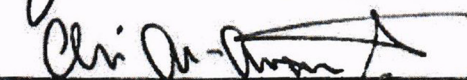
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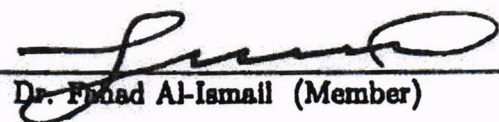
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To my family, friends and colleagues, thank you for supporting me.

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LIST OF ABBREVIATIONS

AC	Alternating Current
BESS	Battery Energy Storage System
DC	Direct Current
ESS	Energy Storage System
EV	Electrical vehicle
FRT	Fault Ride Through
GFL	Grid-Following
GFM	Grid-Forming
ITAE	Integral Time Absolute Error
LFC	Load Frequency Control
PI	Proportional Integral
PLL	Phase-Locked Loop
PSO	Particle Swarm Optimization

PV	Photovoltaic
RES	Renewable Energy Resources
ROCOF	Rate of Change of Frequency
SMES	Superconducting Magnetic Energy Storage
VSG	Virtual Synchronous Generator

THESIS ABSTRACT

NAME: Alhassan Alsharif

TITLE OF STUDY: Stability and Control for Grid Connected Renewable Power Systems

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The need to find innovative methods to utilize the renewable energy for continuous and fluctuation-less operation is highly targeted. Renewable Energy Sources (RES) are known to be an effective alternative to limit the impact of the climate change as well as reduce the undesired fossil fuel consumption. Though there are various obstacles facing the deployment of RES in modern power grids due to intermittency, lack of inertia and the dependency on energy storage applications. In this thesis, a unique combination of renewable energy energy sources are explored including Fuel Cell, PV arrays and Superconducting Magnetic Energy Storage (SMES). They are simulated in grid connected manner that undergoes sudden load changes from the grid side as well as fuel cell fault. Most importantly, Virtual Synchronous Generator (VSG) are modeled for each of the sources associated with adequate inertia constants as well as PI

controller parameters optimized by PSO algorithm to prompt robustness in response, frequency and voltage regulation leading to a stable grid. Four cases are simulated in this research including comparing regular VSG with proposed VSG, load increase and how the regular VSG and proposed VSG respond, and grid fault to ensure the stability and frequency regulation of proposed system. From the simulation in case one, the proposed VSG outperformed regular VGS in terms of power sharing capabilities and frequency regulation. Case two and three show the stability the proposed VSG achieved is more robust than the regular VSG. The regular VSG showed a slower response in regulating the frequency when compared to the proposed VSG. Also, the proposed VSG optimized by the PSO demonstrated a robust response in reaching grid stability after a disturbance or fault, where the regular VSG results where inferior.

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إن الحاجة إلى إيجاد طرق مبتكرة لاستخدام الطاقة المتجددة للتشغيل المستمر والخالي من التقلبات مستهدفة بشكل كبير. من المعروف أن مصادر الطاقة المتجددة (RES) هي بديل فعال للحد من تأثير تغير المناخ وكذلك تقليل استهلاك الوقود الأحفوري غير المرغوب فيه. على الرغم من وجود العديد من العقبات التي تواجه نشر مصادر الطاقة المتجددة في شبكات الطاقة الحديثة بسبب التقطع ونقص القصور الذاتي والاعتماد على تطبيقات تخزين الطاقة. في هذه الأطروحة ، يتم استكشاف مزيج فريد من مصادر الطاقة المتجددة بما في ذلك خلايا الوقود والمصفوفات الكهروضوئية وتخزين الطاقة المغناطيسية فائقة التوصيل (SMES). يتم محاكاتها بطريقة متصلة بالشبكة والتي تخضع لتغيرات حمل مفاجئة من جانب الشبكة بالإضافة إلى خلل في خلية الوقود. الأهم من ذلك ، تم تصميم المولد الافتراضي المتزامن (VSG) لكل من المصادر المرتبطة بثوابت القصور الذاتي المناسبة بالإضافة إلى معلمات وحدة التحكم PI المحسنة بواسطة خوارزمية PSO لتحفيز المتانة في الاستجابة وتنظيم التردد والجهد مما يؤدي إلى شبكة مستقرة. تمت محاكاة أربع حالات في هذا البحث بما في ذلك مقارنة VSG العادي مع VSG المقترح ، وزيادة الحمل وكيفية استجابة VSG العادية و VSG المقترحة ، وخطأ الشبكة لضمان الاستقرار وتنظيم التردد للنظام المقترح. من المحاكاة في الحالة الأولى ، تفوق GSV المقترح على VSG العادي من حيث قدرات مشاركة الطاقة وتنظيم التردد. توضح الحالة الثانية والثالثة أن الاستقرار الذي تحققه VSG المقترح هو أكثر قوة من VSG العادي. أظهر VSG العادي استجابة أبطأ في تنظيم التردد بالمقارنة مع VSG المقترح. أيضًا ، أظهر VSG المقترح المحسن بواسطة PSO استجابة قوية في الوصول إلى استقرار الشبكة بعد حدوث اضطراب أو خطأ ، حيث تكون نتائج VSG العادية أقل شأنًا.

CHAPTER 1

INTRODUCTION

1.1 Background

The Renewable Energy Sources (RES) are in the highest demand ever encountered by the world despite their inventions that date back to as early as 19th century [1], [2]. Variety of research institutions are dedicating all the efforts to increase the penetration of the renewable energy and adapt to a world, where the energy sources are clean and sustainable. The escalation to overcome the global warming problem is justified due the evidence of fossil fuels and power plants being a root cause of the problem. Wide range of reasons behind the high demand of RES, which are the negative impact the conventional power systems cause on the environment, high prices of fossil fuel and health implications caused by air pollution. The urge to maintain cleaner world by replacing fossil fuel energy resources to be environmentally friendly sources has become the center of attention in the recent years [3], [4], [5]. Countries, organizations and companies are now committed to participate in reducing their operational carbon footprint by either deploying renewable energy technologies or changing their operation

methods to be adjacent with the current focus on reducing the raising issue of global warming. Not only are there rules and regulation in place to encourage the implementation of RES but also there are economical incentives to allow for their expansion [6]. In recent review of the RES deployment, there are promising estimation that the renewable energy power production in the world will increase to 45% by 2040[7]. The RES presents the an adequate solution to limit the use of fossil fuel consumption and preserve the environment. Nevertheless, it needs more focused studies to investigate its reliability, sustainability and applicability thoroughly. Variety of challenges are facing the expansion of RES from economical and technological perspectives that an effective collaboration of researchers and industries need to address.

The conventional power systems in the past era contained only rotating mass (generators) that ensure the power transmission is being delivered to each load. The generators by nature have a dynamic behavior due to their physical movement. This trait of the generators are invaluable to the operation of the power systems due to providing inertia from the rotational movement. Unlike the generators, RES include a power converter that is considered as static devices. The static device or the power converter provides the means to convert the DC power generated by the renewable energy sources and convert it to AC to be aligned with the electrical load. The power converter is an essential part when discussing RES and it is important to understand the difference between the conventional generator and the power converter. The power converter does not rotate or engage in any physical movement, which pose a concern to the operation of the RES and the ability to control their output generation. RES applications are equipped with power converters that directly interface with the

grid, which needs be treated differently than generators. Furthermore, when RES are operating along with generators in the same electric grid, the behavior of system change dynamically and it continue to change drastically as more and more penetration of RES are provided [8].

The diversity of power system is currently crucial to contain both conventional generators and RES. The provision of the RES that are connected to the electric grid are challenging and come with obstacles such as the loss of inertia as compared with the inertia-rich conventional power systems[9]. Though the conventional power systems are proven to participate in the climate change that have a negative impact on the environment of the world [10], the RES might cause the loss of power if not studied and implemented adequately. RES advantages are their reliance on clean and inexhaustible source of energy such as the sun, wind, tidal wave, hydro energy and many others. Aside from their advantages RES disadvantages are lack of continuous generation, lack of inertia and dependence on Energy Storage System (ESS). Another problematic concern about the RES is the nature of the their operation, which include fluctuation that can lead to failure to their output power and instability to the power grid. The solution of the fluctuations can be addressed by the provision of the energy storage system, which participates in the smoothing and compensating of the power when there is high load demand, disturbance, and unbalance. Renewable energy sources such as PV and wind have been deployed with ESS to appropriately allow for the energy production to be according to the demand and needs of the power grid as well as the intermittency problem. Despite the fact that the solution of ESS is adequate to get rid of the undesired fluctuation, it remains a costly solution of less

accessibility to end users. The ESS is found mostly in all the applications of RES but the most popular are the PV and Wind configuration. The main duty of the ESS is to ensure stable and reliable operation and to satisfy the equation of power generated vs power demanded. Unlike the conventional power, that can be set to a specific generation operating points, RES can be very difficult to have a set-point due to the change of the wind and sun profile. Therefore, The ESS is deployed to discharge and allow for instant generation.

Photo-voltaic, Wind Turbine and Energy Storage Systems (ESS) are the most advanced configuration of the modern RES applications. There have been significant research conducted in the area of PV, Wind and ESS, which allowed it to be more feasible and attractive in many projects around the world. Further, the particular configuration of PV and Wind consist of large PV arrays that are considered as solar farm and multiple wind turbine that make up a capacity able to replace a conventional power plant. Many research focus mostly on enhancing the PV-wind setup, other research are exploring and developing alternative renewable energy such as Fuel Cells, different energy storage systems and new control schemes to integrate them with grid. In the literature, fuel cells are becoming a popular subject among researchers to integrate them in grid-connected manner and take advantage of their clean emissions [11]. Similarly, different energy storage systems are being considered as an alternative to batteries such as SMES. While the literature indicate many renewable energy sources, few research are addressing the provision of fuel cell or SMES. It is crucial that the new renewable energy applications are researched and validated to not only provide alternative options but also to select them based on efficiency. In order to achieve high

RES penetration percentage, existing clean energy applications such as fuel cell and SMES need to be studied in depth for exploring their benefits that can be added to the power grid stability. Further, the positive estimation of producing 45% of the world energy using RES by 2040, should be reached by the posvision of a variety of different energy storage systems and RES applications [7]. In essence, alternative devices such as fuel cell and SMES need to be introduced to the power grid and enhanced to be competitive to PV and wind turbines.

The challenges of making RES attractive to utilize as sources feeding into the power grid were near impossible. The economics of the PV and wind despite their early inventions dated back in 1839 and 1951 were undesired given that fact that batteries needed to be added to address the intermittency factor[12]. However, recent development had been targeting the cost and assuring the PV, wind and any energy sources can be an exemplary alternative to the fossil fuel in terms of reliability, availability and efficiency. Many studies were conducted for the off grid application and the approach at first was to only incorporate the renewable energy such as solar energy and wind energy for small grid or small-scale applications[13]. The development of RES kept on pushing the boundaries for more satisfying results aiming towards connecting the renewable energy into the electric grid in large-scale generation plants. The idea of connecting the renewable energy to the power grid seemed unjustified at first provided the disadvantaged of intermittency, the lack of developing the power electronic suitable to handle high voltages and the instability issues that may arise. The pathway to make RES connect to the grid meant that significant breakthrough had to be made in the power electronic to not only increase their capabilities to handle

high voltages and high current but also to limit the harmonics, the distortions, and to find a solution to the intermittency problems[14].

Many draw backs are faced in the advancement of the feeding RES into the power grid. Most important issues that exist are the lack of inertia as compared with the conventional power generations systems that use fossil fuels. It was observed that the power converter even if it had the capabilities of operating on high voltage ratings, it is still a static device that does not offer inertia to the power grid. The provision of the static device that connects to the power grid introduce stability issues as the power grid becomes weak and prone to drastic changes due to inertia decreasing. This did not only result in altering the behavior of the power grid stability but also motivated researchers to find new innovative solutions to address the stability issues and to assure that the RES integration can participate in stability of the grid rather than compromising it. Also, it is crucial to address that the Rate of Change of Frequency (ROCOF) can increase quickly as more inverter based renewable energy resources are connected to the main grid [15]. The challenges of decreasing inertia in the power grid and its associated outcomes are new due to relying on huge rotating equipment in the past. Now the power grid understanding is treated differently due to the introduction of the RES that decrease the inertia and change its characteristics. As a result, the power grid that is used to be a strong with capability to withstand periodic disturbances, now it lacks inertia that affect its well-known behavior [16]. The integration of the RESs into the existing AC grid change the entire system response, which result in instability of frequency and voltage[17]. As there is constant attention to the instability issues RESs raise, variety of new techniques are developing to achieve an available, reliable

and strong power systems in terms of frequency and voltage stability[18], [19].

The literature indicate many researchers have developed the power electronic converter responsible of converting DC to AC by using the Grid-Following control. Most of the applications that are grid connected are using the Grid-following approach. Unfortunately, this method was proven to be unstable and can cause inaccurate control when the grid is weak or experiencing faults [20]. The basic operating principle of Grid-Following is obtaining the measured values of the angle of the grid voltage. The value is obtained by Phase-locked loop, which enables the Grid-Following converter to control its frequency output rather than acting on the measured values. However, there is a new approach called Grid-Forming (GFM) that are set to solve the existing issues of the GFL method. Unlike the the Grid-Following (GFL). Grid-Forming converters are using many control approached one of which is the droop control, which allows the controller to act as synchronous machine. The droop control is mimicking the exact behavior of the synchronous machine in order to emulate the inertia and allow for a familiar behavior of the grid. Due to the similarities of the GFM to the synchronous generator, it has the ability to control its output frequency and voltage through the obtaining of the real power (P) and reactive power (Q).

The GFM is represented as a voltage sources, where the GFL as current as showing in Fig(1.1). From the literature the GFL is proven to be inferior to GFM due to have the disadvantage of not being able to supply the required inertia as well as the participation in instability of the power grid during weak conditions. The GFL receives signals of voltage and frequency from the grid as well as active and reactive power from the power plant controller. Therefore, it acts a controllable current sources that

is synchronized with the grid. The GFL tracks the signals from the grid and follows it accordingly, which does not lead to supporting the grid strength. On the other hand, the GFM receive set-points from the grid that should be to maintained. As a result, the GFM simultaneously absorb or supply power in proportion to the deviation of the voltage and frequency from their nominal values. Hence, a grid control scheme based on GFM is more preferred due to its ability to behave as synchronous generator as well as taking part in addressing the stability of the grid. This method of GFM can expand further to not only solve the instability issues but it also can be implemented with adaptive inertia and better power sharing capabilities as compared with synchronous generator. The Grid-Forming is a new control technique that when equipped with the adequate RES can ensure the grid stability, frequency and voltage regulation.

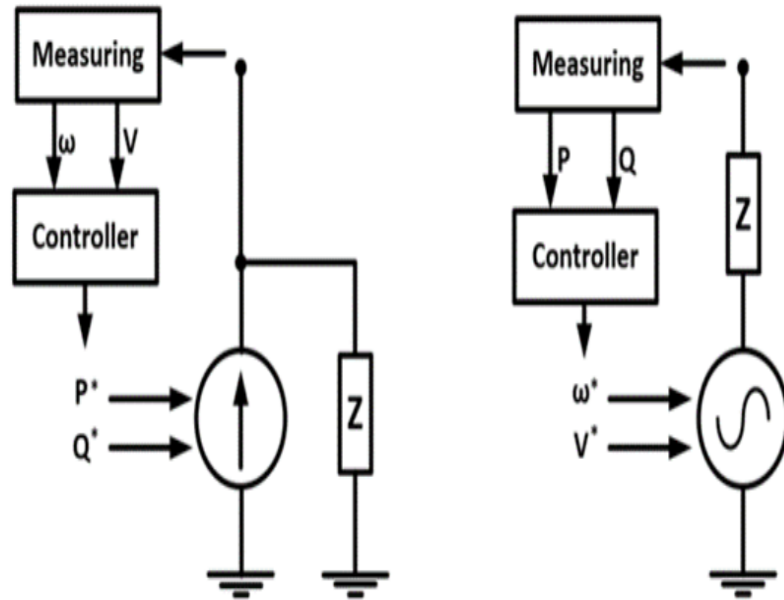


Figure 1.1: GFL VS GFM

From the Fig (1.1), the GFL is represented on the left side of the figure showing the current symbol and the reference signals of active and reactive power from the plant controller. The GFM (on the right side) shows the reference signal of the frequency and the voltage from the grid. Moreover, The power sharing capabilities of the output generation of the GFL is very limited and as previously stated can be unstable under the conditions of the weak grid. The On the contrary, the GFM with the control philosophy of droop outperform the GFL in terms of stability, frequency regulation and voltage regulation due to the fact that, it controls its output generation as well as it can share some of the grid load [21]

1.2 Research Gap and Motivation

Many research works have proposed new control techniques to address the issue of instability of the provision of RESs in the current power grid. The control schemes are manipulating power converters, which are categorized as either grid following (GFL) or grid-forming (GFM) [22]. Though the grid following is prone to failure in supporting the grid in terms of frequency and voltage deviation during weak grid [23], GFM introduces a robust control during the disturbances in the power grid as it acts as voltage source. Its way of operation is based on mimicking the behavior of SG and emulating the inertia. This attribute of GFM enables the generation of RESs to engage in power sharing capabilities as well as control the deviation of the frequency [24].

