INVESTIGATION ON THE EFFECTIVENESS OF INTEGRATED FACTS-FUEL CELLS IN TREATING THE POWER QUALITY ISSUES IN HYBRID POWER SYSTEMS

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A project report submitted in partial fulfillment of the requirements for the award of Master of Engineering (Electrical)

Faculty of Engineering and Science

Universiti Tunku Abdul Rahman

MAY 2017

DECLARATION

I hereby declare that the dissertation is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"INVESTIGATION ON THE EFFECTIVENESS OF INTEGRATED FACTS-FUEL CELLS IN TREATING THE POWER QUALITY ISSUES IN HYBRID POWER SYSTEMS"** was prepared by FOO KOK YUN has met the required standard for submission in partial fulfillment of the requirements for the award of the degree of Master of Engineering (Electrical) at Universiti Tunku Abdul Rahman.

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ABSTRACT

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Foo Kok Yun

Due to the trend of decentralizing grid transformation, renewable energies are greatly utilized to be the alternative green sources to achieve a low carbon electricity industry. Most of them were integrated at the distribution network and as a result they pose challenges in stability and security of such hybrid power system in terms of Power Quality (PQ) problem. Distribution Static Synchronous Compensator (D-STATCOM) which is part of the FACTS family has received great attention in this aspect due to its excellent voltage regulation ability from its reactive power compensation in the hybrid power system. The study focuses on alleviating the voltage problems of the hybrid power system which sourced from PV system by utilizing the reactive power compensation from D-STATCOM. The proposed D-STATCOM here is able to stabilize the 25 kV grid voltage from 0.967 p.u to 1 p.u. and reduce voltage fluctuation from ±1.4 % to ±0.3 %. Furthermore, the D-STATCOM performance can be enhanced by equipping Energy Storage System (ESS) so that it can provide both real and reactive power compensation simultaneously and independently in hybrid power system. Battery Energy Storage System (BESS) is one of the most mature technologies but it comes with the drawback of hazardous to the environment and short life span. Fuel cell is another alternative ESS that is environmental friendly and innovative in the field. The enhancement of D-STATCOM was investigated in this study by equipping the Proton Exchange Membrane (PEM) fuel cell as the ESS. The performance of fuel cell integrated D-STACOM was intended to be compared with BESS in order to quantify the effectiveness of fuel cell technology in alleviating voltage problems since BESS has been proven useful in many other research works. The BESS integrated D-STATCOM is able to reduce the amount of grid voltage drop from 12% to 3.7%. The future enhancement of the work was suggested accordingly to close the gap.

ACKNOWLEDGEMENTS

I would like to acknowledge and thanks everyone who had contributed to the successful completion of this project. I would like to take this opportunity to register my sincere gratitude to my project supervisor, Dr. Stella Morris for her invaluable advice, guidance and patience throughout the development of the project.

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LIST OF ABBREVIATIONS / GLOSSARY

BESS	Battery Energy Storage System
DAB	Dual Active Bridge
DAB3	Three Phase Dual Active Bridge
D-STATCOM	Distribution Static Synchronous Compensator
ESS	Energy Storage System
FACTS	Flexible AC Transmission System
FPT	FRYZE Power Theory
HV	High Voltage
IGBT	Insulated Gate Bipolar Transistor
IGCT	Integrated Gate Commutated Thyristor
IRPT	Decoupled Current Control (p-q) Theory
LV	Low Voltage
MPPT	Maximum Power Point Tracking
p.u.	Per Unit
PAFC	Phosphoric Acid Fuel Cell
PCM	Phase Control Method
PCT	Phase Controlled Thyristor
PEM	Proton Exchange Membrane
PLL	Phase Locked Loop
PQ	Power Quality
PV	Photovoltaic
PWM	Pulse Width Modulation
RE	Renewable Energy

SAFC	Solid Acid Fuel Cell
SC	Super Capacitor
SMES	Super Conducting Magnetic Energy Storage
STATCOM	Static Synchronous Compensator
STC	Standard Test Condition
STFT	Synchronous Reference Frame Theory
SVC	Static Volt-Ampere Reactive Compensator
VSC	Voltage Source Converter

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

This chapter introduces the need and future trend of the power grid in both Malaysia's context and global context, potential issues that arise from the changing trend and the respective controllers to alleviate the issues.

1.1.1 The Need and Challenges of Hybrid Power System

In December 2009, during the Copenhagen Climate Change Summit, the prime minister of Malaysia voluntarily agreed on achieve Green House Gas (GHG) reduction to 40% by the year 2020 compared to 2005 and reduce deforestation. From the projection of the Asia-Pacific Economic Cooperation (APEC), Malaysia, as a developing country, has a growth rate of 3.3% in energy demand between 2005 to 2015, and higher towards 2030 at the rate of 3.4%. Although Malaysia is the 3rd largest oil preserver in Asia Pacific region, it has realized that Malaysia can't solely depend on its oil resources which estimated that it only last for another 15 years and gas reserves for another 29 years. To address such urgent demand, there was a new strategy launched in the 8th Malaysia plan, called as the Five-Fuel Diversification Strategy, to promote renewable energy as an alternative energy source. Malaysia government set the target on having 5% of the electricity sourced from renewable energy, but it was failed to be achieved because there was only 0.3% projected at year 2005 (Ahmad et al., 2011).

The Malaysian Ministry of Energy, Water and Communication (KTAK) was re-formed to continue the efforts on RE promotion, which leads the born of the new functional division which is known as Ministry of Energy, Green Technology and Water (KeTTHA). KeTHHA is aimed to formulate policies, set the direction and develop efficient RE management system (Ahmad et al., 2011). Technical standards and guidelines for RE development are available, such as "Procedure for the Testing and Commissioning of Grid-Connected Photovoltaic Systems in Malaysia – Overview and Reference Standards" (SEDA, 2013), "TNB Technical Guidebook on Grid-interconnection of Photovoltaic Power Generation System to LV and MV Network" (Tenaga Nasional Berhad, 2009), Various Malaysia IEC standards for PV system (Standards Malaysia, 2005), "Handbook for Grid-Connection and Licensing of PV Installations in Malaysia"(Pusat Tenaga Malysia, 2009) and etc.

Various programs have been launched (Abanteriba and Shamsuddin, 2012) by Malaysian government to continuously promote renewable energy, such as Small Renewable Energy Power Programme (SREP), Malaysia Building Integrated Photovoltaic Technology Application (MBIPV), Biomass Grid-Connected Power Generation and Co-Generation (Biogen) and etc. SREP program aimed to promote all sort of renewable energy sources, such as biomass, biogas, solar, wind, mini-hydro and etc. Unfortunately, the SREP program was failed to achieve the target (500 MW, 5% of generation capacities) due to various barriers and the target was revised to 350 MW by year 2010 (Ahmad et al., 2011).

Despite of the under par performance, the Malaysian Government continues to put effort in the development. In the 10th Malaysia Plan (2011-2015), the goal is set to achieve 5.5% of generation sourced from renewable energy (Kardooni et al., 2016). Feed-in-Tariff was implemented in 2nd April 2010 based on the 'polluters pay concept' where consumers with high electricity bills pay more for carbon emission (Ahmad et al., 2011). All of the above information show that Malaysia is currently demanding greatly in achieving RE transformation.

Apart from Malaysia's context, the environmentally-friendly grid technologies are influencing the 21st leading economies significantly, such as Europe and China. The world is now facing major grid transformation from traditional centralized grid to decentralizing smart grid. Such act emerges a host of smart energy devices and systems which are capable to improve the grid reliability and security which promote RE generation. Series of digital information technology applications are intended to be utilized in electrical power network optimization, such as smart meters, sensors, two way communication system that allow customer to re-sale energy surplus back to utility company, rechargeable portal for electric vehicles (EV), and other features stated in the study from (Amin and Wollenberg, 2005). Such grid transformation which intended to make use of RE generation is going to be the trend of the next 20 years in worldwide context and it is estimated to result in higher productivity, lesser green-house gas (GHG) emission and better grid security (Ekanayake et al., 2012).

While Renewable Energy (RE) is playing a major role in the decentralizing smart grid transformation in both Malaysia's context and in the world, it means that the large scale of RE generators are going to be connected at distribution power system which forms the hybrid power system. A good distribution system is able to maintain healthy link between bulk and custom powers at customer end continuously. Even though RE brings environmental benefits, its intermittent nature, such as the sun irradiance variation and wind variation, has projected great challenges in maintaining the stability and security of the distribution hybrid power system in terms of deteriorating the power quality (PQ).

1.1.2 Power Quality (PQ) in Hybrid Power System

Power quality (PQ) is a term describing the deterioration in ideal sinusoidal waveforms of supply voltages or load currents at its fundamental frequency, which its value is usually the rated value in the power system. Deterioration from this aspect can result great deviation from the expected operation of the power system. One of the examples is the stability of electromechanical oscillation between alternators, which is crucial in maintaining the reliability of the power system, was affected by the intermittent nature of RE. The current quality problem that arises from sensitive nonlinear loads in the power system, such as electric arc furnaces which draw non sinusoidal currents from voltage source, is one of the examples as well. The power electronics based converters in hybrid power systems inject undesired harmonic current into the grid is a significant issue too. Furthermore, voltage quality problem can be imposed to the hybrid system with RE. The incessant power and voltage fluctuation supplied from the wind generators to the feeble grid is one of the examples of voltage quality problem (Alepuz et al., 2008). The sun irradiance intermittency causes solar power plant imposes similar fluctuation as mentioned in wind generators too (Haque, 2001).