Many authors have approached the control of GFM by using the virtual synchronous generator (VSG) with many modified controls. In [25] they proposed novel control strategy that optimized the power sharing capabilities of distributed generation network that contributed also to manage the inertia. A similar idea for the enhancement of the VSG has been done in a research by utilizing the Particle Swarm Optimization to allow for a better transient response [26]. However, they only modeled one generation unit, where in our research we model, PV arrays, Fuel Cell and SMES. The works in the literature use the PSO algorithm to be applied in the VSG outer loop only. In our work we apply the PSO for the VSG outer and inner control loops to obtain the minimum error signals. This technique will be enhancing the overall operation of the VSG.

1.3 Problem Statement

The regular operation of the power grid is highly complex and dynamic due to the variation in its parameters. The most concerning aspect is that the power generated and power demanded (PL) is constantly changing. These changes cause both deviation of the real power (P) and reactive power (Q). An Synchronous generator in this case resists the change by having an inertia. Meanwhile, its load frequency control loop (LFC) will command the governor to allow in more steam to maintain the required frequency as 50Hz or 60Hz. This control is ought to be efficient in Synchronous generators that regulates the frequency in prompt manner. In case of RESs, the ESS is introduced to allow for a sudden compensation of power to contribute in a fast action towards providing the needed frequency regulation [27].

The solution we propose of the issues of intermittency and lack of inertia is by constructing a unique combination of RES that are PV Arrays, Fuel Cell and SMES. The reason of using such combination is to have a weak grid that is prone to instability issues. The ESS application in the research is optimized to be discharging and charging based on the frequency profile. A Virtual Synchronous Generator (VSG) based on droop control will be designed for each source to offer power sharing capabilities and enhance the stability. The VSG modification is in applying the PSO algorithm to the outer and inner loop controllers to enhance its response and to obtain the minimum error signals that will allow the VSG to be more robust and address the stability problems efficiently.

1.4 Thesis Structure

This thesis is composed of six chapter. Chapter 1, contains a preliminary literature review of the RES, power converter and stability issues. It explains more about the background of the problem and challenges this thesis is focused on. Chapter 2 provides a detailed literature review on the issues of renewable energy resources; specially when connected to the grid in terms of frequency control and stability. The chapter goes on to explain many methods that have been conducted to solve the problems and provides a unique gap where our thesis comes in. In Chapter 3 has all the mathematical models of the PV, Fuel Cell, SMES, DC bus, and Grid side inverter. Chapter 4 highlights in details the proposed controller of the GFM as well as benchmark controller. Chapter 5 is about the results and discussion of the simulation of the proposed controller. Finally, Chapter 6 discusses the conclusion of the work carried out in this thesis and the future work to be conducted.

CHAPTER 2

LITERATURE REVIEW

2.1 Grid-Connected Renewable Energy Power Systems

2.1.1 Renewable Energy Resources Connected with VSG

The research works in the area of integrating the RES with the power grid is quite diverse. Many authors address the frequency regulation issues from different perspective. For example, in [28] representation of an improvement in frequency regulation by using VSG that connects multiple RES such as Fuel Cell, Batteries, PV arrays, Wind Turbine and Diesel Generator. Their research is primarily on the frequency control by using Lyapunov stability theory. But their diversity of including multiple energy sources such as diesel generator and batteries establishes a stronger grid compared to our research where the frequency regulation is done through each sources with SMES as the primary regulator. Another research is using improved VSG by the use of Adaptive Droop. Their system consist of two wind turbine farms and one PV

farm. They have tested their algorithms in two cases that are sudden load change and wind turbine trips. Their results on the adaptive control were achieved regardless of the existence of the delayed response [29]. The delay cause in their research is being fully dependant on the RES without any storage system. In [30], the use of artificial intelligence in emulating the virtual synchronous generator is carried in their work based on the converter itself without including any renewable energy sources. But, in their work they have used the artificial neural network by applying the double loop with time-back tracking to achieve the dynamic behavior of the synchronous behavior.

Virtual Synchronous Generator (VSG) is a high-performance, real-time operating system for the control of industrial process equipment. It is designed to meet the requirements of users in industries that require reliable and safe operation of their solar PV and wind application. The VSG provides an integrated solution for smooth operation. It has been a promising solution for the converter addressing the intermittency problem, the load demand control and smooth regulation of the frequency and voltage of the grid. In [31], VSG was modelled to adapt to the intermittency issues as well as the load demand by obtaining the characteristics of synchronous generator. Their scheme is including the PV and battery as storage system; and their VSG is based on PI controller without the deployment of artificial methods. Due to the expansion of research regarding the VSG and curiosity to test its capabilities to behave such as a synchronous generator. In [32], They have used the VSG to target tge stability issue. However, their main focus is improving fault ride through (FRT) by deploying SMES and VSG to manipulate the control scheme by the PSO algorithm. They have simulated a fault that causes a voltage drop and dispatching the energy storage system

by the command of the VSG to obtain a robust yet distortion-less operation. While many other research are defining the capabilities of the newly solution called VSG, in [33], a VSG is set to control the frequency deviation for an autonomous microgrid without an energy storage system. Their approach is including novelty in the sense of mimicking the exact behavior with its parameters and characteristics such as active power, power verses voltage curve and power angle as their primary target to control. However, their system is not portraying the connection with the dynamic grid in which we will be investigating as more complexity will arise as compared to only micro-grid dynamics.

While many authors are tackling the stability and frequency regulation issues by the provision of VSG, other authors are enhancing the mechanisms of VSG to enable a more favorable and robust operational results. In [34], a neural network with back-stepping control is simulating the microgrid with a nonlinear control approach to allow for the smooth operation of the micro-grid switching on/off the connection with the grid. Their research is concentrated on reducing the large current that arises during the transition process of connecting/disconnecting to the grid, which causes instability. Another artificial approach is presented in [35], where they applied the neural network method targeting the reliability of the VSG itself. Their problem is the regular control of the VSG reduced the reliability of the VSG due to the variation of the power deviation that cause stress on the semiconductor of the converter. In their proposed solution the double loop neural network showed a fast and accurate estimations of the VSG operation and its reliability. A parameter alternating VSG controller aimed to solve the issues of low frequency damping in the VSG in [36]. Their

work is assuring that the alternating method control was able to improve the the low frequency oscillation (LFO) in order to mimic the synchronous generator precisely. The literature offer multidisciplinary use of the VSG in the sense of controlling the frequency and the voltage.

2.1.2 Energy Storage System Connected with VSG

The use of the energy storage system when talking about the renewable energy has become interchangeability common. Due to the intermittency, fluctuation and instability nature of the renewable energy, ESS has been the most desired yet expensive solution[37]. There are many authors that are prompting the use of the energy storage system in the distributed generation to have an effective microgrid that is not only green but also reliable [38], [39]. It is very important when trying to solve the aforementioned issues that the choosing of the ESS shall but considered for suitability from an economic and technical prospective. Some of the energy storage system such as lithium batteries are ideal to address many of the requirements a microgrid needs such as peak shaving, frequency regulation, power support and damping but are far to expensive at the current time [40].

However, some authors carry on with considering batteries most of the time when including the VSG in their study, where they consider the VSG is the main part of the work and the energy storage capacity is usually given but the model is neglected. For example in [41], their work is mostly concentrated on the VSG where they tackled the issue of lack of inertia by the provision of the a limited capacity energy storage system that was not defined in their work. Much likely, in [42], [43] are considering

Battery Energy Storage System (BESS) to set their control parameters on the VSG to charge and discharge depending on the values of the grid inputs. Their work include frequency regulation but not limited to stability and voltage support.

As ESS has shown great development and much attention is paid towards progressing of the energy storage system technology. In our work we include SMES as a primary part for our frequency regulation and instability problem. But many authors have studied and tested the SMES as a secondary ESS, and energy storage system that is coupled with PV to regulate the shortages of generations and a way to mitigate load changes by dispatching in a quick yet stabilizing fashion [44], [45], [46], [47]. Unlike the large space a hydro energy storage occupies and the disadvantage of the BESS being limited by life cycle and the nature of being dangerous material, we choose SMES due to being the most suitable in our study. The SMES is a special energy storage system due to composing of a large superconducting coil that is able to store the magnetic field generated by DC current flowing inside it [48]

The SMES much like the batteries are proven to have a rapid response in discharging and charging. Also, there has been research to apply solenoid conductors to further reduce the overall economics and increase its attraction [49].

2.1.3 VSG development and Approaches

Since the VSG is promising technology it has been applied to regulate the frequency and enhance the stability of the grid in many connected appliances such EVs, research on black startup of units, highly fluctuated wind turbine, and many optimized techniques to improve the overall performance of the VSG [50], [51], [52], [53], [54]. An

interesting approach is carried to enhance the VSG one step further. In [55], they propose a STO-STC algorithm that targets the inertia of the VSG. Their approach is using the advanced sliding mode control embedded in the VSG control loop to offer flexible inertia following a grid disturbance. Though the work carried has novelty of deploying the VSG with different virtual inertia, they did not include the frequency regulation as their main focus. Further, their main focus was based on the inverter itself without provision and modelling of the RES. The VSG is a new topic that needs much attention and efforts. Many works are trying to tackle the existing issues of the PLL-based RES. In [41], a large scale renewable energy system are put to test with VSG. The VSG is based on Hamilton approach as new control method that offers robustness and prompt for stability. Their work take into consideration the connection of the electric grid and aim towards the improvement of VSG behavior. Their proposed control method is quite successful due to obtaining better stability when compared to regular VSG.

When designing a VSG, two important parameters needs to be addressed carefully. The inertia and damping factor that are part of the swing equation affect the behavior of the VSG operation in terms of its ability to provide stability. In [56], a control approach focusing on self-adaptive inertia is proposed to support frequency stability. Their work is on changing the parameters of J and D in the swing equation of the swing equation that is implemented in VSG. They simulate the disturbance of the grid along with changing the inertia and damping parameters to address the stability in a swift and adequate manner. However, they do not cover the renewable energy sources but rather a simulation of the VSG by itself and it is response to the simulated

disturbance i.e. load shedding. Similar work was carried to establish new tuning of the VSG control parameters. The issue of finding the appropriate inertia constant can be difficult. A conventional work is carried to tune the VSG parameters based on trail and error method. The observation against the inertia constant is its direct effect on the rate of change of frequency and the frequency nadir. There is a trade-off, which is when increasing the inertia the rate of change of frequency decreases but the frequency nadir is also becoming slower and changing the system dynamic response. In their work they tune the VSG inertia constant to find the optimal inertia constant that stabilizes the system and engage in robust frequency regulation [57].

Authors in the field of integrating renewable energy resources with the power grid are tackling the arising issues of the inverters that are stability and frequency regulation. Instead of acknowledging the risks of introducing renewable energy resources that participate in weakening the power grid, wide range of researchers are coming up with many innovative solutions to the stability issues. In a research conducted recently [58], the observation made against the VSG is not adequate solution for oscillation damping. They noticed that when there is a disturbance to the grid or even load change the oscillation of the grid magnify without the inverter rectifying them, which cause instability. In their work, the focus on the creating a new control mechanism that solve the oscillation problem by introducing the bouncy control into the VSG. The bouncy control is composed of the reference signals that are taken from the grid and converted to d-axis and q-axis. Then, they are being fed to a control block called emergency control that feeds the internal control loop of the VSG. The VSG takes the new parameters and adjust its real power and reactive power to remove the unwanted

oscillation.

New approaches are being implemented on the VSG and multiple of new techniques are progressing. In [26], they have carried on a similar work to our research objectives, which is to employ the particle swarm optimization in a VSG to enhance its capabilities. Their work is focused on the outer loop of the VSG, where the droop controller parameters are run thru the PSO algorithm to minimize the feedback error signals. They employed the PSO VSG after gaining the optimized parameters in a strong microgrid. Their approach is entirely new, where they have experimented with Particle Swarm Algorithm to optimize the swing equation. The similarity of their work is close to what we propose in this research but we apply the PSO not only in the swing equation but also in the dual loop of the VSG. In their work, they implement the VSG on a microgrid that is not defined. They only simulate the load change and the participation of the VSG due to the change. They compared their results to the regular VSG and their proposed VSG had outperformed.

The work on improving the Virtual Synchronous Generator is widely investigated. Many authors are improving the swing equation to allow for more accurate response. Others are more focused on the control equations and parameters of the VSG to not only tune the behavior of the controller but to implement a robust and resilient response. Further, many authors are also focused only on the adaptive inertia and damping factors that can add tremendous value to the oscillation and fast response of the VSG [59], [60], [61], [62], [63].

A regular VSG control scheme can be observed in the Fig(2.1), as the work

conducted by the authors in [64].

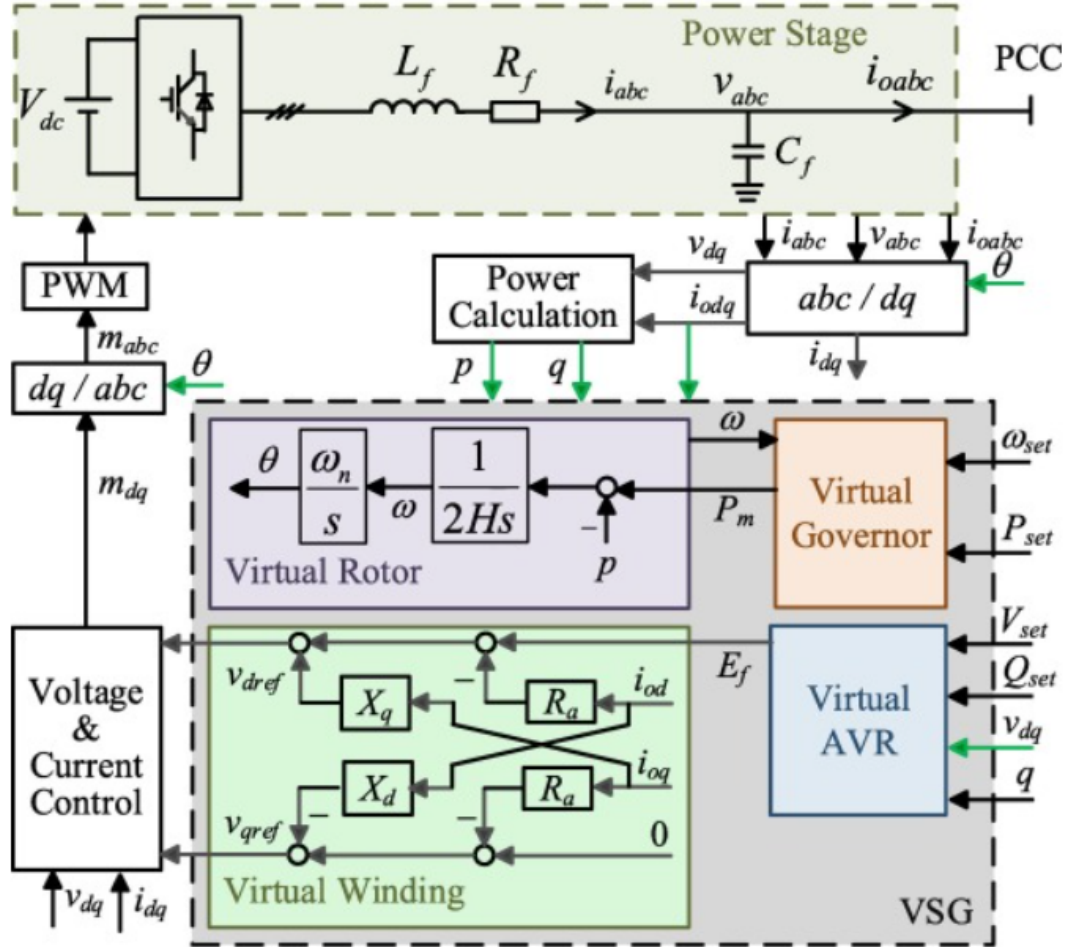


Figure 2.1: Regular VSG control scheme[51]

2.1.4 Proposed System

In our work, we investigate the frequency regulation using Fuel Cell, PV array and SMES. The Fuel Cell and PV arrays are the generating energy and feeding the grid at all times except under some conditions such as low irradiance and high temperature that can affect the Fuel cell. The overall diagram of the system we propose can be observed in Fig(2.2):

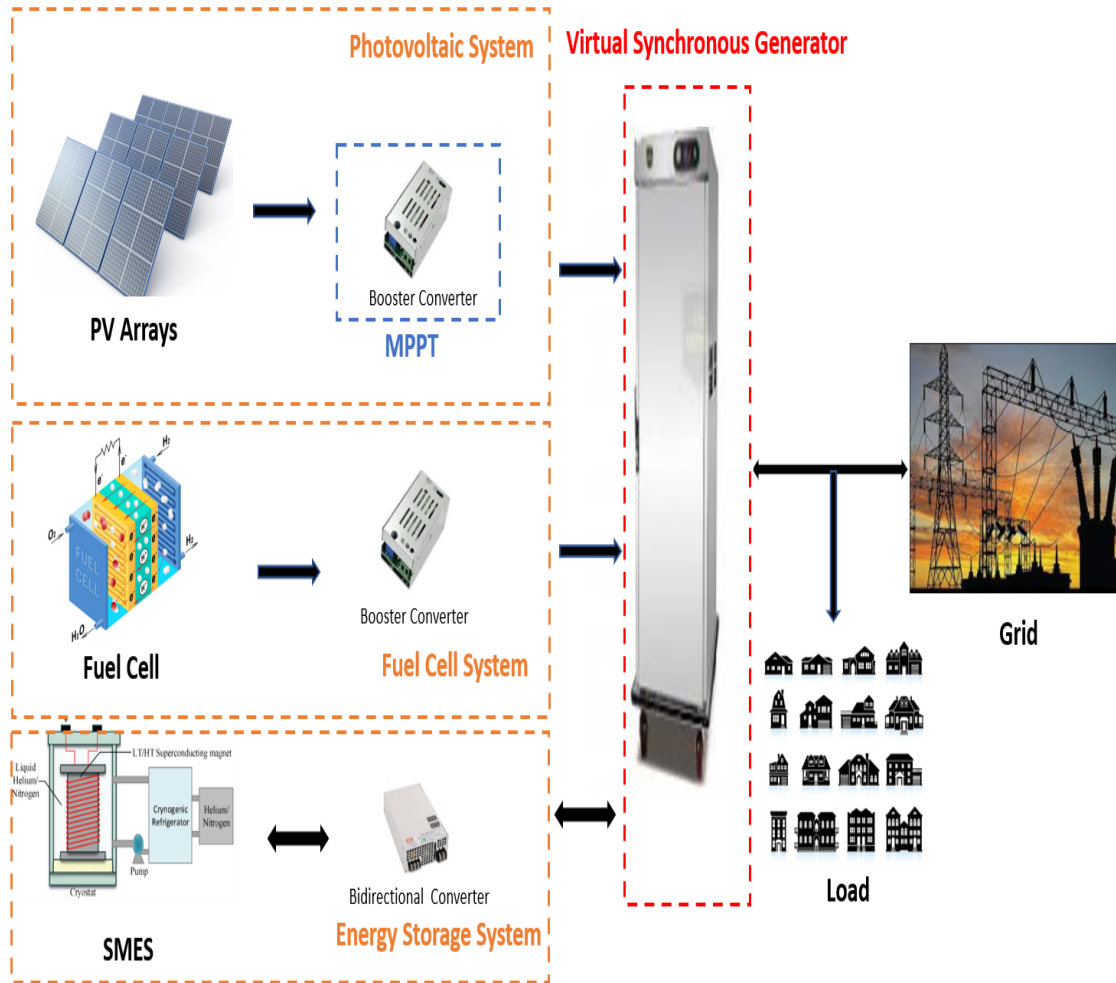


Figure 2.2: A general scheme of the system

2.2 Photovoltaic Background

The Photovoltaic effect as many individuals consider it as a new invention, was first observed in 1839 by Alexandre Becquerel, who was a physicist from France. He was experimenting with electrochemical components which lead to noticing the photovoltaic effect on the platinum electrode he was using when there was sun exposure. Later in 1873 Willoughby Smith expressed his curiosity of the effect in a letter to one of his colleagues, when he noticed this effect on selenium. At this time more scientist were very attracted about this effect and wanted to explore more of the features it can offer. Not long after, in 1877 the design of the first solar cell was made using selenium by Adam and his student Richard. Unfortunately, there efficiency of the solar cell was as low as 0.5%. One year later a scientist by the name Charles Fritts had made significant increase in efficiency to double what had been set by Adam and his student[65]

Invaluable contribution was made by Albert Einstein towards the photoelectric theory that was proposed in 1905. The photoelectric theory has detailed explanation of the light waves and how the energy is related to the photons. The theory was a scientific breakthrough that Einstein received the Nobel Prize in 1921[66].

In the early 19th century and after the photoelectric theory set the ground rules to commence the development of solar cell comprehensively, solar energy gain more attention but the selenium was a problem to be solved due to low efficiency. During 1939, great discoveries were made when Russel Ohl replaced the selenium with Silicon. Higher efficiency were reported, which made this new discovery generate new

approaches and technological solution to further improve the efficiency. Researchers and inventors had indeed reach new achievements by creating the first silicon solar cell in 1940, after utilizing the photoelectric as light sensors[67]. As the technology became more advanced there were finished products put to use in the market. USA National Academy of Sciences had taken the initiative to deploy the first ever solar cell application connecting it to a telecommunication network. Soon after that, NASA launched Vanguard-I satellite marking the first one of its kind to have a solar system in 1958[68]. The applications of solar cell were proven to be effective after the successful deployment by NASA and other organizations. Industries were motivated to diversify the approaches to tackle the economics and efficiency challenges. Nowadays, there are different kinds of solar cell with better improved efficiency.

Now the solar energy after the recent development is recognized as a reliable source to extract the energy from the sun. Various applications and use for the PV from residential to commercial to industrial with many optimistic buyers. Many companies have made the process of manufacturing the PV comparatively low to what the solar cell used to be constructed of. The materials of the current PV varied from Monocrystalline, Polycrystalline and thin films, which vary in efficiency and cost as well. Not only there is a noticeable variety of options in the PV industry but also the capacity of $1m^2$ solar panel has increased reaching to 600 Watt from Sunpower company.

2.2.1 PV Operating Principle

The previously mentioned photoelectric effect is responsible for the operating of the PV arrays. In the PV cell, there are electrons hole pairs that have the ability to generate electricity given the field forced from the p-n junction, which case the holes and the electrons go in opposite side. Then, a potential difference is existing on the semiconductor [69]. The p-n junction contains the electrical field stationed from the n to the p area, specifically in the thin region known as the transition. It can be observed in the figure (2.3):

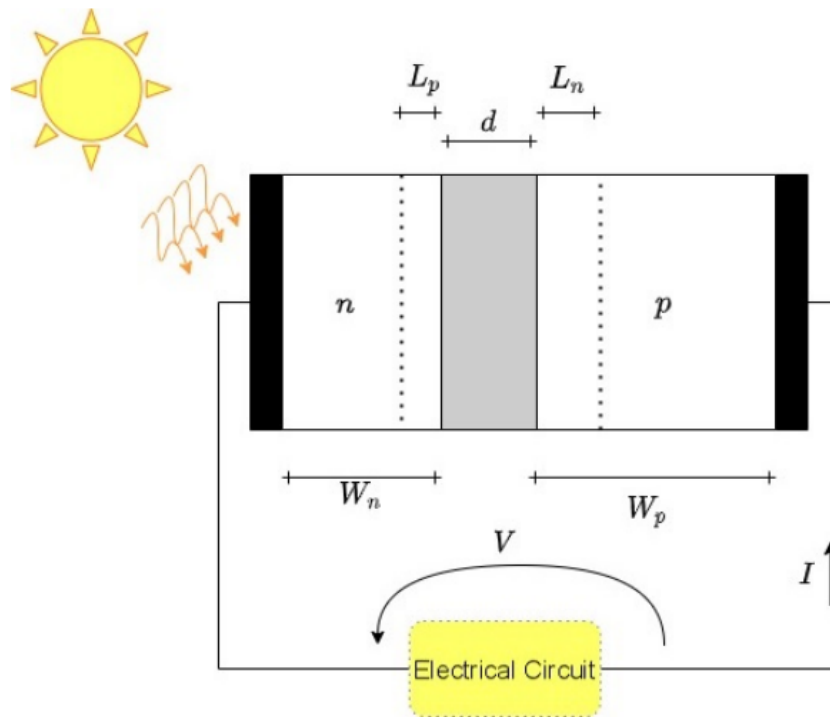


Figure 2.3: p-n junction of a solar cell

The current of the solar cell can be expressed as the following:

$$I = I_{is}(e^{\frac{V}{nUT}}) - I_{ph} \quad (2.1)$$

where I_{is} and I_{ph} is the reverse saturation current of the p-n junction and current under the illumination condition of the semiconductor. n , u , T are the junction non-ideality factor, thermal voltage and temperature. The thermal voltage can be expressed below:

$$U_T = \frac{K}{q}T \quad (2.2)$$

Where T , K , and q are the certain temperature, Boltzmann's constant and electron charge.

The Solar Cell is also modelled from an electrical prospective to allow for a more simpler explanation of it is inner working. It is a crucial that an electrical model needs to be formulated to allow the power generation engineer to understand the inner working of solar cells and apply ohmic laws. One of the simplest electrical model of solar cell can be seen in Fig(2.4). The model is referred to as 1D3P model. This mean 1 diode and 3 parameters, in which the diode is being modelled as p-n junction and the current source is treated as independent parameter that relied on radiation. The equivalent circuit in Fig(2.4) can be analyzed by the Kirchhoff's

Voltage and Current laws (KVL) (KCL) to obtain the output current, voltage and overall all power generation of the cell. Most importantly, the solar cell generated a DC power that simplifies the calculation of its parameters.

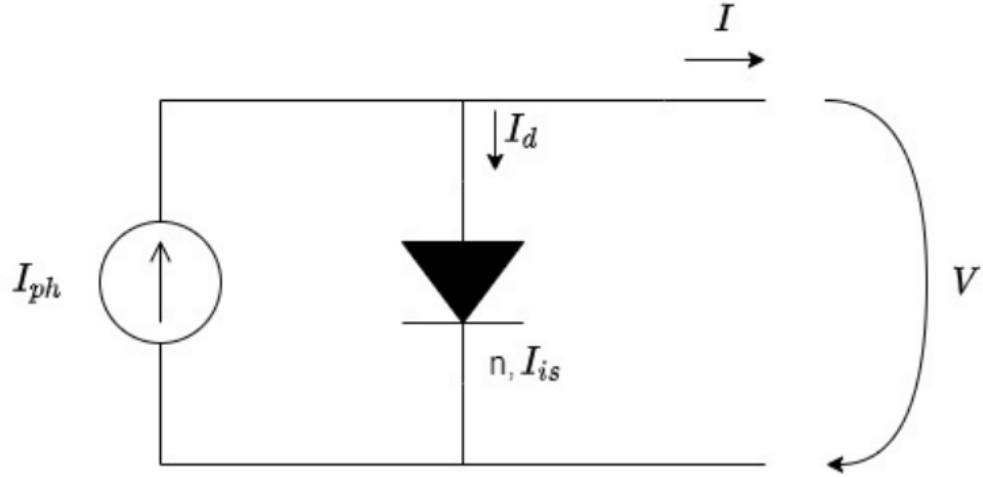


Figure 2.4: Equivalent circuit of a solar cell

Since the electrical model of the PV is mentioned, it is crucial to understand the electrical performance of it. The circuit is generating DC power, in which the equation of calculating the power is the product of the current and voltage. The characteristics of the PV contains a point in its graph denoted as the Maximum power point as shown in the graph of Fig(2.5).

The corresponding equations to find the maximum point of the current and voltage are as follows:

$$\left(\frac{dP}{dV}\right) |_{V=V_{max}} = 0 \rightarrow I_{ph} + \left(\frac{V_{max}}{n u T} + 1\right) I_{is} e^{\frac{V_{max}}{n u T}} + I_{is} = 0 \quad (2.3)$$

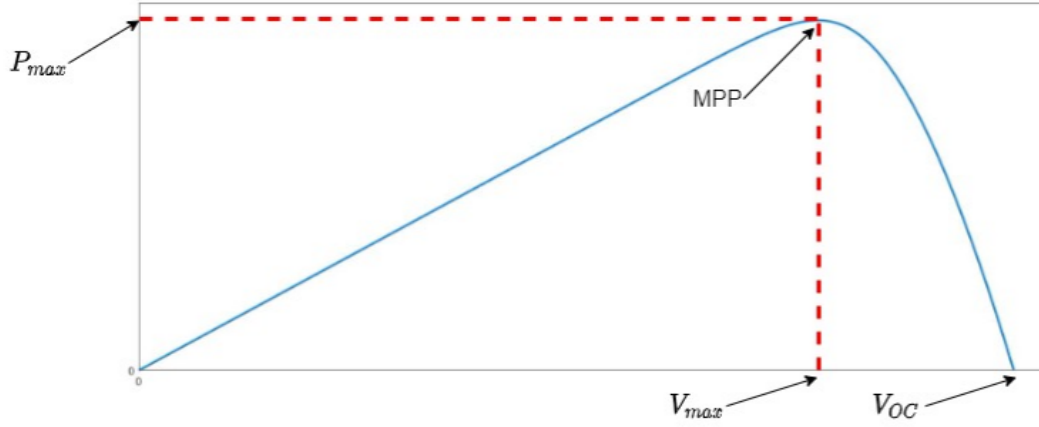


Figure 2.5: PV Cell Characteristics

$$V_{max} = nu_T \ln\left(\frac{\frac{I_{ph}}{I_{is}} + 1}{\frac{V_{max}}{nuT} + 1}\right) \quad (2.4)$$

$$I_{max} = I_{ph} - (I_{is}(e^{\frac{V_{max}}{nuT}} - 1)) \quad (2.5)$$

The equations above find the maximum power point of the solar cell. Expression (2.4) is for the maximum point of voltage, where expression (2.5) is for the current. In our work, we choose the solar panel as one of the primary sources of generating the power. The engagement of the frequency regulation and voltage regulation is provided by the means of the PV arrays. We optimize the solar cell with the highest efficiency to share the load with other generation units.

2.3 Fuel Cell Background

Similar to PV development, fuel cell have become known recently despite the fact that the invention goes back to 150 years ago[70], [71]. Fuel cell in the modern times presents an ultimately great generation systems due to their operating principle that does not depend on fossil fuels. Not until 1900s, did the intensified research for the fuel cell begun. The two British scientists Nicholason and Anthodny made a significant contribution to the area of fuel cell after realizing that they can generate electricity by decomposing water to oxygen and hydrogen elements. The chemical reaction was named the process of electrolysis in 1800 and the reaction can be seen in the below: [72], [73]



Great scientist Michael Faraday made another contribution in the development of the fuel cell as he made the observations of the two laws that is considered the fundamentals of the electrolysis. The observations were made on the basis of physical experiments as there were no mathematics theory behind them. Comes William Grove with another advanced idea to further the fuel cell technology by indeed coming up with the first fuel cell, which was considered as a gas battery back then. The contribution by Grove earned him the right to be referred to as the fuel cell's father due to his applicable prototype [74]. Not long after Grove, Ludwing along with his colleagues in 1889 had an experiment that was worth while. In their experiments, they test the

gas-powered battery using coal. The current was rated at 6amp and voltage at 0.73 volts, which meant that their experiments was a success that turned into business [75].

The Fuel Cell in 1900s had a big scientific leap, as more applications were been commercialized. Various applications of fuel cells were available from applications that generate electricity from the conversion of air and fuel to applications that are composed of new elements. The cost of the fuel cell had witnessed a great decrease as the process of manufacturing the fuel cell was optimized. Not only an optimization of process but also the fuel cell materials were changed to be less costly and more effective.

What makes the fuel cell attractive is the hydrogen. But why hydrogen in particular? Hydrogen by itself is not an energy source but an energy carrier. It has the ability to deliver and stored energy in a suitable form. Multiple advantages include using domestic and abundant energy resources such as fossil fuel, natural gas and coal. Also, it can extend to be used in the renewable energy systems such as Wind, PV, Biomass and many others [74]. When fuel cell are combined in the renewable energy resources schemes, it can be an effective resolution that can produce no carbon emission. This reason contribute to reducing the climate change that are faced globally. It also yields an exemplary methods to be utilized in microgrid for either large scale or small scale renewable energy generation plants such as the one in our research. The issue of the fuel cell is being sensitive to hot environmental conditions can be solved by providing air condition environment but the cost associated by air conditioning should be reduced to obtain an effective solution. Proven applications for fuel cell have been heavily utilized in many sectors such as transportation, industrial building and energy.

2.3.1 Fuel Cell Operating Principle

Fuel Cell is an electrochemical device much alike the regular batteries. The device is dynamic that it converts the chemical reaction of hydrogen and an oxidant into energy and most specifically electrical energy. Then, the electrical energy can be consumed for any types of load. The main difference between a fuel cell and a battery given there similarities are the fuel cell does not need to be recharged. The design of the fuel cell is for continuous operation as long as it is being fed by the external supply of the air or fuel. There are three main part in any fuel cell and they are the following:

1-Electrolyte

2-Anode

3-Cathode

The operation of a battery does not differ much when compared to the fuel cell. The electrolyte is placed in-between the two electrodes that consist of anode and cathode. The main difference is the deterioration of the fuel cell does not exist such as the battery, which makes its life span longer and more reliable. The fuel cell produces energy in form of electricity and heat as long as the fuel is supplied. The oxygen and hydrogen pass over the two electrodes, one for hydrogen and other for oxygen, in which electricity is being generated. The fuel is hydrogen, which is fed to the anode of the fuel cell. On the other hand, oxygen is being fed to the fuel cell

entering the cathode. The chemical reaction take place along a catalyst, where the splitting of atoms to proton and electron occur. These atoms elements take different paths to the cathode. More specifically, the proton go through the electrolyte, where the electrons create a separate current able to be utilized before going back to the cathode to merge back to the molecule of water. A visual depiction of the working of the fuel cell can be seen in Fig(2.6).