The potential PQ problems from hybrid power system can be too wide to be covered, and it is obvious that RE is going to put up greater challenges to PQ in the grid transformation. In this thesis, the parameters relevant to voltage are interested. The figure below shows an overview of PQ by categorizing it to two groups, which are variations (voltage and current) group and events group. Such overview provides an overall picture of the terms used to describe the events that cause respective PQ problem (Carastro et al., 2008).

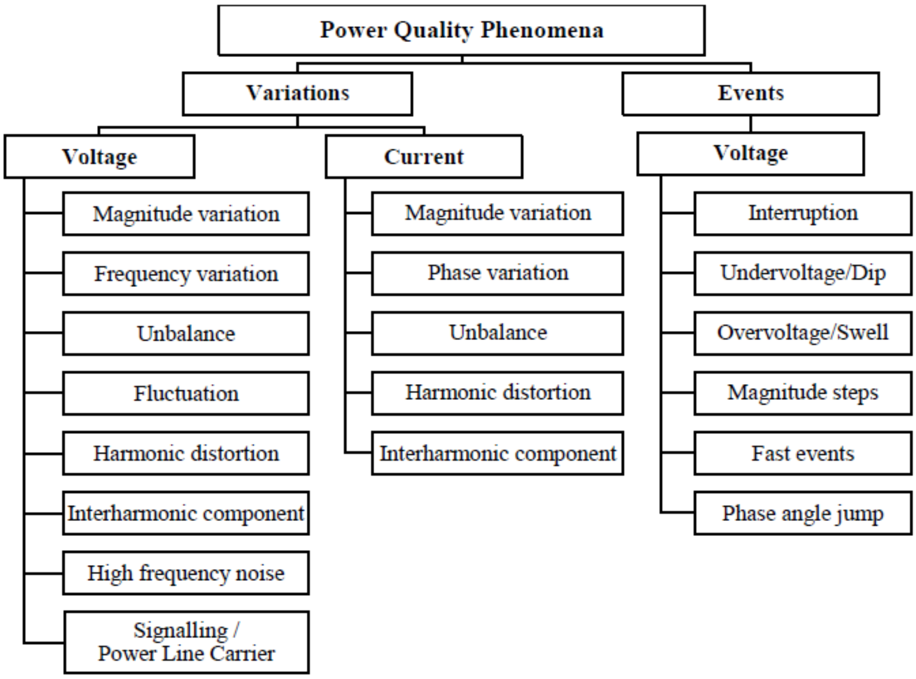

Figure 1.1 PQ Phenomena

(Carastro et al., 2008)

From Figure 1.1 above, the specific terms can be determined to describe each PQ problem and event. The list below further describes these PQ terms"

- Voltage fluctuation is a series of changes in voltage magnitude in the voltage waveform. It can be in the form of either periodically change or random changes or combination of both.
- Flicker is the rapid variation in load current which cause rapid voltage variation.
- Three phase voltage unbalance is the ratio of the deviation among the three phases over average three phase voltage. Such unbalance rises neutral current which contribute to negative sequence current that can cause motor overheat.

- Harmonics are the sinusoidal components of voltage or current with a frequency in multiple integer of the fundamental. It can reduce the efficiency of the system.
- Voltage swell describes the increase in RMS voltage or current from half cycles to 1 min.
- Voltage drip describes the decrease in RMS voltage between 0.1 p.u. to 0.9 p.u.
- Overvoltage describes voltage rise over nominal voltage for a longer period, which is greater than 1 min. Typical values are 1.1 p.u to 1.2 p.u.
- Undervoltage describes in contrast to overvoltage, which is voltage drop below nominal voltage for a longer period which is greater than 1 min. 0.8 p.u. and 0.9 p.u. are the typical values.
- Interruption describes the loss of voltage (less than 0.1 p.u.) in one or more than one phase conductors. It is lasting in shorter time, and 1 to 3 min are short interruptions.

To maintain a healthy operation of power system, regulations over PQ problems are critical and there are standards to suggest recommended limit on these PQ problem. The figure below shows the regulation guidelines from EN 50160 and EN 61000. EN stands for European Union.

Parameter	EN50160	EN61000
Voltage variations	±10% for 95% of week, mean 10 minutes RMS values	±10% applied for 15 minutes
Rapid voltage changes	LV: 5% normal, 10% infrequently, $P_{lt} \leq 1$ for 95% of week MV: 4% normal, 6% infrequently, $P_{lt} \leq 1$ for 95% of week	3% normal, 8% infrequently $P_{st} < 1.0$, $P_{lt} < 0.8$
Supply voltage dips	Majority: duration <1s, depth <60%. Locally limited dips: LV: 10 - 50%, MV: 10 - 15%	up to 30% for 10ms, up to 60% for 100ms (EN 61000-6-1, 6-2), up to 60% for 1000ms (EN 61000-6-2)
Short interruptions	few tens - few hundreds/year, Duration 70% of them < 1 s	95% reduction for 5 s (EN 61000-6-1, 6-2)
Long interruption	<10 - 50/year	
Supply voltage unbalance	LV, MV: up to 2% for 95% of week, mean 10 minutes RMS values	2%
Harmonic voltage	2% - 2nd, 5% - 3rd, 1% - 4th, 6%-5th, 5%-7th, 1,5% - 9th, 3.5%-11th, 3%-13th, …	6%-5th, 5%-7th, 3.5%-11th, 3%-13th, THD <8%

Figure 1.2 PQ Regulation from EN

(Carastro et al., 2008)

From Figure 1.2 above, it can be seen that PQ control is very important to maintain the security of the power system, and the decentralizing grid transformation is going to pose greater difficulty in meeting these PQ regulation standard. As such, technologies that can alleviate PQ play a greater role than before in the future wave of RE integration of decentralizing grid transformation.

1.1.3 FACTS Family – SVC and STATCOM

In the present, several approaches were adopt to control PQ issues in distribution system, such as capacitor banks, tap changing transformers, synchronous machines, and flexible AC transmission system (FACTS). A few examples for FACTS device are static volt-ampere reactive compensators (SVC) and Static Synchronous Compensators (STATCOM). In the decentralizing grid transformation that comes with the intermittent nature of RE generators, these controllers are needed for much better performance in various aspects, such as real and reactive power compensation, voltage regulation, power factor correction, and energy storage facilities in customer loads. These aspects induce different type of controllers to be used to fit different needs.

Regarding the FACTS device examples in the aforementioned, both SVC and STATCOM are shunt-connected static compensators as the name suggested. They are commonly used as a reactive power sources for the purpose of voltage regulation, power factor correction and reactive power control. SVC is a thyristor based device that uses passive components, such as capacitors and reactors, to achieve its role as a reactive power sources. It exchanges the reactive power with the system in bi-directional via thyristor switch. Since SVC can be capacitor or reactor based, these are known as Thyristor Switched Capacitor (TSC) and Thyristor Controlled Reactors (TCR) respectively. TSC provides quick switching of capacitor banks resulted in step changing of reactive power to the grid, which TCR is a firing angle controlled inductor for controlling the supplied reactive power to the grid. The Figure 1.3 below shows the block diagram describing the connection of TSC and TCR in a power system in simplified manner:

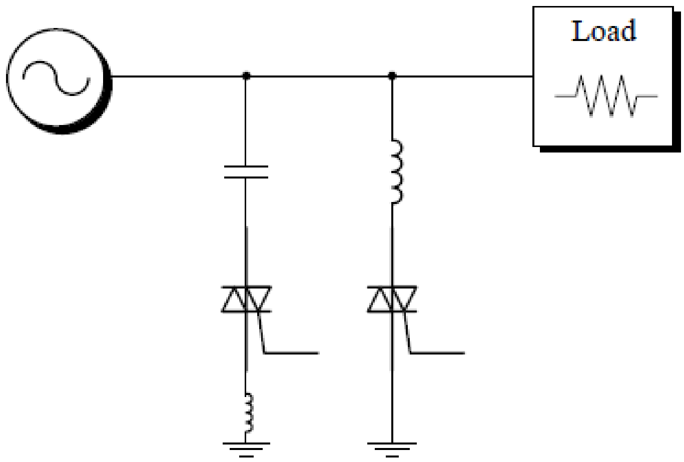

Figure 1.3 TSC and TCR

The SVC technology which utilizes thyristor switching technology for the reactive power exchange is considered the first generation of FACTS device. Due to the great technology advancement and lower cost of power electronics, this thyristor based controller is replaced by power electronic switches for the same reactive power exchange role, and it is known as Static Synchronous Compensator (STATCOM). STATCOM is a new generation of FACTS device which behaves as converter based shunt compensator. It offers more advantages over traditional thyristor based technology. One of the advantages that STATCOM can offer is that it offers quick response time and compact size and structure. These advantages overcome the drawback of SVC in which the passive components used is found to be slow in response time, high costs and large footprint. Furthermore, the reactive power generated by SVC is greatly depending on the system voltage, and such shortcoming is not found in STATCOM due to the converter based technology. It means that the reactive power control of STATCOM is completely independent of system voltage, and it is able to generate rated reactive current with full voltage range in bi-directional. Such feature is considered as the most important advantage of STATCOM over traditional SVC technology (Chen et al., 2000). The figure below shows the simplified block diagram of STATCOM in a power system (Gjerde, 2009). It consists of AC to DC converter and a DC link capacitor. This capacitor is the DC input terminal of the converter which induces the STATCOM to be a voltage source based converter.

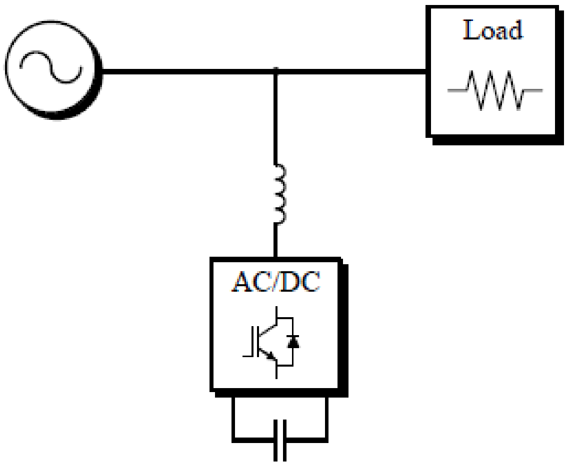

Figure 1.4 STATCOM Block Diagram

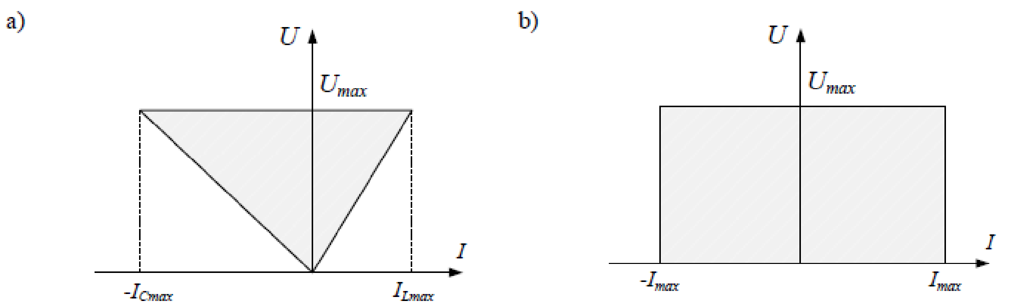

Figure 1.5 Static Characteristics of a) SVC, b) STATCOM

Traditionally, the term “STATCOM” is considered a FACTS device which is meant for transmission networks. In the aforementioned future trend of grid transformation, the stability and security of distribution power system is getting more attention than before because RE is going to be massively connected at distribution level. Hence, it is relatively a new concept to utilize STATCOM into distribution networks instead of transmission systems for controlling actions. The term is further specialized “D-STATCOM”, where “D” stands for distribution to indicate that the STATCOM is at distribution level (Sung-Min et al., 2001).

1.1.4 Significant and Potential of D-STATCOM

STATCOM is a term describing its usage in transmission network, and it has been widely used for a long time, thus its development is considered more mature than D-STATCOM. Since STATCOM and D-STATCOM are supporting different networks, they adopt different control strategies though both of them behave the same as shunt compensators (Kumbha and Sumathi, 2012), thus they can’t be treated exactly the same which spurred the need of individual research work. Because of the rising demand in maintaining security of the distribution network in future due to RE integrated grid transformation, D-STATCOM is getting more attention hoping to bring its potential benefits into the system. There are research groups in the world investigating D-STATCOM to enhance its capability into alleviate PQ problems in distribution network and numbers of multinational companies are investing into D-STATCOM technology, such as S & C Electric Company, ABB, Schneider and Hitachi Europe (Boyi Bukata, 2013).

There are more potential enhancements of D-STATCOM that attract more research effort to be invested. From the introduction earlier, regardless D-STATCOM or STATCOM, both are considered as shunt compensators which provide reactive power exchange. The DC link capacitor used is not a bulk storage device, and it merely provides DC reference for the operation of the converter to behave as voltage source converter. Hence, this DC link capacitor plays no part in real power compensation and as a result the PQ control by STATCOM/D-STATCOM is merely based on reactive power compensation. Limited real power compensation is the drawback of D-STATCOM, but such situation provides an opportunity to enhance its capability in real power compensation. Enhancement in real power compensation can be realized by integrating energy storage system (ESS) on the DC terminal of the converter and shunted with DC link capacitor. Few examples of the available ESS technologies are super capacitors (SC), super conducting magnetic energy storage (SMES), fuel cell, battery energy storage system (BESS). Such enhancement is technically feasible because D-STATCOM is a converter based device unlike traditional thyristor technology (Hingorani and Gyugyi, 2000). The distribution network turns out to be much secured as it has a buffer from D-STATCOM that can provide both real and reactive power compensation independently in any emergency cases. As such, ESS integration D-STATCOM behaves like another standby synchronous condenser to provide real power output in the power system, but the difference is that D-STATCOM operates with much faster response time than the conventional rotating synchronous generators (Kuiava et al., 2009a). Also, the ESS is able to maintain the DC voltage of the D-STATCOM that keeps them from being tripped off or that limits overcurrent in case there are system faults, such as three-phase fault, line-line to ground fault, single line to ground fault and etc (Zhengping et al., 2008). Hence, ESS integrated D-STATCOM is an amazing breakthrough in functionality and it offers great flexibility in operation.

The above mentioned integration of ESS is not only attractive in functionality term, but also in economic term. Since the real power output of ESS is working as a buffer for any emergency cases in the network, it is needed to supply for only a short duration of time. As such, the size required for the ESS in the D-STATCOM is not huge and the cost of the entire system of D-STATCOM itself is still the dominator. Hence, such integration is not going to immensely increase the cost of the whole D-STATCOM system which is very attractive to transmission service providers since since it offers great enhancement which does not come with unreasonably high cost (Muyeen et al., 2007). Furthermore, the size of the DC link capacitor can be reduced in a ESS integrated D-STATCOM, because smaller rating of the capacitor is sufficient to regulate the DC current (Cheng et al., 2006).

As a conclusion from the above information, ESS integrated D-STATCOM system brings great advantages in terms of functionality and cost, and it has drawn great attention around the world to utilize its benefits into the future trend of hybrid power system.

1.2 Problem Statement and Research Approach

From the above introduction, it can be seen that the research works around the world are aimed to align with the trend of RE integrated grid transformation in order to achieve the low carbon future and this is the same in Malaysia. Such transformation is definitely going to pose greater challenges to PQ problems in distribution network than before, thus the thesis is attempted to answer the research questions:

- What is the distribution hybrid power system model that suitable for study?
- What are the PQ problems in such a hybrid distribution system?

Regarding the PQ aspect, the PQ problems can be too wide to be covered as mentioned previously, and this thesis intended to address parameters relevant to voltage regulation. Furthermore, the study here is aimed to deliver an analysis that is able to contribute to both Malaysia context and global context, and hybrid power system can be sourced by many different RE technologies, such as wind, solar, biomass, and ocean. Hence, when it comes to the selection of the suitable hybrid power system model for study, this model has to be able to represent a context common to both Malaysia and worldwide aspect. Bearing in mind with this standpoint, the research approach is taken by first analyzing the potential REs that can be developed in Malaysia, and then they are chosen only if similarity to worldwide context is presented. These findings are as follow:

According to the study from (Mustapa et al., 2010) and (Kardooni et al., 2016), there are many of potential RE resources in Malaysia that can be greatly developed, and these include forest residues, palm oil biomass, solar energy (solar thermal and PV), hydro and mill residues. These RE resources were all quantified in annual energy value in Riggit Malaysia (RM), and it was found by the researchers that forest residues, biomass and solar energy are the top three most valuable resources that can be greatly utilized (Kardooni et al., 2016). Hence, in the consideration of studying a context that is applicable to both Malaysia and worldwide context, the hybrid power system sourced from solar energy is selected. The simulation model of such system and its relevant PQ problem were to be identified. After identifying the PQ problems, it is followed by another research questions which required to be answered:

- What is the suitable approach that can alleviate the PQ problems that arise from such hybrid power system?

From the aforementioned FACTS and D-STATCOM information, it can be seen that D-STATCOM has a great potential to be utilized in addressing the research question because it is working in distribution level with reactive power compensation, as well as its potential enhancement by integrating with ESS. Series of different ESS technologies are available currently and proper consideration is required in the selection of the suitable

ESS for integration. Bearing in mind with the above two aspects, it then leads to the below research questions:

- What is the D-STATCOM model that can alleviate PQ problem in the system?
- What is the suitable ESS in this study to be integrated into D-STATCOM for achieving real power compensation?

As shown in the session earlier regarding the type of ESS, there are plenty of possibilities that can be considered for the integration. Among all of these possibilities, BESS is the most matured technology because it has been widely used for a long time in many applications. However, it is having several disadvantages, such as limited life cycle, voltage and current limitation and environmental hazards (Guha et al., 2014). The thesis is intended to explore on a green and sustainable solution, thus fuel cell is selected to be the ESS in this study. A detail review regarding ESS technologies were included in the later chapter.