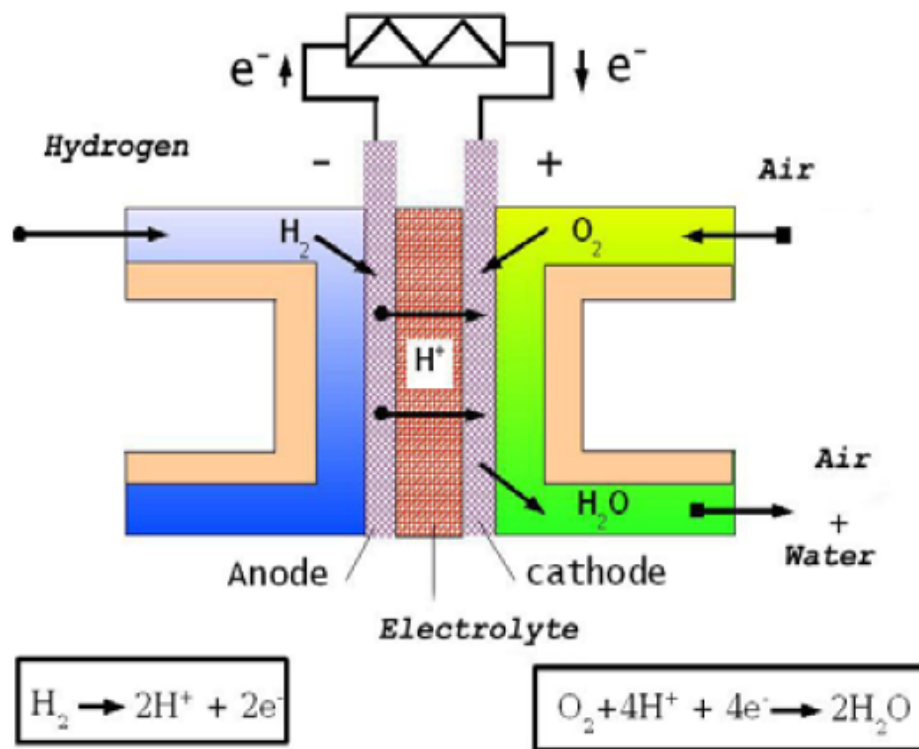


Figure 2.6: Fuel Cell Electricity Production

The fuel cell technology had progressed in the recent years. There are various of technology and ready-to-use applications with various operation efficiencies and constrains. Some of the types of the fuel cell are listed below:

- 1- Proton Exchange Membrane (PEM)
- 2- Molten Carbonate (MCFC)
- 3- Solid Oxide (SOFC)
- 4- Alkaline (AFC)
- 5- Direct Methanol (DMFC)
- 6- Phosphoric Acid (PAFC)

Fuel Cell Characteristics					
Type	AFCs	PEMFCs	PAFCs	MCFCs	SOFCs
Electrolyte	KOH	Perfluoro-sulfonic acid ionic exchange membrane	H_3PO_4	Li_2CO_3 – K_2CO_3	$Y_2O_3 \rightarrow ZrO_2$
Conductible ions	OH^-	H^+	H^+	CO^{2-}	O^{2-}
Fuel	H_2	H_2, CH_3OH	Reformed fuel (CH_4, CO, H_2)	Purified coal gas, natural gas, and reformed fuel (CH_4, CO, H_2)	Purified coal gas and natural gas (CH_4, CO)
Oxidant	O_2	Air	Air	Air	Air
Catalyst	Pt/Ru	Pt/Ru	Pt	NiO	Ni
Operating temperature	65–220 °C	–40–90 °C	150–200 °C	650–700 °C	600–1000 °C
Theoretical voltage	1.18 V	1.18 V	1 V	1.116 V	1.13 V
System efficiency	60%–70%	43%–68%	40%–55%	55%–65%	55%–65%
Application	Special ground and aerospace	Electric vehicle, submarine, and mobile power source	Regional power supply (e.g., power plant)	Power station	Power station

Table 2.1: Fuel Cell

2.4 Superconducting Magnetic Energy Storage System Background

Superconducting magnetic Energy Storage System is a new application that firstly appeared in 1970[76], [77]. it had gain increasing interest to scientists and industrialists due to its high efficiency reaching to 96%. Due to the integration of the renewable energy the with the grid, the issue of intermittency can be managed by the deployment of SMES. The device act as a current source, which is the opposite of the capacitor. The main advantage of the SMES is the ability to efficiently transfer power up to 96% as previously mentioned but also it can be utilized for energy storage system such as batteries. The first proposal for SMES as a device to store energy was in 1979, in which the proposal explain the capabilities of the technology being able to store the electric energy in the magnetic field generated by the DC current flowing through it. The concept of the SMES is the same of the less development since it is first proposed in 1979. There are many challenges facing the SMES from mechanical point of view. These challenges present the SMES as a costly solution[78], [79].

The technology of SMES is based in the superconductivity that is a phenomenon of having zero electrical resistance and generating large magnetic fields by using specific materials when cooled below a certain temperature. The metal materials are often of superconducting nature to opt for the appropriate working of the device. In simple terms, in electrical engineering there is a proportional relation between the heat and resistance. This relation indicate that as the heat increases the power loss increase respectively due to the increase of the electrical resistance. From mathematical point

of view, if the SMES is cooled below the critical temperature the resistance becomes zero. When the electrical resistance is zero that means the current can flow in the conductor for infinite time. The conductor becomes superconducting when operated in the cryogenic temperature this is due time constant of a coil as shown in equation below:

$$\tau = \frac{L}{R} \quad (2.7)$$

τ here is the time constant of the coil, L is the inductance of the coils and R is the resistance of the coil. As the resistance goes to zero, the coil become very inductive the time constant become infinite. Then, the stored energy of the SMES can be written as the below:

$$E = \frac{1}{2}LI^2 \quad (2.8)$$

Where E is the energy calculated, L is the inductance, and I is the electrical current. The above equation is nothing but the formula for the electrical inductor. From basic electrical engineering, the inductor is a current storage system and the SMES as the result of this fundamental.

2.4.1 SMES Operating Principle

To fully understand the operating principle of the Superconducting Magnetic Energy Storage System, its main parts and components need to be identified. The SMES is very simple in the application and does not contain many complicated parts such as other energy storage system. It only consist of the following main parts:

- 1- Superconducting magnet with its structure
- 2- Cryogenic System
- 3- Power conditioning system
- 4- Control System

The superconducting magnet is where the main electricity is stored and the magnetic field is generated. It is a set of coil that is placed in respect of the proximity effect to avoid any losses. Further, The cryogenic system is where the superconducting magnet is stored. It is usually a refrigeration systems that operate to the below critical temperature of zero loss. Thus system is usually equipped with its own controls such as temperature monitoring, ON/OFF buttons, and fault monitoring system. The Cryogenic is the most important part of the SMES. Hence, the separate control system is usually considered. The power conditioning system comes in the form of rectifier, inverters and transformer. This power conditioning system is not part of the SMES itself but is there when the SMES is grid connected. The control system is what actually operate the SMES system. It has the set point of each parameters such as the energy stored, temperature and faults. The main part of the SMES in a

grid-connected scheme can be seen in Fig(2.7).

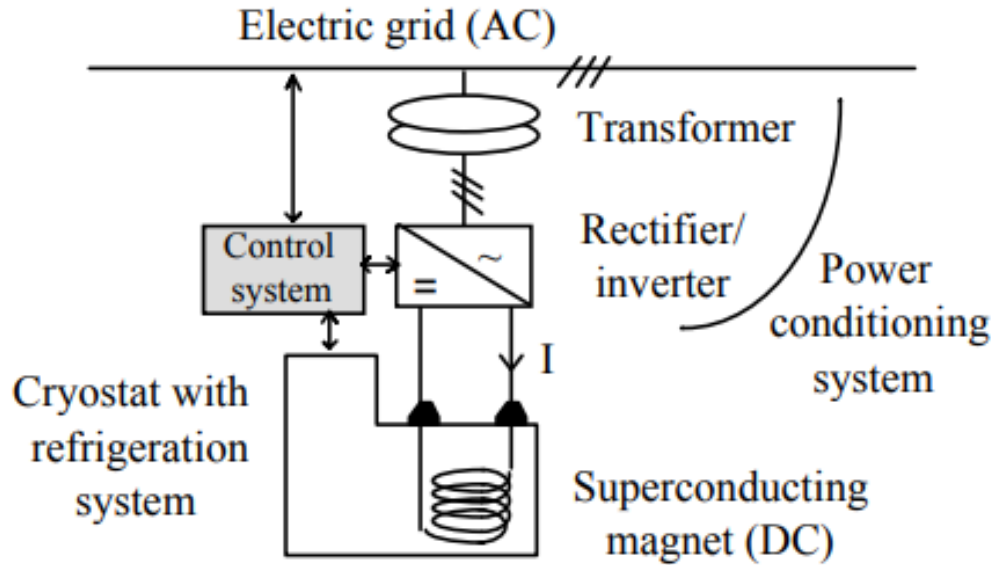


Figure 2.7: SMES in a grid-connected scheme

The SMES despite it is high efficiency and desired performance, it lacks many development as there are many limitations. There are high cost associated with manufacturing of the SMES due to the expensive materials [80]. With the current increasing penetration of the RES into the power grid, the need of multiple energy storage system such as the SMES need to be connected to the grid to support it. The options of choosing the energy storage system needs to be on the basis of high efficiency, in which the SMES offer.

CHAPTER 3

MATHEMATICAL MODEL

3.1 Mathematical model

The model presented in this work is concentrated in providing the stability of the power system when the RES are connected to it. As a result, a brief explanation of the stability of power grid is crucial. The power system stability is defined as the condition of operating in state of equilibrium under normal operating condition and regain an acceptable state of equilibrium after being subjected to a disturbance. Moreover, The power system is said to be in stable condition when the total power demanded equals the total power generated. If Eq(3.1) is not satisfied, the power system might be experiencing instability due to sudden increase in load demand, sudden decrease in load demand and faults in the network.

$$P_T = \sum_{i=1}^k P_{G(i)} - \sum_{j=1}^L P_{L(j)} \quad (3.1)$$

The P_G here is denoted as the total power generated from i^{th} number of generators to meet the load demand of P_L with as many as j^{th} loads including K^{th} generator units and L loads. The P_T in the above equation is the total power of the system, which defines the power generated and the power consumed by loads. Also, when P_T is zero when the system is stable.

The stability of the power system expands beyond the simplified equation in the aforementioned. Mainly, the power system stability can be affected by two types of disturbances as follows:

- Small Disturbance
 - 1- Increase in load
 - 2- Increase in generation
- Large Disturbances
 - 1- Loss of a large generator or load
 - 2- Faults of transmission lines

Dynamics of Synchronous Machine

The synchronous machine in the power stability plays an important role due to the interaction with grid to reset the state of the power system to equilibrium. The dynamics of the synchronous machine are expressed below:

The kinetic energy of the rotor in synchronous machine is given as:

$$KE = \frac{1}{2} J w_s^2 \cdot 10^{-6} \text{ MJoule} \quad (3.2)$$

Where J is the rotor moment of inertia in kg-M^2 and w_s is the synchronous speed in mechanical radiant/sec. Converting the speed to electrical radiant expressed as:

$$w_{se} = \left(\frac{P}{2}\right) w_s \dots \dots P = \text{no.of machine poles} \quad (3.3)$$

From equation above equations (3.2 & 3.3) we obtain:

$$KE = \frac{1}{2} \left[J \left(\frac{2}{P}\right)^2 \cdot w_{se} \cdot 10^{-6} \right] \cdot w_{se} \dots \text{ MJ} \quad (3.4)$$

Or:

$$KE = \frac{1}{2} M w_{se} \dots \text{ MJ} \quad (3.5)$$

where:

$$M = \left[J \left(\frac{2}{P}\right)^2 \cdot w_{se} \cdot 10^{-6} \right] = \text{moment of inertia} \dots \text{ MJ.sec/elect.radian} \quad (3.6)$$

Now we shall define the inertia constant, such that:

$$GH = KE = \frac{1}{2}Mw_{se} \dots MJ \quad (3.7)$$

Where G and H are the three phase MVA rating of the machine and the inertia constant in MJ/MVA or MW.sec/MVA

From Equation (3.7) we can write:

$$M = \frac{GH}{180f} \dots MJ.sec/elect.degree \quad (3.8)$$

Swing Equation

The synchronous machine consist of prime mover that provide the required torque of the rotor to reach the electromagnetic power P_e . The electromagnetic power is the resultant of the developing electromagnetic torque while operating at synchronous speed w_s . The input prime mover torque is denoted is T_i and if there is no disturbance in the power system,we obtain the following:

$$T_e = T_i \quad (3.9)$$

Neglecting any retarding torque we can write the following equation:

$$T_e w_s - T_i w_s = P_i - P_e = 0 \quad (3.10)$$

Where $T - e$, w_s , and T_i are the electromagnetic torque, synchronous speed and prime mover torque. Respectively, P_i and P_e is the input mechanical torque from the prime mover and the output electromagnetic power of the synchronous machine.

When there is a disturbance on the power system the synchronous machine is effected. Equation (3.10) becomes no longer valid as P_i does not equal P_e . As a result, there is a torque accelerating to satisfy the equation, which is P_a . Then, the equation now becomes as such:

$$P_i - P_e = M \cdot \frac{d^2\Theta_e}{dt^2} + D \frac{d\Theta_e}{dt} = P_a \quad (3.11)$$

Where Θ_e is the electrical angular position of the rotor and D is the damping coefficient.

The more convenient way is to obtain measurement of the angular position of the rotor with respect to the synchronously rotating frame of reference as stated below:

$$\delta = \Theta_e - w_s \cdot t \quad (3.12)$$

The we obtain the following:

$$\frac{d^2\Theta_e}{dt^2} = \frac{d^2\delta}{dt^2} \quad (3.13)$$

Where delta is the power angle of a synchronous machine as shown in the below figure

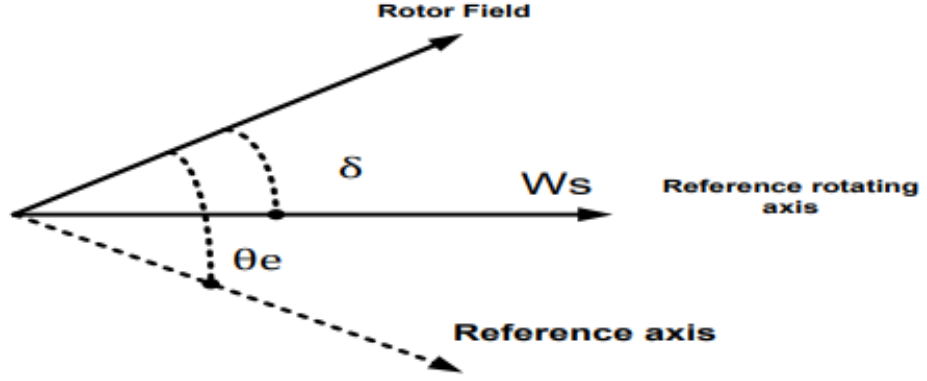


Figure 3.1: Angular position of rotor with respect to reference axis

In order to represent the behavior of the synchronous machine and understand its rotor dynamics to assess the stability study of this research, the below equation is the swing equation that allows synchronous machine to ensure the stability of the power system:

$$\frac{H}{\pi f} \cdot \frac{d^2\delta}{dt^2} = (P_i - P_e)pu \quad (3.14)$$

Equation (3.14) is the representation of how the synchronous machine operate. It also shows the relation between the prime move torque of the synchronous generator and the electromagnetic torque. The damping in this equation is neglected but it is very important to include it in dynamic stability studies

3.2 PV Model

Our PV model in this work is modeled by the combination of the multiple PV arrays that are composed of the well known materials, which are the n-type and p-type semiconductor. Similarly to any renewable energy source, the PV generates a Direct Current (DC). The DC output is the end result of transforming the solar energy (irradiation) to electricity exploring more details about the PV operational principle can be seen in [81]. Furthermore, the representation of the solar PV is quite the simple circuit because it contains only a current source, a diode, and resistors one in series and another in parallel. The output current from the PV can be calculated by the equation below and from [82]:

$$I_{pv} = N_p(I_{ph} - I_s[\exp(\frac{qV_{dio}}{N_sAk_BT}) - 1] - \frac{V_{dio}}{R_{sh}}) \quad (3.15)$$

where;

$$V_{dio} = \frac{V_{pv} + I_{pv}\frac{N_s}{N_p}R_{se}}{N_s} \quad (3.16)$$

From the equation above we can see that where I_{ph} is the current generated by PV internally, which is not the same as I_{pv} that denote the output current from the PV. Similarly, I_s is the current for reverse saturation, N_s and N_p indicate the number of cells that are connected in parallel or series, q is the charge of electron, V_{dio} is the

voltage of diode, A is the factor for P-N junction, kB is the constant of Boltzmann, T is the temperature of the cell, and R_{se} is the equivalent series resistance and R_{sh} is the equivalent shunt resistance.

3.3 Fuel Cell Model

The Fuel Cell in our system is a source of energy that is environmental friendly. Fuel cells have gain popularity in the most recent era due to being a green source of energy. It operates on the principle of electrolysis, where the hydrogen fuel and air are being fed from two opposite sides of the cell. There is a catalyst and membrane at the anode where the positive charge of hydrogen are passed through the membrane to the electrolyte and then to the cathode. Later, the negatively charged electrons are not able to pass and make the molecule of water when combined with air. This electrochemical reaction that takes place inside the fuel cell creates flow of electrons. Further details in the operation and the principle of Fuel cell technology can be explored in [83]. We can also model the fuel cell mathematically as expressed in [84].

$$V_{fc}(t) = E - V_{act} - V_{oh} - V_{con} \quad (3.17)$$

Where V_{fc} is the output voltage of the fuel cell, E is the electric potential, V_{act} is the activation potential, V_{oh} and V_{con} are the ohmic voltage and concentration voltage.

Further, the power output of the fuel cell can be expressed as such:

$$P_{fc}(t) = P_{fc} V_{fc} I_{fc} \quad (3.18)$$

Where P_{fc} is the power rating of the fuel cell and I_{fc} is the current of the fuel cell.

Hydrogen reminds the major part of the fuel cell operation and takes part in determining the power rating of the fuel cell generation of electricity. The hydrogen consumption of a given kW can be expressed as:

$$m_{H_2} = \alpha_1 P_{fc} + \alpha_2 P_{fc}(t) \quad (3.19)$$

Where M_{H_2} is the mass flow rate of hydrogen, α_1 and α_2 are the fuel cell intercept coefficient in kg/hr/kW and fuel cell slope curve in kg/hr/kW. Respectively, P_{fc} is the rated capacity of the fuel cell in kW.

3.4 SMES Model

The SMES contains various internal parts that shape the energy storage capabilities. The main part of the superconducting magnetic energy storage system is a large coil that must be made of superconducting material. The large coil is placed in a cryostat that consists of a vacuumed vessel; which provides the cooling to the coil by the use of liquid vessel [48]. The control of the temperature is a must to obtain by the cryogenic system that serves the main purpose of maintaining the required temperature for the superconductor. Similarly to any storage system, there is an AC/DC converter that

is bidirectional, which achieves the charging and discharging of the coil. At last, there is a transformer that connects to the converter responsible to maintaining the tolerable voltages [85]. The superconducting magnet energy storage is storing energy by inductive means in forms of (E in joules) and its rated power (P in watts), which are usually determined for the specifications of the SMES and it can be expressed as below:

$$E = \frac{1}{2}LI^2 \quad (3.20)$$

$$P = \frac{\partial E}{\partial t} = LI \frac{\partial I}{\partial t} = VI \quad (3.21)$$

Here we have L expressed coil's inductance, I DC current through the inductor V is the voltage of it. The operation of the superconducting condition must be maintained to establish proper overall function of SMES. The other crucial part is to also maintain the temperature by the means of some cooling equipment as the temperature can have a direct impact of the efficiency of the overall performance [77].

3.5 Boost Converter Model

The boost converter plays a crucial rule in the PV and fuel cell. The sole reason the booster converted is added in our network is to optimize the production of the renewable energy. Due to temperature and irradiation dependence, PV and Fuel cell can have a direct impact that reduces their energy production [86],[87],[88], [89], and

[90]. The mathematical model can be expressed as below:

$$L_{sm} \frac{dI_{sm}}{dt} = (V_{sm} - I_{sm}R_{sm} - DV_{dc}) \quad (3.22)$$

where L_{sm} is the SMES inductance, I_{sm} is the SMES current, V_{sm} is the SMES voltage, V_{dc} is the DC-link voltage, and D is the duty cycle of the SMES buck/boost

3.6 DC Link Model

The DC-link is used to transport power generated by renewable sources to the grid-side converter. At the DC-link node shown in Fig (2), the dynamic mathematical model of the DC-link voltage is obtained below as it was explained in [82]

$$C_{dc} \frac{dV_{dc}}{dt} = I_{fdc} + I_{pv} + I_{sdc} + (1 - D)I_b - Igdc \quad (3.23)$$

Where I_{sdc} , is the DC output current of the renewable sources converter as well as I_{fdc} and I_{pv} . Respectively, V is voltage of the SMES, D is known to be duty cycle, C_{dc} is the DC-bus capacitance, and $Igdc$ is the DC current input of the grid side converter.

3.7 Grid Side Converter

The grid side converter in our model is what converts the DC electricity into the AC shape. It can be expressed as the following:

$$V_d = U_d - L_f \omega_g I_q + R_f I_d + L_f \frac{dI_d}{dt} \quad (3.24)$$

$$V_q = U_q - L_f \omega_g I_d + R_f I_q + L_f \frac{dI_q}{dt} \quad (3.25)$$

where I_q and V_q are the q-axis AC current and voltage of the gride side converter, respectively, U_d and U_q are the d-axis and q-axis voltages at the point of common coupling (PCC), L_f and R_f are the grid-side filter inductance and resistance, respectively, and g is the electrical angular speed.

3.8 VSG Model

The Virtual Synchronous Generator is mostly used in the renewable energy integration with the AC grid due to RESs lacking the inertia that exist in the synchronous machine [91]. When the AC grid contains more RESs the less the inertia of the system becomes, which contributes into becoming a low-inertia power system that is sensitive and fragile to changes. Moreover, the VSG rule is to emulate the operating principal of SG to allow the system to behave as if it were a synchronous generator. It is a solution in the hope to resolve the low inertia power systems. It is based on the droop characteristics of real power and frequency (P-w) and reactive power and voltage amplitude (Q-V).

The characteristics of droop control and their profiles are shown in Fig(4.5).

$$P = \frac{3}{2}(V_d I_d + V_q I_q) \quad (3.26)$$

$$Q = \frac{3}{2}(V_d I_q - V_q I_d) \quad (3.27)$$

Where P is real power, Q is the reactive power, I_q and V_q are the q-axis AC current and voltage of the grid side. Respectively, I_d and V_d are the d-axis voltage and current at the point of common coupling (PCC)

3.9 Particle Swarm Algorithm

Though the control scheme of the VSG will be enhanced by using Particle Swarm Optimization (PSO) algorithm for a better performance than the current droop control VSG with virtual inertia. The approach of using the particle swarm optimization algorithms is to enhance the response of the VSG. The VSG controller will be running first to generate enough data and observe the response of the controller in terms of robustness of response. Then, we will apply the particle swarm to find the optimized values for the virtual inertia to all the VSG to outperform. The algorithm of particle swarm can be seen in Fig(3.2):

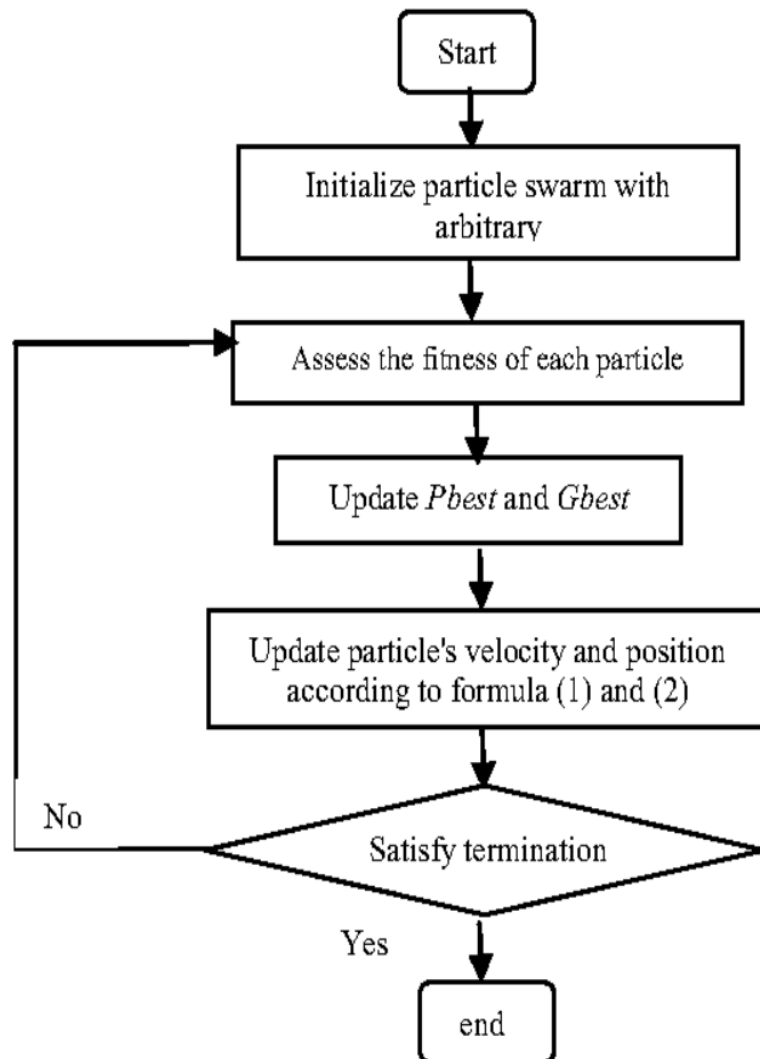


Figure 3.2: PSO Algorithm Procedure

CHAPTER 4

PROPOSED CONTROLLER

4.1 Introduction

The characteristic of the current electric grid has been recently changed due to the high penetration of inverter based resources. Most of the renewable energy resources are being fed to the electric grid by inverter. The issue behind this is the lack of inertial resistance. The inverter is a static device. Therefore, it does not contain any rotating mass and offers no resistance for load changes. Unlike the inverter, the synchronous generator contains bulk of inertial resistance due to its rotating mass. The synchronous generator does not only offer a rigid electric grid but also offers reliability features such as frequency and voltage regulation.

The challenges many researchers face, is how to maintain the integrity of the electric grid provided the utilization of the RES. The fact, is the inverter based resources participate in increasing the rate of change of the frequency, which results in unstable conditions of the grid or even loss of the renewable energy resources. Further, most of the RES that are connected to the present electric grid are using Grid-Following

(GFL) methodology. The GFL operates in the electric grid by obtaining the voltage angle from the grid by the PLL, which help the GFL to regulate its power. However, the GFL does not take part in the load sharing or frequency regulation due to its mechanism [92]. Due to the disadvantage of the GFL, grid-forming (GFM) scheme is more favourable due to addressing the issues of GFL. In addition, GFM is equipped with synchronous generator control with virtual inertia to act such as a regular synchronous generator.

4.2 Benchmark Controller

In our simulation, a benchmark model is used to allow for comparison of the results of the proposed controller and the regular controller. Therefore, the benchmark controller is on the grid-forming principal, which is the same controller in our work. Furthermore, the benchmark model is taken from the IEEE paper, which studies a microgrid stability and control [93].

The controllers parameters in the benchmark paper are as follows:

Benchmark VSG Voltage Controller	
Parameters	Value
K_p	0.29
K_i	595
D_i	0.606

Table 4.1: Benchmark VSG Voltage Controller

Benchmark VSG current Controller	
Parameters	Value
K_p	59.97
K_i	1570
D_i	0.606

Table 4.2: Benchmark VSG current Controller

Benchmark VSG Droop Controller	
Parameters	Value
nq	0.003
mp	0.00005

Table 4.3: Benchmark VSG Droop Controller

Since the benchmark paper and our work use the droop controller, the equations of the proposed controller apply to the benchmark. The difference between the two droop controllers is the use of PSO algorithms that is applied to the proposed VSG. There is not any change to the system parameters of the PV, fuel cell and the SMES as they remain the same throughout the comparison of the two controllers.

4.3 Proposed Controller

Our proposed controller in this work is a modified Virtual Synchronous Generator. There has been many doubts about the VSG controller in the sense of getting rid of its advantage to offer fast response. In our work, we propose the VSG that offers fast response, stability and frequency regulation.

The VSG is based on Droop controller and the theory of the droop can be seen in the Fig (4.3), to allow for detailed explanation. Also, the equations of the dual loop

of VSG are as per the below:

$$I_d^* = (K_{pvd} + \frac{K_{ivd}}{s})(V_d^* - V_d) - \omega C_f V_q + I_d \quad (4.1)$$

$$I_q^* = (K_{pvq} + \frac{K_{ivq}}{s})(V_q^* - V_q) - \omega C_f V_d + I_q \quad (4.2)$$

$$V_{sd}^* = (K_{pcd} + \frac{K_{icd}}{s})(I_d^* - I_{sd}) - \omega L_f I_{sq} + V_d \quad (4.3)$$

$$V_{sq}^* = (K_{pcq} + \frac{K_{icq}}{s})(I_q^* - I_{sq}) + \omega L_f I_{sd} + V_q \quad (4.4)$$

Where K_{pvd} , K_{ivd} are the proportional gain for the voltage controller in the d-axis and the integral gain of the voltage controller in the d-axis respectively. K_{pvq} and K_{ivq} are the proportional gain for the voltage controller in the q-axis and the integral gain voltage controller in the q-axis. Further, K_{pcd} is the proportional gain for the current controller in the d-axis, K_{icd} is the integral gain for the current controller in the d-axis, K_{pcq} is the proportional gain for the current controller in the q-axis and K_{icq} is the integral gain for the current controller in the q-axis. V , V_s , C_f , L_f , I_s and I are the capacitor voltage, inverter output voltage, filter capacitor, filter inductor, stator current and load current.

The VSG mathematical model is represented in the droop method incorporating the famous swing equation shown in Eq(4.5);

$$J \frac{\partial(w - w_g)}{\partial t} = \frac{P_{ref} - P}{w} - D(w_g - w) \quad (4.5)$$

where the P_{ref} and P denote the reference power and the real power output; respectively, J , w_g , w , and D are the virtual inertia of the VSG, angular frequency from the grid side (reference frequency), angular frequency output and the droop coefficient. It is crucial to show the control block of the real power and reactive power. Fig (4.2& 4.5) show the parameters of the control blocks of the complete VSG. The proportional integral controller here are optimized by the PSO algorithm which will be explained later.

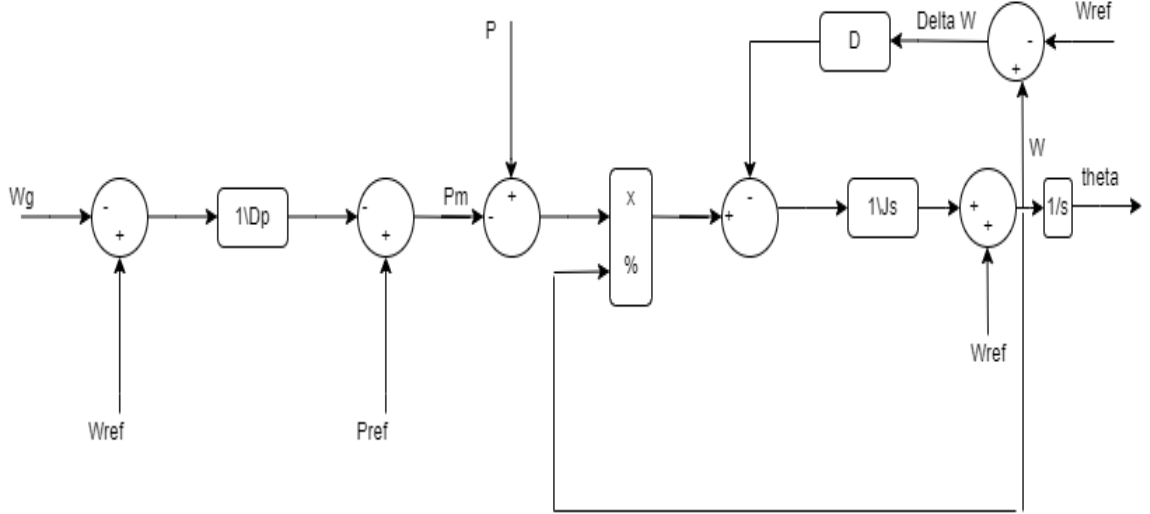


Figure 4.1: Real Power VSG Control Block

In order for the VSG to be functioning accurately, it calculated the grid frequency, real power P and reactive power Q from the outer loop voltage, inner loop current by the frequency and measuring the signals. The park transformation is essential in

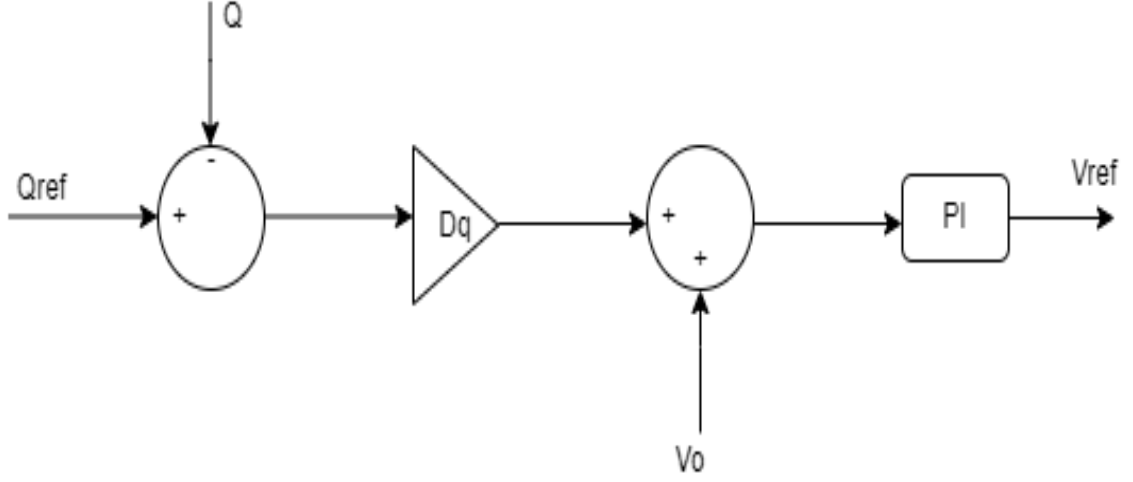


Figure 4.2: Reactive Power VSG Control Block

the control scheme as it transforms the 3ϕ to dq - axis [94]. The current and voltage signals is utilized in VSG as a monitoring and measurement device, where the angular frequency can be obtained. The measurements of the real power and active power is represented in Eq(3.26)(3.27):