While the fuel cell technology is much younger than BESS technology, its effectiveness in real power compensation after being integrated into D-STATCOM is required to be investigated. The best approach to carry out the investigation is by having a performance reference to a mature technology, such as BESS. Based on this reference, the fuel cell integration into D-STATCOM can be concluded as good if its real power compensation ability is similar to the mature BESS technology. Therefore, it leads to the research question below:

- What is the difference in the capability of real power compensation of fuel cell integrated D-STATCOM to a BESS integrated D-STATCOM?

The review of the research works carried out around on D-STATCOM and different ESS integrated D-STATCOM is covered in the later session.

1.3 Objectives

From reviewing and concluding all the problem statements, research questions, and standpoint of the thesis in the aforementioned, the objectives of the thesis can now be derived as follow:

1. To formulate a solar sourced hybrid power system model.
2. To identify the PQ problems (voltage quality) from such hybrid power system.
3. To propose and develop a D-STATCOM system which can alleviate the PQ problem identified with its power compensation.
4. To integrate fuel cell into D-STATCOM for having real power compensation.
5. To evaluate the effectiveness of such fuel cell integrated D-STATCOM system in treating PQ problems with respect to BESS integrated D-STATCOM system.

The research works were aligned with these research questions and objectives. The outline of this thesis in presenting the research works is mentioned as below.

1.4 Outline of the Thesis

The outline of this thesis that shows the presentation of this work is as shown in below table.

Table 1.1 Outline of the Thesis

Chapter No.	Title	Content
1	Introduction	Background of the study, followed by the research questions and problem statement, and lastly the objectives of this work
2	Literature Review	Review of D-STATCOM operation principle, ESS technologies, the relevant works that carried out by the researchers and derivation of the approach of this work.
3	Research Methodology	Discuss in details for each of the working model involved in terms of the design and parameters set. These include hybrid power system, D-STATCOM and ESS integrated D-STATCOM.
4	Result and Discussion	Discuss in details on the outcome of the working model and analyse the results in aligned with

		objectives of the thesis.
5	Conclusion and Future Enhancement	A conclusion of the thesis by commenting the overall outcome of the thesis work, limitations of the work and relevant future enhancement.

CHAPTER 2

LITERATURE REVIEW

In the aforementioned, it is known that D-STATCOM is a great fit in treating PQ problem in hybrid power system at distribution level and having great potential to be enhanced in its flexibility of operation. By taking a step further, this chapter is going to extend the depth of discussion by reviewing D-STATCOM in various aspects, such as operation principle of D-STATCOM, relevant control strategy, compensation mechanism, different feature of ESS and etc. The relevant research works from others were reviewed in here as well. These reviews were important to validate the value of this study.

2.1 D-STATCOM Operation Principle

In the previous mentioned thryistor based SVC technology, it is known that it generates or absorbs reactive power from the switching step of capacitor (TSC) or firing angle controlled reactor (TCR). It is technically possible to achieve the same reactive power exchange without involving any capacitors and inductors by replacing them with converters formed by various power electronic switches, and due to the lower cost of these power electronics, this replacement is economically feasible as well. Such condition leads to the born of D-STATCOM (or STATCOM, as "D" is merely meant for distribution) technology (Hingorani and Gyugyi, 2000). The converter behaves as voltage or current sources to the grid and the supply of reactive power is independent of reactive energy storage by circulating current in the phases of the AC system. Looking at the reactive power generation aspect, the operation of D-STATCOM is akin to an ideal rotating synchronous generator whose reactive power output is controlled by excitation. Due to such similarity, the term Static “Synchronous” Compensator (STATCOM) is analogous with rotating synchronous generator.

These converters are made of an array of power electronic switches, such as Insulated Gate Bipolar Transistor (IGBT), Integrated Gate Commutated Thyristor (IGCT), Phase Controlled Thyristor (PCT) and etc, and IGBT is better fit in STATCOM design due to its high switching frequencies which is essential for high dynamics of compensation, and higher harmonics component compensation capability (Hingorani and Gyugyi, 2000). They are connected in input and output terminals, and when there is no internal energy storage, the instantaneous input power has to be same with instantaneous output power for balance. The converters can be either voltage sourced or current source when the DC terminal, which is the “input” for the converter, is shunted by capacitor (voltage source) or inductor (current source). The voltage sourced converter (VSC) is much preferred in the operation instead of current sourced converter (CSC), due to several reasons below (Hingorani and Gyugyi, 2000), and thus the study takes VSC as the research approach of D-STATCOM:

- Current sourced converter requires bi-directional voltage blocking in the switch which is unable to be achieved since they cannot block reverse voltage.
- Current charged reactor that forms the source is having higher lose than voltage charged capacitor.
- Current sourced converter requires additional overvoltage protection or higher voltage protection of the power electronic switch.

Since the operation principle of D-STATCOM is akin to conventional rotating synchronous compensator in terms of reactive power generation, the review of the operation is started out by referring to rotating synchronous compensator as shown in the below figure:

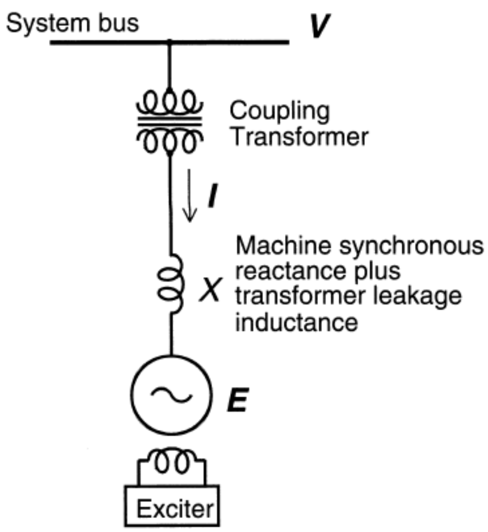

Figure 2.1 Rotating Synchronous Compensator

(Hingorani and Gyugyi, 2000)

The reactive power can be derived as below equations:

$$I = \frac{V - E}{X} \tag{1}$$

$$Q = \frac{1 - E/V}{X} V^2 \tag{2}$$

where Q is the reactive power output, I is the current circulating, V is the system voltage, E is the internal voltage and X is the total circuit reactance which is the sum of synchronous machine reactance plus transformer leakage reactance. By referring to equation (2), the excitation of the machine can be controlled which in turn controlling the ratio of *E* over *V* and as a result, it controls the reactive output power, *Q*. These steps are illustrated below:

- Three-phase induced electromotive forces (EMF), e_a, e_b, e_c of the machine is in phase with system voltage V_a V_b V_c.
- Increasing *E* above *V* (over-excited) results in a leading current *I* and the machine behaves in capacitive mode in the aspect of the ac system.
- Decreasing *E* below *V* (under-excited) results in a lagging current *I* and the machine behave in inductive mode in the aspect of the ac system.
- Small amount of real power is consumed by the machine to compensate its mechanical and electrical losses.

If the above excitation control which in turn controlling reactive power output is attempted to regulate the voltage level of the system, then the machine is a “rotating synchronous compensator”. The above four principles are the same when it comes to D-STATCOM operation, which is as shown in the simplified D-STATCOM block diagram below:

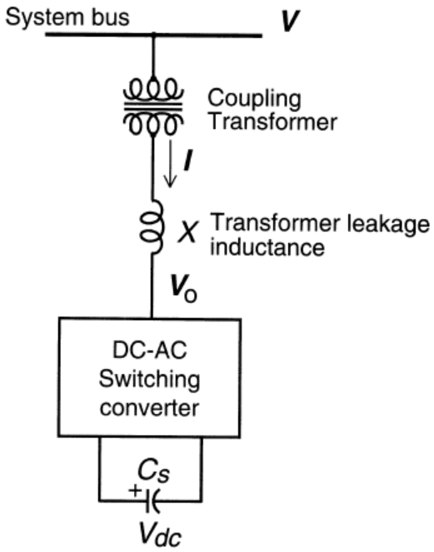

Figure 2.2 D-STATCOM Simplified Block Diagram

By referring to the above figure, the similar operation mechanisms can be derived for D-STATCOM as below:

- The input of the converter, which is DC terminal that shunted by charged capacitor, C_s (which also known as DC link capacitor) induces the converter to produce three-phase output voltage, V_o that is in phase with the system bus voltage, *V*, and coupled to the system via the transformer leakage inductance, *X*.
- Increasing V_o above *V* results in a leading current *I* and the machine behaves in capacitive mode in the aspect of the ac system.
- Decreasing V_o below *V* results in a lagging current *I* and the machine behaves in inductive mode in the aspect of the ac system.

- Small amount of real power is consumed by the converter to compensate its internal losses, such as switching loss, thus there is a small amount of phase difference between V_o and V in practice.