The dual loop of the VSG is allowing for the a better control as it has superior measurements. The outer loop is voltage and the inner loop is current and it can be seen in the below Fig(4.4):

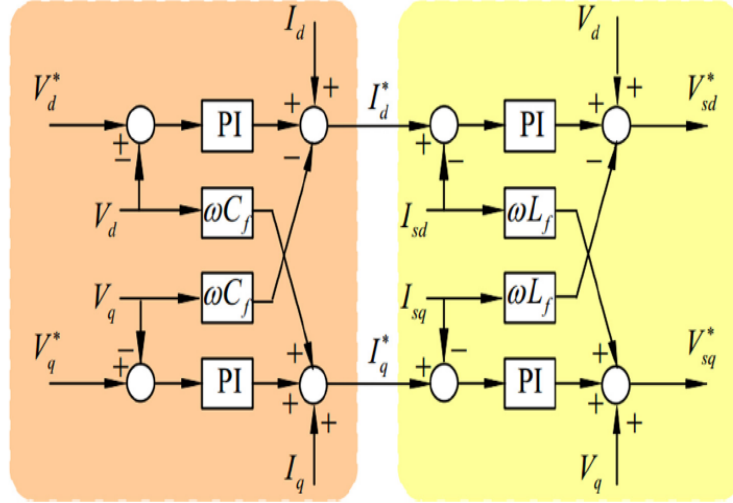


Figure 4.3: Voltage and Current Loops of the VSG

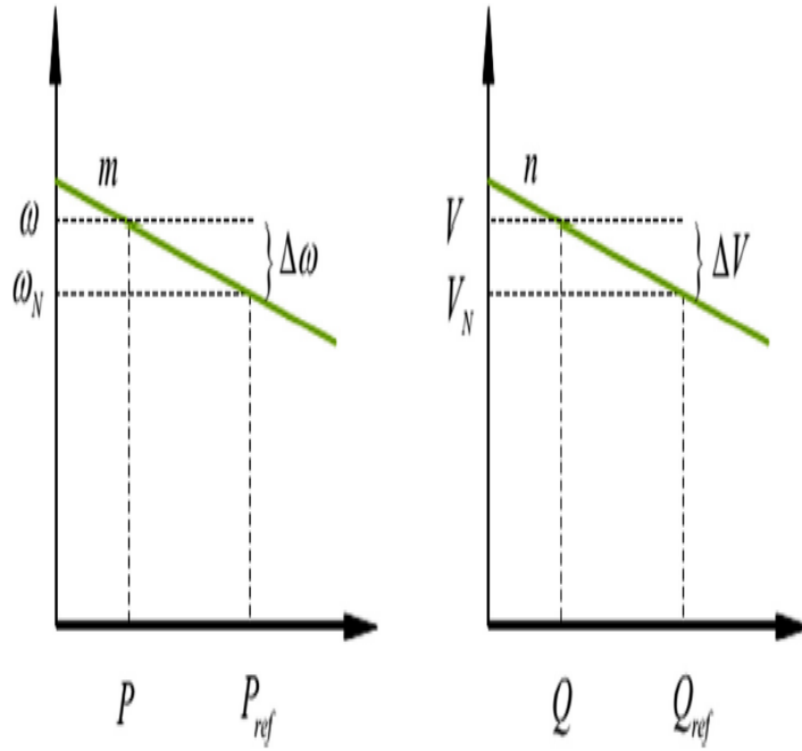


Figure 4.4: VSG Droop Behavior

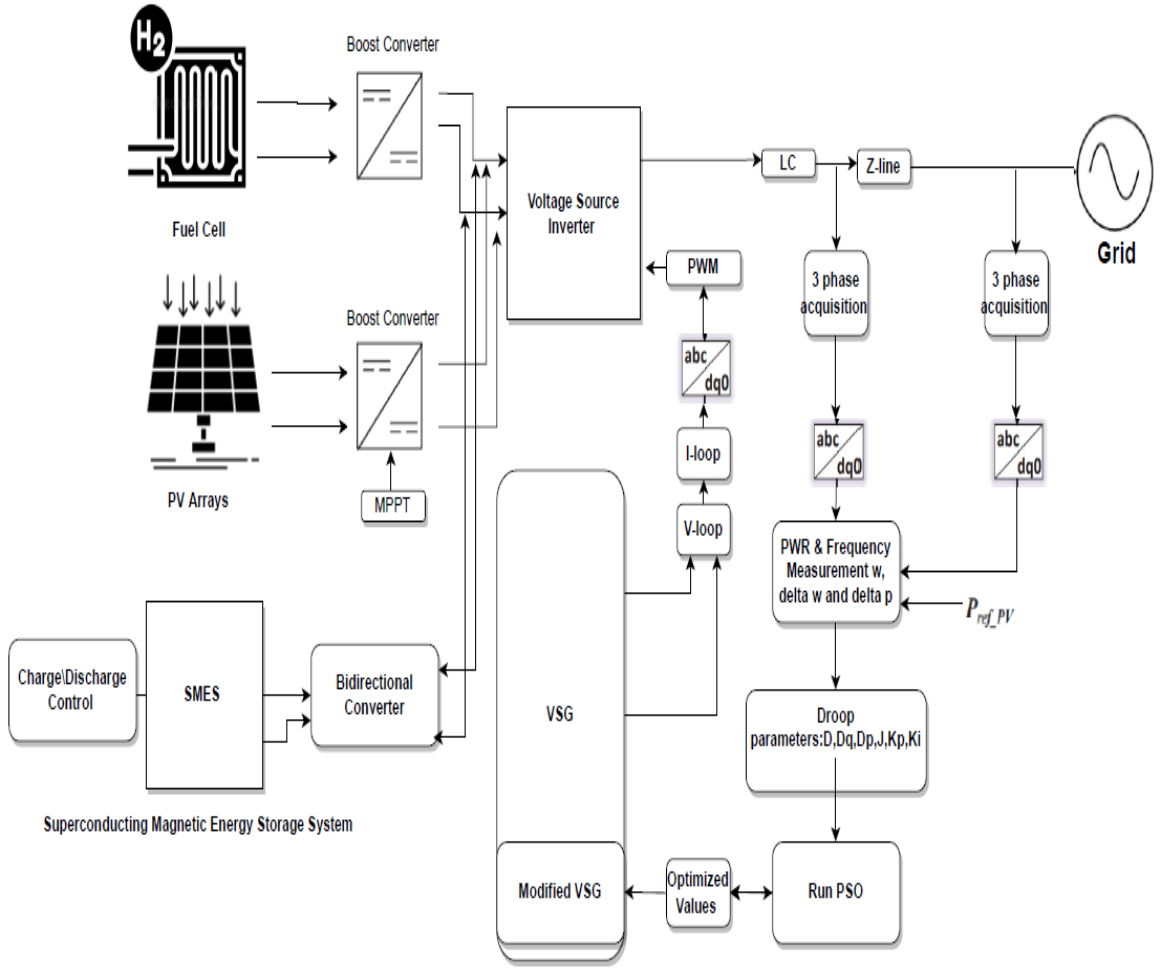


Figure 4.5: VSG control with PSO Algorithm

The PSO algorithm is applied to the dual loop in this research to optimize the performance of our modified VSG. The reason behind the PSO deployment is the accurate tuning of the PID controller. Tuning by the PID is proven to enable accurate parameters that enhance the operation of the controller [95]. The equations for the PSO algorithm can be seen in the below along with the objective function.

$$V_i^{kg+1} = w(t) + V_i^{kg} + c_1 r_1 (P_i^{kg} - X_i^{kg}) + c_2 r_2 (bestS_i^{kg} - X_i^{kg}) \quad (4.6)$$

$$X_i^{kg+1} = X_i^{kg} + V_i^{kg} \quad (4.7)$$

Where r_1 and r_2 are random values between 0-1, $g = 1, 2, \dots, G$, $i = \text{populationsize}$. c_1 and c_2 are the local learning factor and the global learning factor. The c_2 parameter is commonly bigger than the c_1 . Further, the Objective function used in the PSO algorithm is the Integral of Time-weighted Absolute Error (ITAE), which can be seen in Eq(2.8):

$$ITAE = \int t | e | dt \quad (4.8)$$

PSO Algorithm	
Parameters	Value
Variables	3
Particles	50
Number of iterations	100
r_1	0.2
r_2	0.5
Local fitness significance factor	2
Global fitness significance	10

Table 4.4: PSO Optimization Parameters

Regular VSG VS Enhanced VSG		
Parameters	Regular VSG	Enhanced VSG
Frequency	Fixed	Dynamic
Damping	Yes	Yes
Inertia	Yes	Yes
Power-Deliver	Fixed ref	Variable ref
P- ω droop	Static-Dynamic	Dynamic
Q-V droop	Yes	Yes

Table 4.5: VSG Comparisons

PV VSG	
Parameters	Value
P_{ref}	1MW'
V_{ref}	320KV
ω_{ref}	$2\pi \cdot 50$
f_n	50Hz
R1	0.005
L1	0.15
C1	0.06
V_{dc}	640

Table 4.6: VSG Parameters for PV Arrays

Tables (4.1), show the PSO parameters that are used in the optimization of the VSG PI controller. Table (4.2) is mainly a comparison between the regular VSG and the proposed VSG. Tables (4.3-4.5) are the parameters for each generating source in the network.

Fuel Cell VSG	
Parameters	Value
P_{ref}	0.5MW
V_{ref}	320KV
ω_{ref}	$2\pi \cdot 50$
f_n	50Hz
R1	0.005
L1	0.15
C1	0.06
V_{dc}	640

Table 4.7: VSG Parameters for Fuel Cell

SMES VSG	
Parameters	Value
P_{ref}	0.8MW
V_{ref}	320KV
ω_{ref}	$2\pi \cdot 50$
f_n	50Hz
R1	0.005
L1	0.15
C1	0.06
V_{dc}	640

Table 4.8: VSG Parameters for SMES

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 Simulation Results

In this section, an explanation of the simulation will be addressed accurately to allow for full comprehension of the difference between the proposed VSG and the regular IEEE VSG. Further, the simulation is done thru three main parts, which are 1. testing of the proposed VSG vs regular VSG during load increase 2. testing of proposed VSG vs regular VSG during fuel cell fault 3. discharging of SMES in proposed controller when fuel cell fails 4. charging and discharging of SMES

5.1.1 Case 1: Comparison Between Proposed VSG and Regular VSG During Load Increase

The first case contains the successful simulation of the proposed VSG that is optimized by particle swarm algorithms. The provision of a regular VSG was also simulated to show the difference. The results can be compared in the below figures along with a

detailed explanation of how the conditions of the simulation were made.

The simulation in this part consist of two results of power and frequency of the system. The IEEE model is presented first and following the results of the proposed controller. The PV/fuel cell/SMES configuration are connected to the grid with a nominal frequency of 50Hz and a nominal power output of each source at 0.62 p.u. The intention of this simulation is to observe the behavior of the both the IEEE controller and proposed controller when a sudden load increase is presented. Therefore, a 100KW load is introduced at $t=1.5s$ to $t=2.5s$. The simulation results of the IEEE controller and proposed controller can be seen in Fig(5.1-5.4)

Optimized VSG Voltage Controller	
Parameters	Value
K_p	0.52
K_i	1.161022
D_i	0.707

Table 5.1: Optimized VSG Current Controller

Optimized VSG Current Controller	
Parameters	Value
K_p	0.73889
K_i	1.19
D_i	0.707