Similarly, when the control of V_o by the converter is attempted to regulate the system voltage at specific value, then the converter is known as the term, "Distribution Static Synchronous Compensator" (D-STATCOM). The above mentioned mechanism is illustrated graphically in the figure below (Baran et al., 2008):

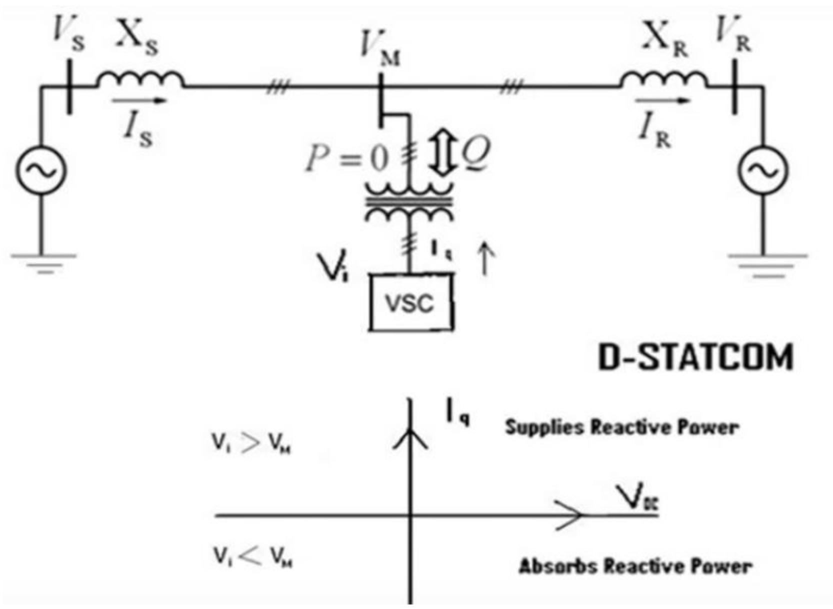

Figure 2.3 Reactive Power Generation of D-STATCOM

The above D-STATCOM block diagram is simplified for the explanation purpose in the operation principle. To show the full components involved in a D-STATCOM system to carry out the operation as mentioned previously, they are illustrated in the block diagram below with red texts (Weidenmo, 2012):

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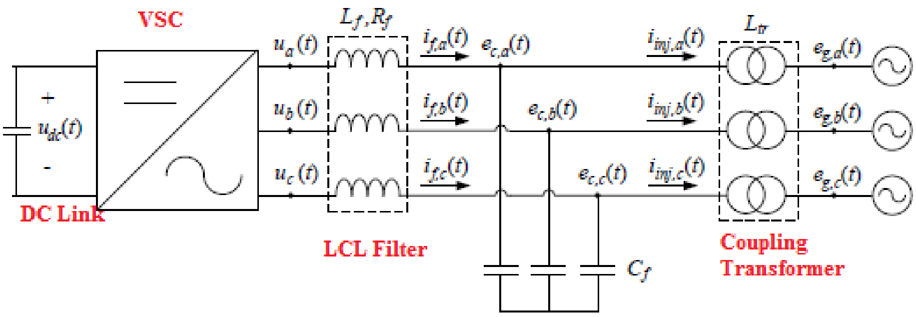

Figure 2.4 D-STATCOM Structure

From the above D-STATCOM structure block diagram, it can be seen that there are a total of four major components involved for a complete D-STATCOM system and they are as listed below with respective function description beside. These components are needed to perform the four operation principles mentioned previously.

- DC Link capacitor (input terminal of VSC),
- VSC (DC to AC conversion),
- LCL filter (Higher harmonics filtering)
- Coupling transformer (ensure coupling from the output of VSC and grid by correct voltage magnitude translation)

The above reviews covered most of the D-STATCOM operation details, but there are two more aspects regarding the function of the DC link capacitor are important to be reviewed. Firstly, due to the facts that net instantaneous power at the input terminal of the converter has to be equal with net instantaneous power at output terminal and it supplies only reactive power (assume no internal energy storage here), the real power of the DC link capacitor must be zero, and the capacitor plays no part in the reactive power generation. Bearing in mind with these facts, the DC link capacitor has to supply ripple current to the converter in order maintain the above mentioned instantaneous power equality (input and output). This is because the switches in the converter do not generate perfect voltage sinusoidal waveform in practical case which caused ripple in the waveform. This is as shown in the figure below by considering a typical voltage waveform generated by the converter. This voltage ripple would draw current from the capacitor to maintain instantaneous power equality. It can be reduced by using higher order of multilevel bridge of the converter, such as three phase, three level 12-pulse bridge converter can produce lesser ripple than two level 6-pulse bridge converter and 48 pulse is better than 12 pulse converter and etc. However, it should be aware that harmonics can be produced from these power switches (Chivite-Zabalza and Forsyth, 2007).

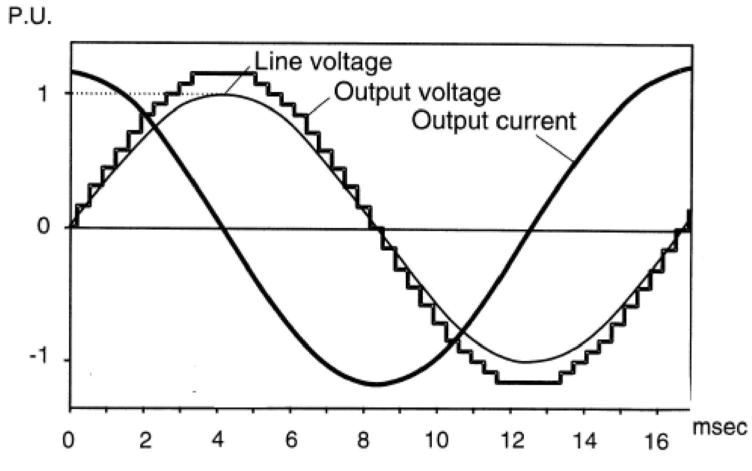

Figure 2.5 Voltage Output from Converter with Ripple

(Hingorani and Gyugyi, 2000)

Secondly, there are switching losses induced by the power electronic switches in a practical converter, thus the energy stored in the DC link capacitor would be used to compensate the internal losses from the switches. However, such situation can be avoided by making the output voltage of the converter lag the AC system by a small angle. This phase shift was not revealed in earlier session because it was assumed that the D-STATCOM is working merely in reactive power exchange, thus no phase difference is required for the output voltage to the system voltage. Hence, it should be aware that in practical case the output voltage from the converter can be lag with the system voltage in a small phase angle to draw some real power from the system in order to compensate its internal switching losses even it is operating for reactive power compensation only. At this rate, it is obviously possible to equip the converter with ESS so that the real and reactive power exchange with the AC system can be controlled for better operation flexibility and effective alleviation in PQ problem. This is discussed in details in the later session.

To summary the above review in D-STATCOM operation, it can be concluded that the reactive power compensation is achieved by establishing a circulating current flow where system voltage and converter output voltage are in phase with instantaneous power equality. The mechanism “in phase” has to be highlighted, because this is the key to achieve the entire reactive power compensation. Such requirement leads to the need in adopting the control topology for the converter to ensure “in phase” can be achieved. There are plenty of control topologies were used to address this need and the review is in the following session.

2.2 Converter Control Topology

The control topology is required in the converter for D-STATCOM due to the need of producing output voltage that is in phase with the system voltage for compensation as mentioned earlier. Such “in phase” condition is known as synchronism, and the magnitude of the synchronized converter output voltage determine the reactive power exchange mode (either capacitive or inductive). The amount of compensation needed (which determine the voltage magnitude) from the converter depends on the intended regulation value which is known as the reference signal. These are the main functions of the controller in the converter, but it is still having many other functions to be included which are not relevant to application viewpoint and mostly are related to safety operation, such as keeping the individual power switches within the maximum voltage and current limits to prevent damage and maintaining safe operation of the converter under all system conditions (Daniel et al.) , 2015).

The below block diagram shows the role of a controller for the converter in overall system viewpoint which includes AC system, transformer, ESS, controller and converter (Rathore et al., 2015):

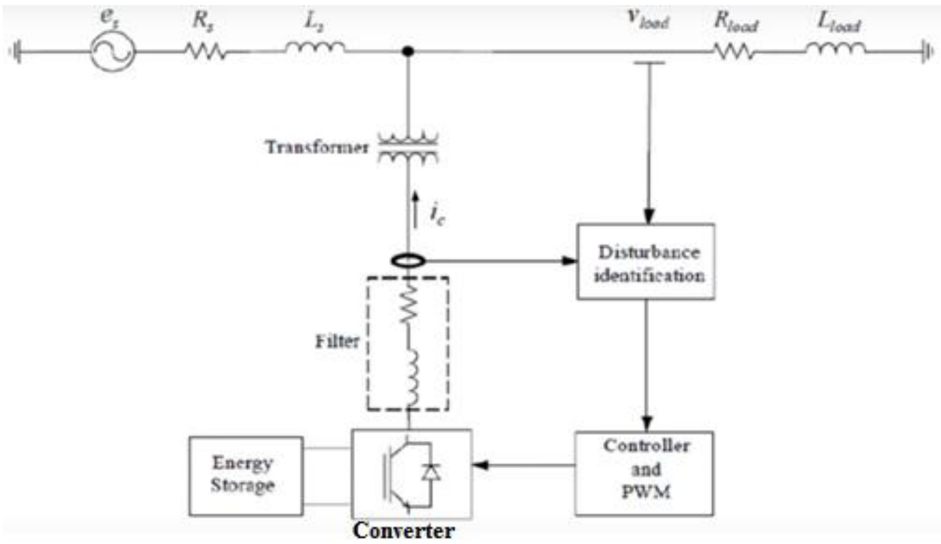

Figure 2.6 D-STATCOM Block with Controller

Referring to the above diagram, it can be seen that the controller block diagram comes with the Pulse Width Modulation (PWM) scheme. The function of this PWM scheme in the controller is as follows: The magnitude of the output voltage from the converter is actually depending on the DC link capacitor and both of them are in directly proportional relationship. As a result, in order to control the magnitude of the voltage, the DC link capacitor voltage level has to be varied. To refrain from varying the DC link capacitor voltage, there is another approach can be used in the controller, which is PWM scheme. This scheme can keep the DC voltage of the capacitor at constant while the magnitude of the output voltage is still controllable by adjusting the firing angle of the converter. Such control is known as “direct” control of output voltage, while the approach on varying the DC voltage of capacitor to control the magnitude of output voltage is known as “indirect” control (Hingorani and Gyugyi, 2000).

At this rate, the above discussion concludes three important functions for a control topology, which are synchronism, reference signal reading and control of output voltage (direct or indirect). These functions are expected to have satisfactory performance, flexibility, easy implementation, and fast response. Hence, the operation of the controller can be concluded in the three steps below (Rathore et al., 2015):

1. Measurements of signal conditioning and variables of the system (synchronism)
2. Reading of reference value of compensating signals (reference signal)
3. Generation of firing angles for switching devices (output voltage control)

The above steps can be visualized in the form of functional block diagram that marked with step number for reference purpose, and it is as shown below:

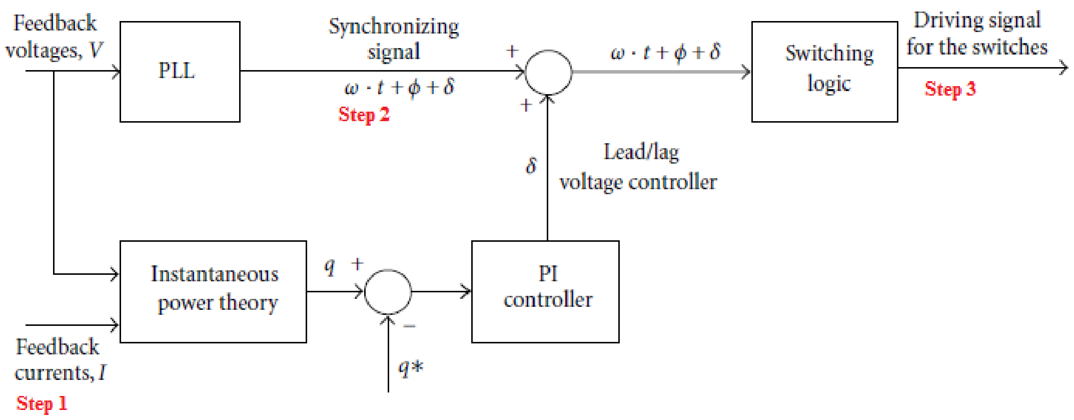

Figure 2.7 Controller Implementation Block Diagram

There are plenty of different control topologies available currently, but the above steps are the same to be implemented in all of these topologies. The key difference among them is in terms of different methods they used to perform these steps. The list below shows a number of different control topologies that can be utilized in D-STATCOM (Mohod and Aware, 2010) :

- Decoupled Current Control p-q Theory (IRPT)
- Synchronous Reference Frame Theory (STFT)
- FRYZE Power Theory (FPT)
- Phase Control Method (PCM)
- Hysteresis Current Control Method

Plenty of research works were done to analyze the effectiveness and advantages of different control topologies (Blazic and Papic, 2006, Chen and Hsu, 2003, Hatano and Ise, 2010, Rao et al., 2000), but it is not the main focus here to investigate the best fit controller since the study is interested in the application and potential enhancement of D-STATCOM. Hence, thorough analysis and review of these topologies are not shown in here, but a walkthrough review of commonly used topologies is presented for the purpose of getting the idea and deeper understanding in these control actions.

2.2.1 Phase Control Method (PCM)

In this topology, the voltage regulation is achieved in D-STATCOM by measuring the RMS voltage at the load side, but the reactive power is not measured. Such approach can be visualized in the below block diagram (Rathore et al., 2015) :

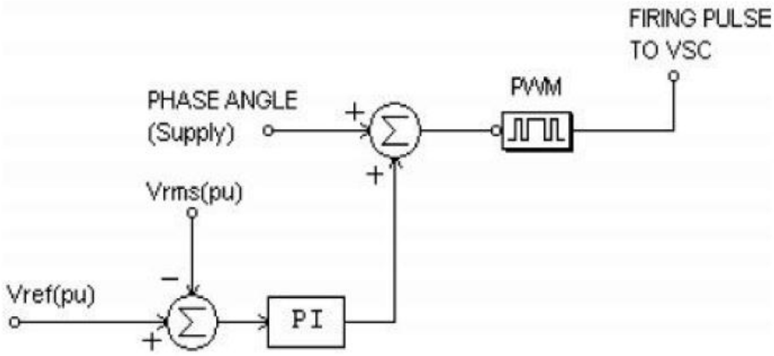

Figure 2.8 Phase Control Method (PCM) Block Diagram

Referring to the above block diagram, the error signal is obtained via the comparison of the measured system RMS voltage and the reference voltage which is the target value of regulation. This error signal is then fed into PI controller to generate the angle that determines the necessary phase difference between system voltage and the converter output voltage. This angle is then sum with the phase angle between the three phase supply voltage (which is assumed to be 120 degree at each phase equally) to achieve synchronizing signals. Lastly, these signals were fed to PWM generator and it produces series of pulses which represent the firing angle of the switches that can vary the magnitude of the converter output voltage and remain synchronism with necessary phase shift derived from the PI controller.

At this rate, it can be seen that PWM generator is adopted in this PCM topology, which is attempted to control the magnitude of the output voltage without the need of varying DC voltage of the input capacitor, thus it can be said that PCM method is using “direct” control of output voltage as mentioned earlier. This PWM technique gives a good response and it is simple to be implemented in the controller (Rathore et al., 2015).

2.2.2 Decoupled Current Control p-q Theory (IRPT)

In this topology, it is measuring the instantaneous values of three phase voltage and current unlike PCM topology. The functional components of this topology are as shown in below list:

1. Two measurement blocks V_{abc} and I_{abc}
2. One inner current control loop
3. One outer voltage control loop
4. One Phased Locked Loop (PLL)
5. One DC Voltage regulator

The overall block diagram of this topology that shows the interaction of the above functional components is as shown in the below figure (Blazic and Papic, 2006):

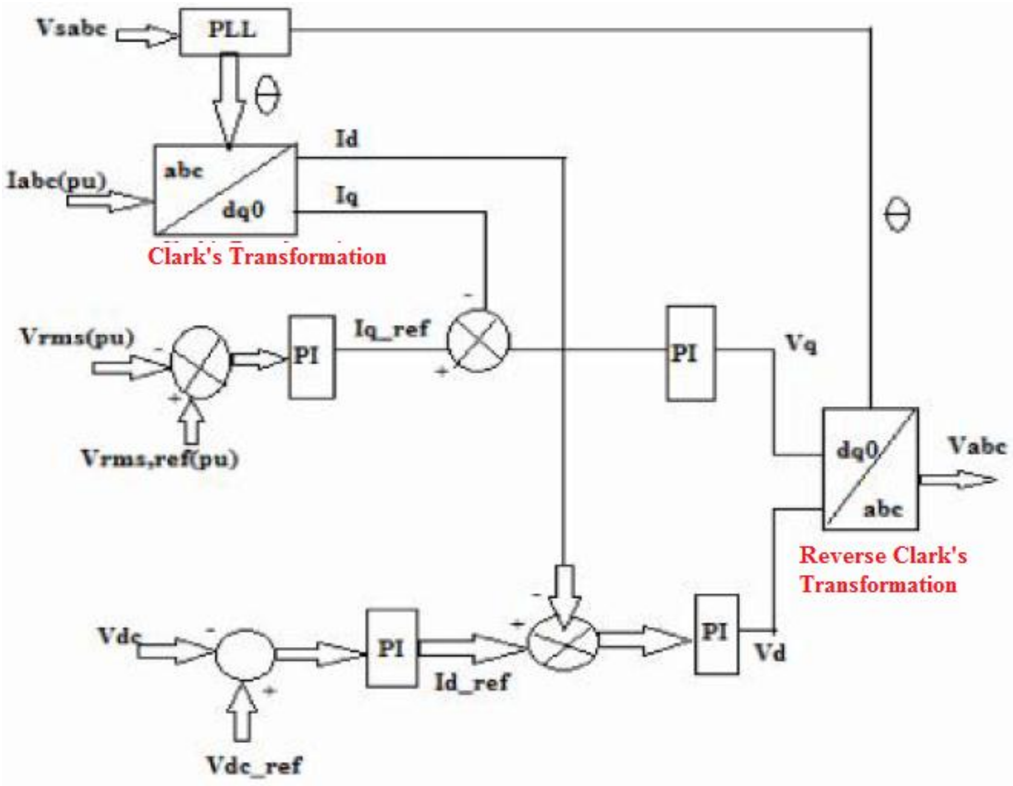

Figure 2.9 Decoupled Current Control p-q Theory

With the listed components and the above functional block diagram of this topology, the operation principle is explained as follows: The measured three phase system voltage and current from the *measurement blocks*, V_{abc} and I_{abc} went through the Clark Transformation to produce I_d and I_q, and these I_d and I_q are able to represent the instantaneous value of the real and reactive power of the system. This can be explained from the relationship of I_d and I_q with real power P and reactive power Q which expressed as below:

$$P = V_d I_d + V_q I_q \tag{3}$$

$$Q = V_q I_d + V_d I_q \tag{4}$$

According to the definition of instantaneous reactive power theory (IRPT) for a balanced three phase three wire system, the quadrature component of the voltage is always zero, which means V_q is 0. Substituting $V_q = 0$ in the equation (3) and (4), it can be seen that P and Q are solely described by I_d and I_q respectively. As such, the three phase signals were transformed by Clark Transformation, which is the *abc* to *dq0* block in the above diagram. The mathematical process of the transformation can refer to APPENDIX A – Clark Transformation.