Table 5.2: Optimized VSG Voltage Controller

Optimized VSG Droop Controller	
Parameters	Value
nq	0
mp	0.02

Table 5.3: Optimized VSG Droop Controller

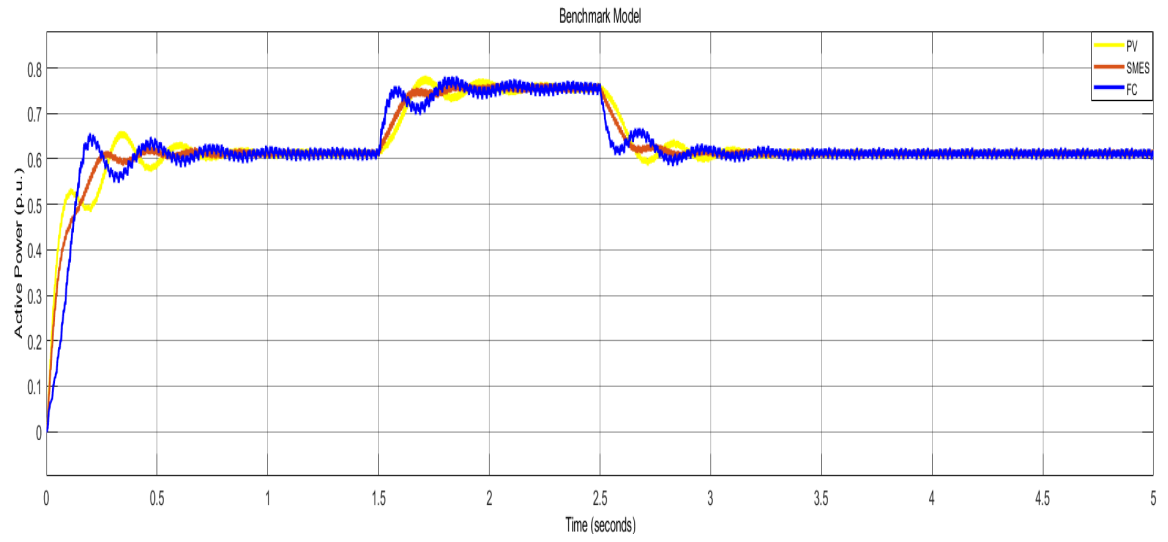


Figure 5.1: P IEEE VSG

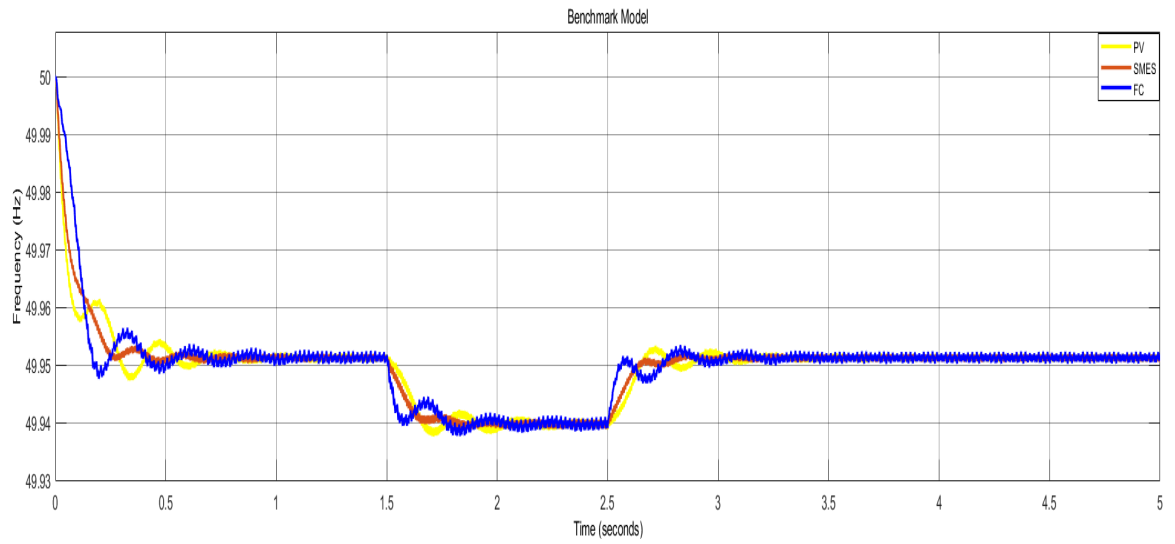


Figure 5.2: f_n IEEE VSG

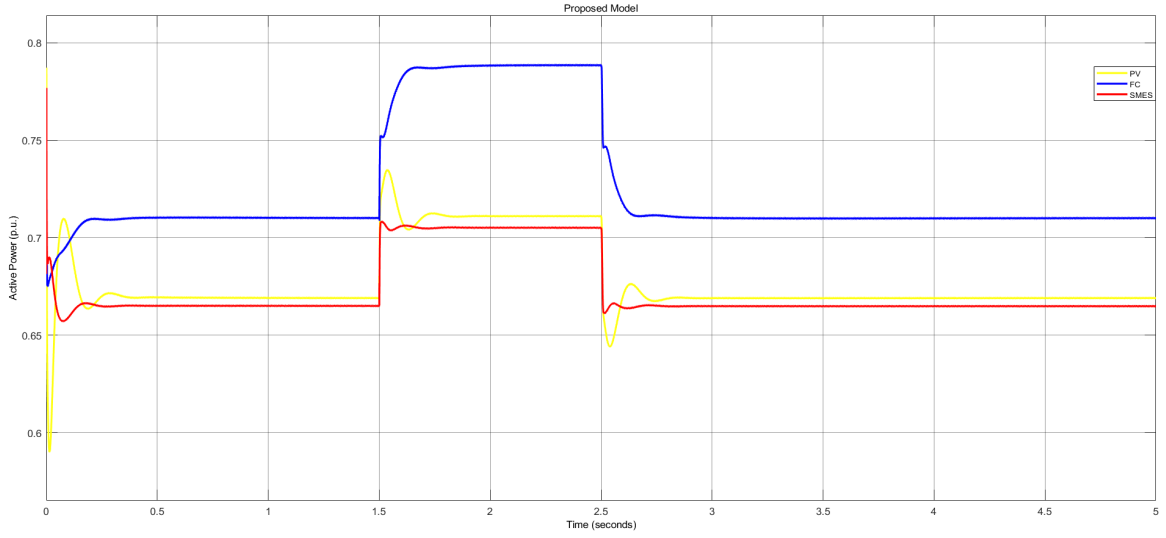


Figure 5.3: P Proposed VSG

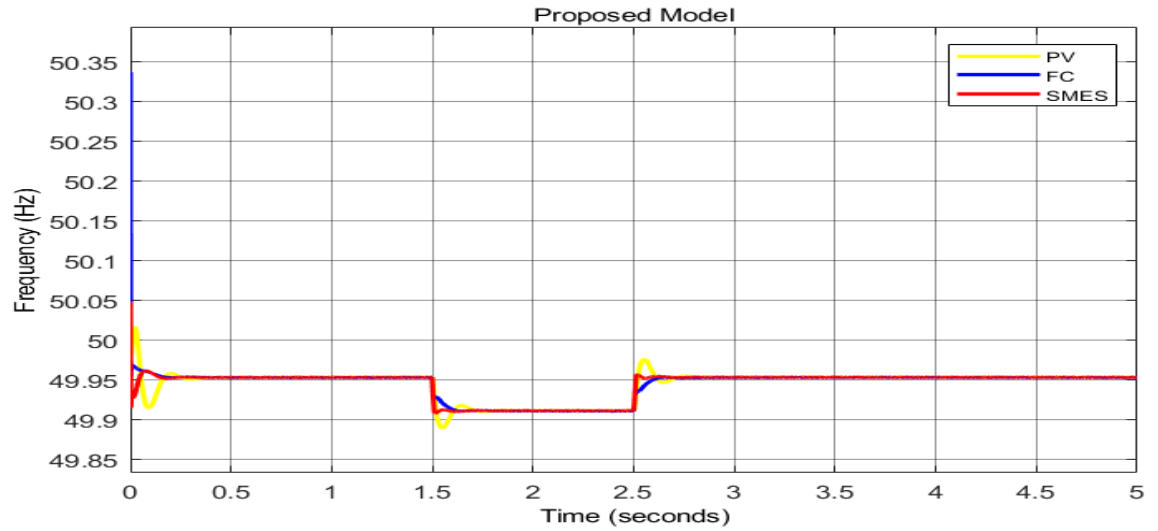


Figure 5.4: f_n Proposed VSG

From the results above, the IEEE VSG shows slow response as compared with the proposed VSG. The raise time of the controller to reach the reference point of power

and frequency takes 1 second to reach steady state condition. It is also observed that there are some oscillation at the start of producing power that affect the quality of the power produced as well as the frequency of the grid. When the load is introduced at $t=1.5s$, we noticed that the IEE VSG is responding to the change in the power load and adjust its output power accordingly. But, the response of the IEEE VSG remains inferior to the proposed controller. On the other hand, Fig(5.3&5.4) show the output power and frequency of the proposed VSG. It is noticed that the settling time of the proposed controller is robust, fast and smooth. There aren't any oscillation as compared with the IEEE VSG that is due to the optimization of PSO. Similarly, the output power and the frequency regulation is adjusted faster to meet the required load at $t=1.5s$ to $t=2.5s$. The settling time is almost instant and the controller reach steady state in less than 0.3 seconds.

In conclusion, the proposed VSG outperformed the IEEE VSG in terms of better response in order to provide instant stability to the frequency. The IEEE VSG response was slower than the proposed VSG even though it had the capability of power sharing and frequency regulation. In the proposed VSG, the power sharing is not divided equally between the sources due to having different power angles as compared with the IEEE VSG.

5.1.2 Case 2: PV, Fuel Cell and SMES Faults and Stability

This case presents a simulation that is consisting of the PV, fuel cell and SMES all operating at the reference power output of 0.62 p.u. and a nominal frequency of 50Hz. The simulation is constructed to test the ability for two sources to share the load and regulate the frequency in case of a failure of one the sources. Hence, the simulation of fuel cell fault is carried out at $t=2.5$ s to observe the changes that happen to the IEEE VSG and our proposed VSG. The results of the simulation can be seen in Fig(5.5-5.8):

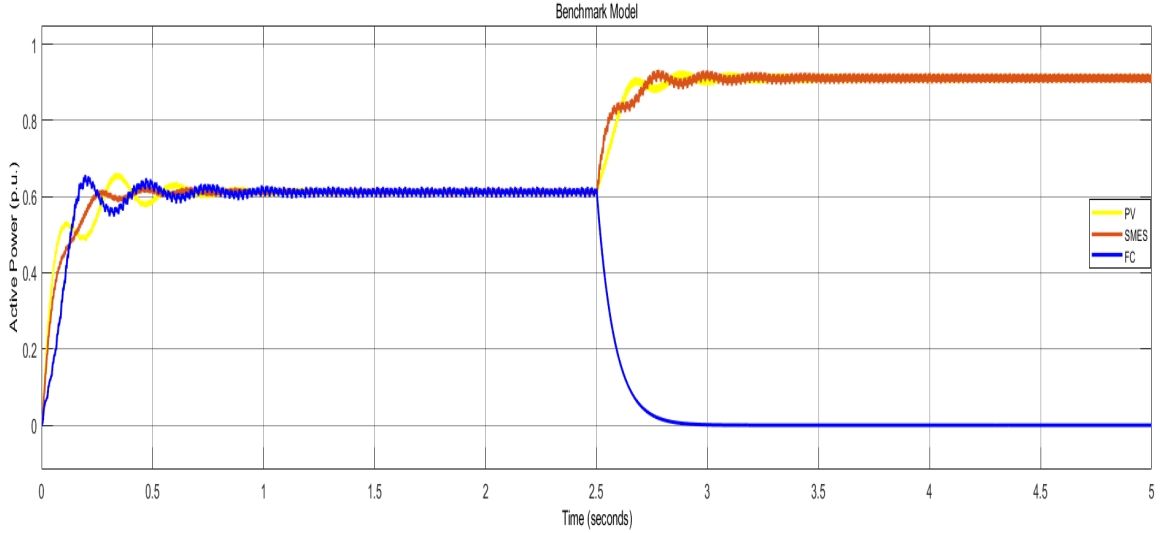


Figure 5.5: P IEEE VSG

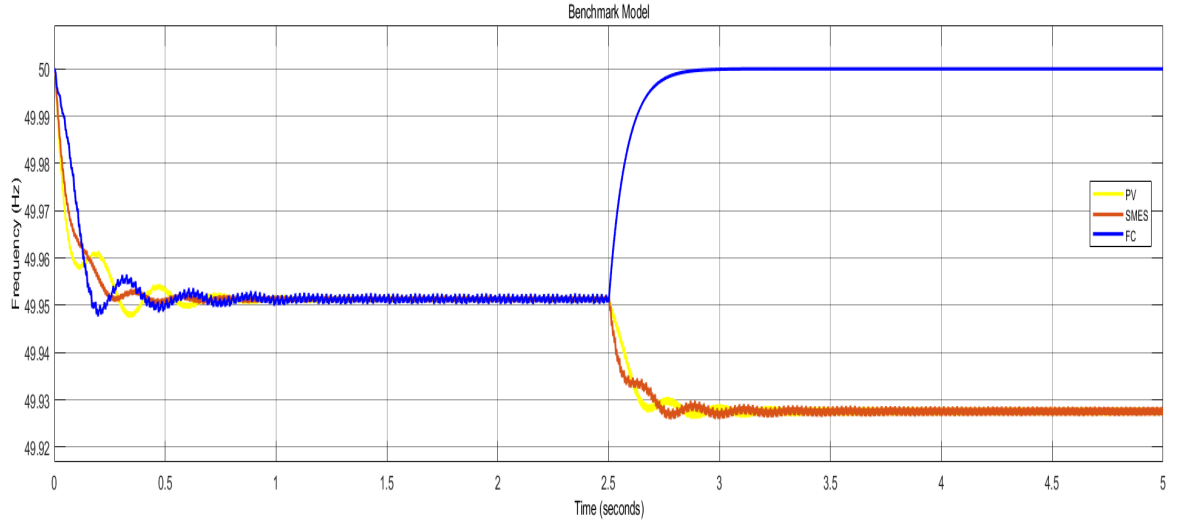


Figure 5.6: f_n IEEE VSG

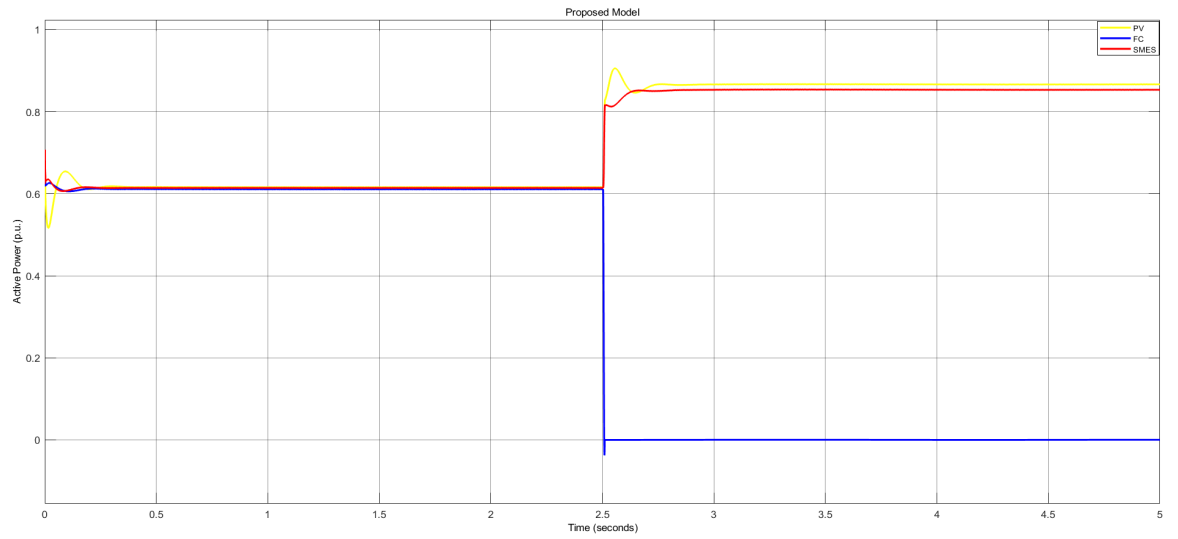


Figure 5.7: P Proposed VSG

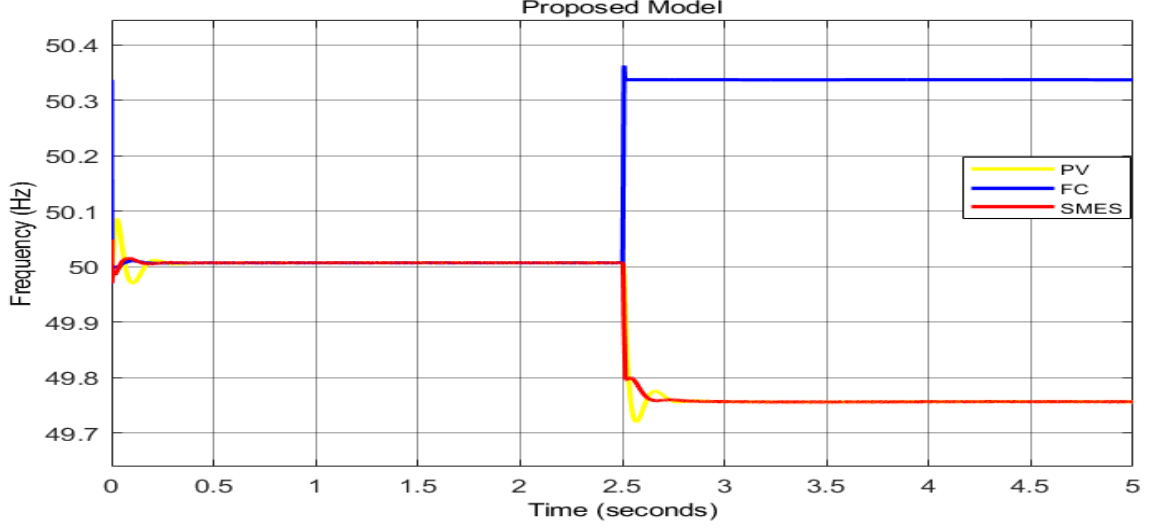


Figure 5.8: f_n Proposed VSG

From the above simulation results, we notice that the proposed VSG obtained promising results in terms of fast response. When the fault of fuel cell occurred at $t=2.5s$, the PV and SMES immediately increased the output power in order to meet the demand of the load. When a loss of generation happens, the frequency is dropped due to an increase of the load demand that the generations need to meet. Therefore, the faster the response to the new reference power the better the stability of the system. The IEEE VSG responded to the new load demand by increasing the output power, but the response is observed to be slower than the proposed VSG as the frequency of the system experienced oscillation until it reached stable condition at $t=3.4s$. Fig(5.7) shows the power output of the proposed VSG that have an instant compensation of power almost instantly from SMES and PV systems. At $t=2.7s$ the proposed VSG provided the new required power to compensate for the loss of fuel cell, which is a

short time to regulate the system. At $t=2.5s$ the PV system on the proposed VSG reflected a minor peak in power, which is negligible due to having no major impact on the stability of the system. Further, at $t=2.7s$ the frequency is at steady state condition, which means that the proposed VSG regulation of the frequency is highly robust.

In summary, the proposed VSG showed better results than the IEEE VSG. The raise time of the proposed VSG was shorter than the IEEE VSG as well as smoother. When the fuel cell failed at $t=2.5s$ the proposed VSG took 0.3s to regulate the system stability, where the IEEE VSG took 1s. Though the IEEE VSG demonstrated frequency regulation during the disturbance, the results were slower with oscillation that were not desired. Therefore, the proposed VSG outperformed due to faster response and smoother regulation due to the PSO optimization controllers parameters.

5.1.3 Case 3: System Stability Through Discharging of SMES

In this part, we test the smooth charging and discharging of the energy storage system we propose, which is the SMES. Though the PV and fuel cell are able to withstand the load change and the disturbances as simulated in the first 3 cases, the SMES testing is crucial to assure that if the two previously mentioned system have reached their maximum operating limits. The SMES can compensate to insure the reliable operation of the proposed system.