Bearing in mind the real and reactive power representation in I_d and I_q,, they are decoupled and each of them is regulated by individual PI regulator via the *inner current control loop*, which is having I_d reference and I_q reference. These two I_d and I_q reference are obtained from the control of DC voltage of input capacitor of the converter and the system voltage measured respectively. As a result, the regulation to reference value is happened in here, and it follows by sending to another two PI controllers respectively to produce the controlled V_d and V_q with desired magnitude for compensation. One point is needed to be highlighted in this topology is that V_q and V_d is actually converted from I_q and I_d. This can be achieved by the current to voltage conversion scheme of the *outer loop voltage control* and it is illustrated in below block diagram (Hatano and Ise, 2010):

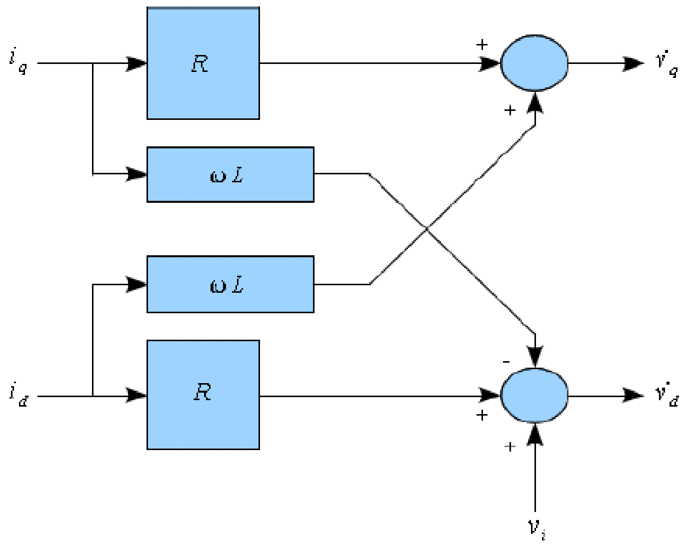

Figure 2.10 Outer Voltage Control Loop

Since the voltages are still in *dq0* domain, they have to gone through the Inverse Clark Transformation to be converted back to three phase *(abc)* domain as the last step. The mathematical process of the inverse transformation can refer to APPENDIX B – Inverse Clark Transformation.

The above IRPT review demonstrates the process of controlling magnitude of the converter output voltage with IRPT topology by utilizing Clark (*abc* to *dq0*) and Inverse Clark transformation (*dq0* to *abc*). In overall, there are four PI regulators involved for this topology for tracking control as shown in the above review. Another component in this IRPT topology is the *Phase Locked Loop (PLL)*. This is used in the *abc* to *dq0* reference frame to ensure the synchronism between the system voltage and converter output voltage in order to achieve the circulation reactive current due to the power compensation need.

At this stage, two of the commonly used control topologies, which are PCM and IRPT, were reviewed. As mentioned earlier, the study here focused in the application point of view instead of investigating the best topology, thus IRPT topology was adopted in this study due to its common usage and proven effectiveness (Blazic and Papic, 2006). The actual model was discussed in details in the later chapter.

Regardless of the differences in these converter topologies, all of them are seeking synchronism of voltages and the control of magnitude converter output voltage to provide shunt compensation for PQ problem alleviation. To further extend the topic of compensation, the next session reviewed in details for the effectiveness of shunt compensation by correlating to voltage regulation so that the role of D-STATCOM can be appreciated and understood better.

2.3 Shunt Compensation Principle and Enhancement

Bearing in mind that D-STATCOM is a shunt compensator in FACTS family, this session is aimed to review shunt compensation in two aspects. Firstly, it reviews on how shunt compensation can achieve voltage regulation, and secondly the great benefits when the compensation is able to be enhanced to both real and reactive power instead of reactive power alone.

2.3.1 Effect of Reactive Power in Voltage

To understand why shunt compensation is useful in voltage regulation, it can be started by reviewing the effect of injecting reactive power to system voltage. A simplified per phase AC system equivalent circuit as shown in the figure below (Rashid, 2009) was considered:

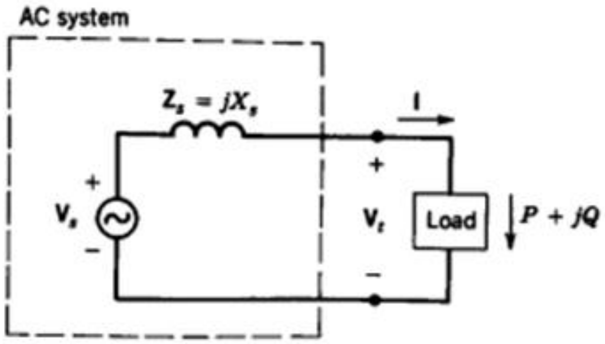

Figure 2.11 Simplified Per Phase Equivalent Circuit

The equivalent circuit above is by means of Thevenin equivalent, where internal impedance of the AC system is assumed to be purely inductive. The load is dragging current $I=I_p+jI_q$ from the source at a lagging power factor with $P+jQ$ power consumption. Assuming an increase of lagging reactive power, ΔQ was drawn by the load, it causes the reactive current component to be increased from I_q to $I_q+\Delta I_q$, and I_p is remained unchanged. The phasor diagram of such condition is as shown below (Rashid, 2009):

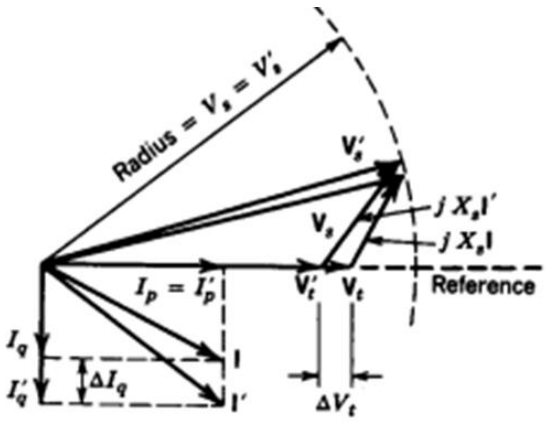

Figure 2.12 Phase Diagram of Iq Increase

The terminal voltage, V_t is chosen to be the reference phasor in the above phasor diagram, and the magnitude of internal system voltage V_s is the same. From the above phasor diagram, it can be seen that there is a drop in the terminal voltage by ΔV_t due to the increase of lagging reactive power drawn from the load. The real power, P will decrease even I_p doesn't change because of the drop of V_t.

In contrast to the above condition, assuming another example where the I_q remains unchanged, instead I_p is increased by ΔI_p , which is having the same amount of percentage drop in I_q in the previous example. The phasor diagram of such condition is as shown below (Rashid, 2009):

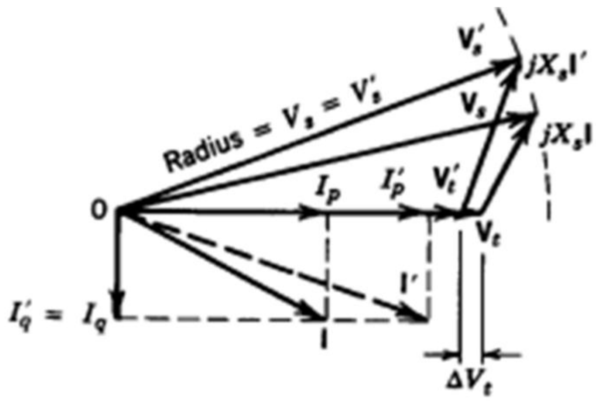

Figure 2.13 Phasor Diagram of Ip Increase

Comparing to the above two phasor diagram, it can be found that the dropping of $V_{t,}$ (ΔV_t) in, I_q change is much greater than in I_p change even though both of them are changed by the same percentage. Hence it can be concluded that reactive power has greater effect in the voltage magnitude changes. Such effect of reactive power in voltage magnitude serves the foundation of the born in shunt compensators for voltage regulation, and D-STATCOM is one of the examples. These shunt compensators attempted to inject or absorb reactive power from the target system in order to regulate the system voltage to desired value.

While the above review shows the amazing voltage regulation ability by reactive power compensation alone, it is interested to investigate the possibility in enhancing the compensation to both real and reactive power and how such enhancement increase the flexibility of operation in a compensator like D-STATCOM. Such review and discussion are as shown below.