This simulation shows the PV and Fuel Cell resources are operating at full capacity from $t=0s$. The fuel cell and PV systems are only producing power, where the SMES

is in the charging state. The purpose of the simulation is to ensure the participation of SMES to regulate the voltage and frequency when there is a fault or a disturbance. Due to the fuel cell and PV systems being operating close to their threshold limit i.e. 0.9 p.u. any disturbance that will occur, can jeopardize the stability of the system. Therefore, a fault to the fuel cell is simulated at $t=2.5s$, which triggers the immediate dispatching of SMES to compensate for power and arrest the frequency. The simulation is carried out for the IEEE controller as well as the proposed controller. The results of the simulation can be seen in Fig(5.9-5.12):

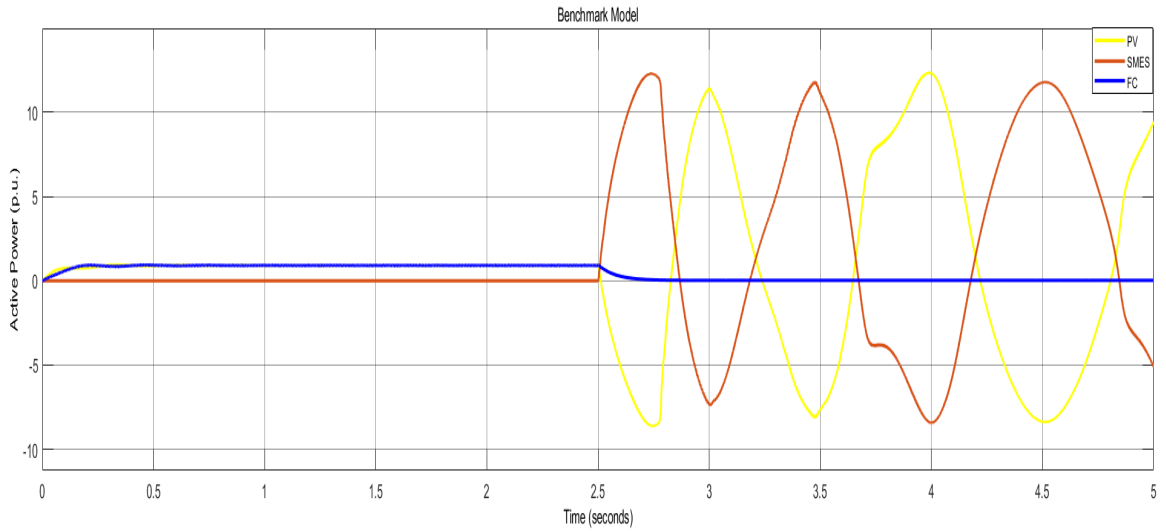


Figure 5.9: P IEEE VSG

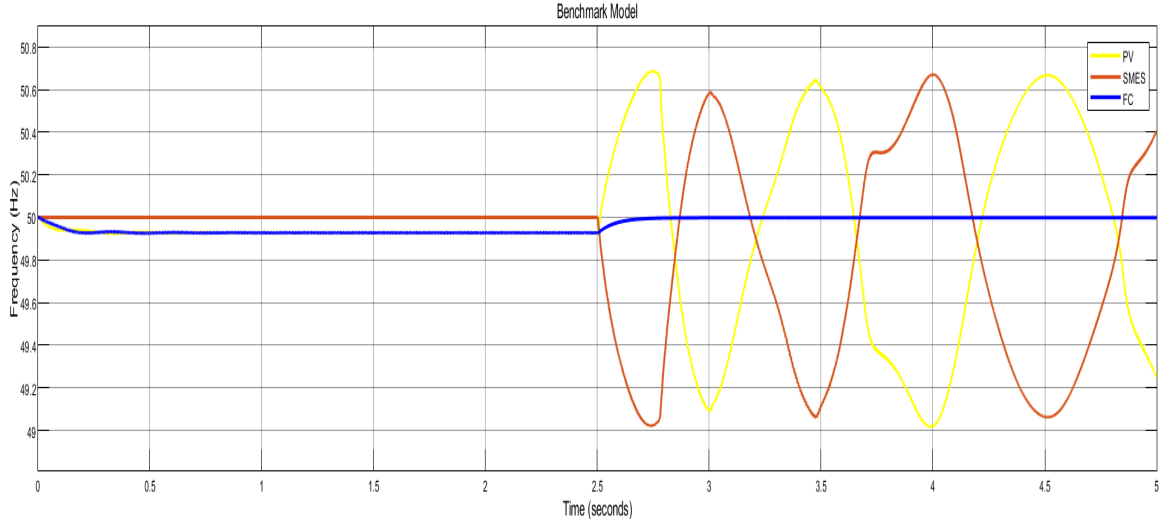


Figure 5.10: f_n IEEE VSG

From the graphs above, we can see the loaded operation of the PV and Fuel Cell from $t=0$ s to $t=2.5$ s where the frequency was below the nominal frequency of 50Hz due to the heavy load. The SMES is in the charging state from $t=0$ s to $t=2.5$ s. Once the fuel cell failed at $t=2.5$ s, the SMES is dispatched to regulate the frequency as it was dropping below the acceptable limit of 49.5Hz. However, due to the slow response of the IEEE controller, the system failed to maintain stability and the PV and SMES generation was altered. Major oscillation was observed and the system is said to be out of synchronization due to the major fluctuation in power and frequency.

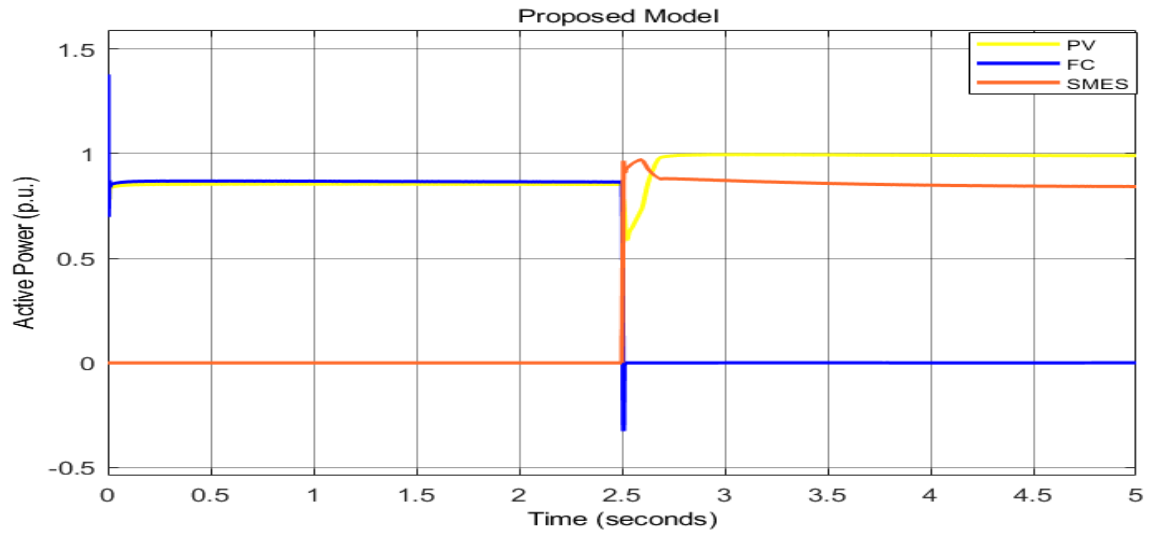


Figure 5.11: P Proposed VSG

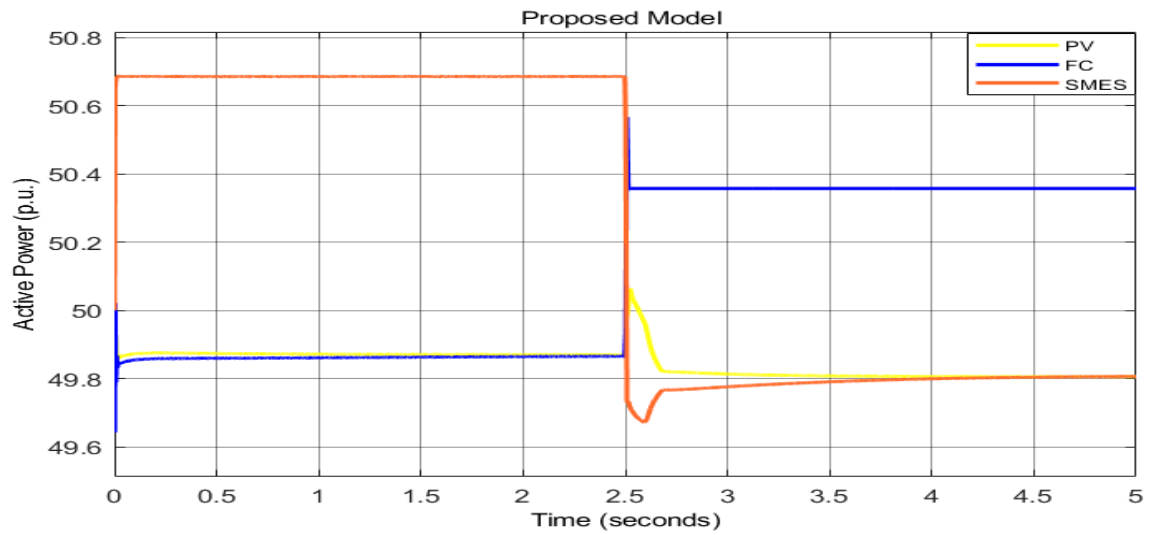


Figure 5.12: f_n Proposed VSG

From Fig(5.11&5.12) the simulation results of the proposed VSG is shown. The same conditions of the simulation of the IEEE VSG is applied. The fault of the fuel

cell at $t=2.5s$ triggered the dispatching of SMES successfully. From Fig(5.11), the PV experienced a short decrease of power production that is due to the failing of fuel cell. The decrease of power was only for less than 0.1s, which is acceptable. Similarly, the SMES output power after the failing of fuel cell reached maximum power production to compensate for the power loss from fuel cell. Then, the output power of the SMES reduced due to sharing the load with the PV. From Fig(5.12), the frequency was able to be maintained within the acceptable limits even though the grid is said to be in weak condition. At $t=2.5s$, the frequency of SMES dropped from 50.6Hz to 49.7Hz due to the disturbance caused by the fuel cell failure and generating large amount of power to ensure the load demand is met. The PV frequency also experienced a minor disturbance that occurred at $t=2.5s$. Fortunately, the PV frequency was not affected because it was regulated by the SMES.

The simulation in this part showed that the proposed controller is able to regulate the frequency and ensure the stability of the system when compared to the IEEE controller. Despite the minor disturbance of power and frequency that was experienced by the proposed controller, the system was stable. Unlike the proposed VSG, the IEEE VSG did not maintain the stability of the system as seen in Fig(5.9&5.10). The frequency and the power were swinging significantly, which made the renewable energy sources fall out of synchronization. In essence, the proposed VSG had shown better results in terms of stability and frequency regulation, where the IEEE could not maintain the stability due to the slow response.

5.1.4 Case 4: Charging/Discharging of the SMES

In this section, the smooth charging and discharging of the SMES is simulated. The purpose of the simulation is to employ the charging and discharging of the energy storage system as per the requirement of the grid frequency. The SMES is responsible for frequency regulation as well as stability of the system. Therefore, the simulation consists of a disturbance at $t=1.2\text{s}$ that caused a significant drop to the frequency of the system. The SMES parameters is set to discharge if the frequency is below 49.9Hz and charge if the frequency is above aforementioned value. The simulation results can be seen in the figures below:

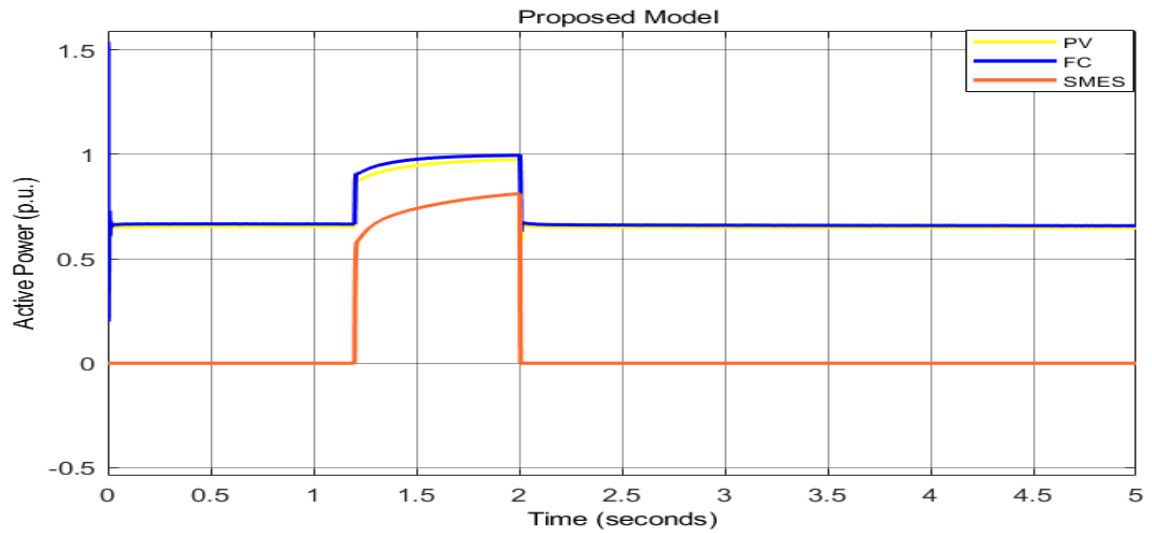


Figure 5.13: Charging/Discharging of the SMES

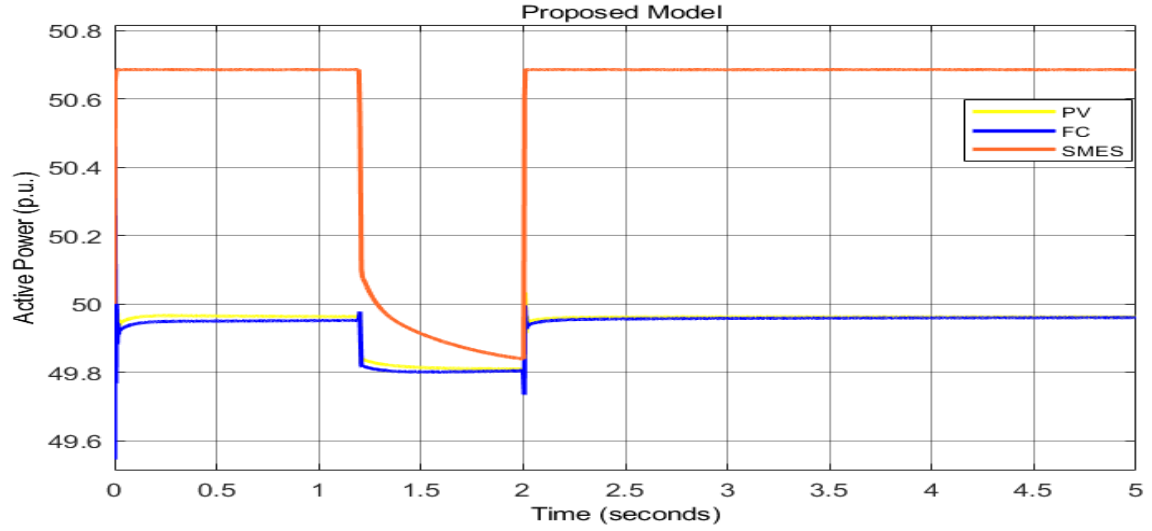


Figure 5.14: Charging/Discharging of the SMES

The simulation of the charging/discharging of the SMES showed promising results in terms of fast regulation of frequency. The disturbance at $t=1.2s$ caused a drop in frequency as well as increase in the power output. The SMES engaged to regulate the frequency as well as provide stability to the system. At $t=2s$ the disturbance is cleared, which allowed the SMES to disconnect from the grid and start charging again. In conclusion, the SMES smooth charging and discharging as shown in Fig(5.13&5.14) is satisfactory to the stability and frequency regulation of the system. the response of discharging was robust to regulate the frequency in prompt manner without any unbalance to the grid. Further, the power compensation was adequate, which eliminated the failing of PV and fuel cell.

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

The renewable energy resources are the ultimate solution to solve the current climate change problem. There has not been a time that is more favorable to shift from the conventional fossil fuel-based resources than now. The renewable energy resources offer various of well-constructed applications. Despite their early inventions and theoretical observations dating back to the 19th century, their applications have begun to be utilized appropriately. Moreover, the obstacles facing the RESs are typically their operating mechanism that depends on the weather mostly. Even with most precise weather predictions instruments, the weather remains unpredicted. This participates in the instability issues of the RES making it less favorable choice compared to the fossil fuel. On top of the instability issues, the intermittency factor plays a crucial role.

The technology of the renewable energy has progressed to tackle all the existing issues from intermittency, instability to lack of inertia. The Grid-Following was introduced first to allow for the RES to be integrated with the electric grid. The definition of the grid-connected RES remains a huge area to be explored since the grid-following control participates in making the electric grid unreliable. As there are many works dedicated to the enhancement of the GFL converters, GFL based VSG has been proven to outperform it. Further, the GFL currently dominating all the RES applications that are deployed, where VSG is rarely applied. The advantages of the GFM VSG are the capability of load sharing, frequency, and voltage regulation.

In our work, regular VSG and optimized VSG are discussed in details to show their operating conditions, advantages and disadvantages. The use of regular VSG is based on an IEEE paper with the droop control parameters implemented without optimization. On the contrary, the proposed controller used in this work is based on Virtual Synchronous Generator. The VSG is mimicking the behavior of the Synchronous Generator with emulated inertia. The advantage of emulating inertia is to allow for reducing the ROCOF, which cause instability issues. Also, the VSG controls the output real power and active power the same as synchronous generator with the most accurate results compared to regular VSG. The PSO algorithm is applied to optimized the droop parameters of the VSG to allow for faster response and robust control.

The simulations show PV, Fuel Cell and SMES applications that are grid connected with variable load. Each source of the previously mentioned is connected to a VSG. The tests of the simulation include comparison of the regular VSG and optimized VSG,

comparison of benchmark and optimized VSG controllers under many conditions such as load increase and network faults. The proposed VSG controller showed successful results as it outperformed the regular VSG controller. From the simulations we notice that the VSG participated in stabilizing the grid with support of frequency regulation voltage regulation, where the regular VSG collapsed failing to assist the electric grid.

6.2 Future Works

In this work, the successful implementations of the VSG that is optimized by PSO showed promising result but it can be further enhanced. There are many artificial intelligence algorithms that has not been proposed to the VSG as of now. The future work shall include experimenting with different AI techniques to test if the response of the VSG can show even better results than what is obtained in this work.

As the emulated inertia is crucial part of the VSG, the future work will focus on manipulating the inertia constant in a variable method to obtain more stability to the grid. The issues with emulated inertia is if the constant is large number it can cause the inverter to respond slowly, which does not take the advantage of the fast response of the inverter.

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