2.3.2 Enhancement of Compensation

While the previous session discussed the effect of reactive power alone, the case presented here is aimed to demonstrate the benefit and effectiveness of having real and reactive power compensation together for voltage regulation in a system. Considering a shunt compensator is used to regulate the voltage in a distribution line as shown in the below figure (Kuiava et al., 2009b):

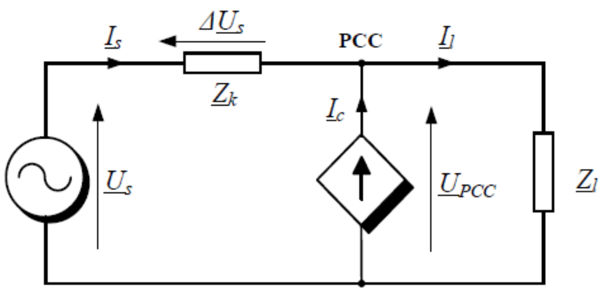

Figure 2.14 Shunt Compensator in a Distribution Line

The phasor diagram of the above circuit is derived as shown below (Figure 2.15) with the following considerations: It is assumed that the source voltage is reduced from the nominal magnitude, $|U_n|$. By neglecting the influence of the load on the voltage, the load voltage U_{PCC} is the same as the source voltage U_s (refer to Figure 2.15a). In order to regulate the voltage to nominal magnitude $|U_n|$, reactive power compensation is provided by the shunt compensator by injecting reactive current (refer to Figure 2.15b).

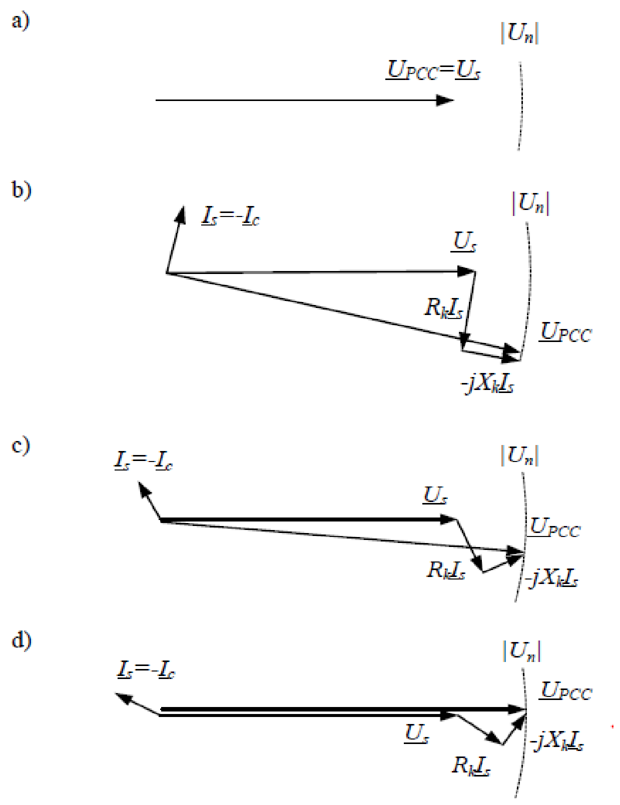

Figure 2.15 Compensation due to Source Voltage Dip

-a) source voltage dip, b) reactive power compensation for voltage regulation, c) real and reactive power compensation for voltage regulation, d) zero phase difference of regulated voltage in compensation of real and reactive power

From Figure 2.15b, it can be seen that such regulation requires high values of reactive current and a significant phase angle jump is possible, which can be a concern for phase controlled loads. Assuming the shunt compensator is now able to operate real power compensation, the voltage regulation resulted from both real and reactive power compensation can reduce the phase angle jump and the apparent power needed from the compensator (refer to Figure 2.15c). If there is a strategy presented, the phase angle jump and the apparent power needed for compensation can be reduced to minimum in order to achieve the same voltage regulation (refer to Figure

2.15d). Such real and reactive power compensation together with a strategy can get the voltage regulated to nominal magnitude without any phase difference, which is beneficial for certain loads that required phase controlled.

While the above review shows one of the benefits of simultaneous real and reactive power compensation, the example here is to extend further to other condition, which is as shown in Figure 2.16 below (Kuiava et al., 2009b):

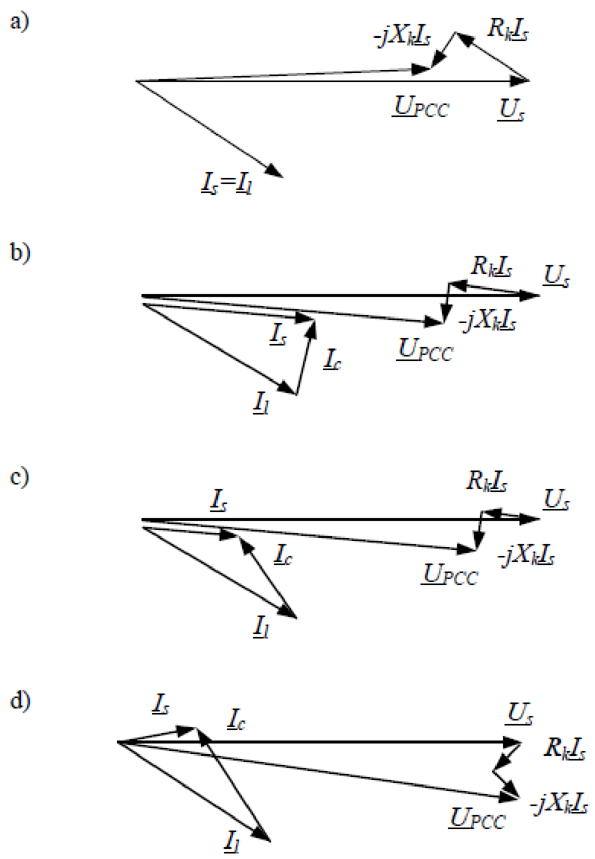

Figure 2.16 Compensation due to Line Impedance

- a) voltage drop caused by line resistance, b) reactive power compensation, c) partial real power compensation and full reactive power compensation, d) overcompensation of reactive power

Referring to the above phase diagram, the considerations are as follow: Assuming there source voltage is remained at nominal magnitude and the load effect in voltage drop is neglected, the voltage drop of U_{PCC} from U_s due to line resistance (refer to Figure 2.16 a) can be compensated by the real and reactive power compensation working together (refer to Figure 2.16 Figure 2.16 Figure 2.16 Figure 2.16 Figure 2.16 Figure 2.16 Figure 2.16 . This is because it is more effective than only reactive power compensation (refer to Figure 2.16 b) since U_{PCC} is much closer to U_s compared to reactive power compensation alone. Practically, the real power used for compensation has to be drawn from the energy storage system at the input DC terminal which shunted with capacitor in the converter, which is having a limited capacity since it is acting as a buffer under reasonable cost instead of a full scale real power generator. Hence, the real power that can be used for compensation is limited, and there is an overcompensation of reactive power happened if it was going to fully regulate the voltage back to source voltage, U_s (refer to Figure 2.16 d).

From the above two conditions reviewed, it can be seen that although reactive power compensation is effective in voltage regulation, there are more advantages and flexibility if such compensation can be enhanced to both real and reactive power, such as the benefits demonstrated in the above examples: Minimum phase jump and apparent power used in compensator for voltage regulation and effective compensation for drop due to line resistance. Apart from these mentioned benefits, the list below shows further possible advantages for the power compensation enhancement to both real and reactive (Hingorani and Gyugyi, 2000):

- Power oscillation damping
- Sudden load transient respond
- Peak load shaving / Levelling of peak power demand
- Uninterrupted power supply for critical loads
- Refrain comparator from being trip off in case of system fault
- Better compensation in short circuit fault of distribution network since it has a resistive component

At this rate, it can be seen that compensator with both real and reactive power is a breakthrough from its usual shunt compensation by providing many advantages and greatly enhance the flexibility of operation. This is going to be a better fit in addressing the PQ problems that arise from the trend of decentralising grid transformation with RE generators. Such enhancement can be achieved by integrating ESS into D-STATCOM so that real power can be drawn from the ESS for compensation purpose, and the review of the ESS technologies and integration mechanism were included the following session.

2.4 Energy Storage System (ESS) and Integration

While the great benefits that can be extracted from the real and reactive power compensation were reviewed earlier, this session is aimed to discuss and review in details for the types of ESS technologies that can be used for integration. This is to analyze the best ESS that can fit for the standpoint of this study. Furthermore, technical details on how to achieve the ESS integration were included as well.

2.4.1 Types of Energy Storage System (ESS)

The ESS technologies have been rapidly advanced over the last decade due to intensive research works done to address the great demand for a better and efficient energy storing mechanism (Weidenmo, 2012). While the ESS technologies is expected to be continuously enhanced in the future, the list below shows the current available technologies as of now and may be subjected to be changed in the future (Ibrahim et al., 2008):

- battery energy storage systems (BESS),
- flywheels,
- super capacitors (SC),
- superconducting magnetic energy storage (SMES),
- fuel cell and etc.

Battery Energy Storage System (BESS) utilized bidirectional electrochemical reactions in converting electric energy to chemical energy for charging, and reverse of this operation for discharging. Different types of chemical substances are used in batteries and they provide different characteristics, and these differences are by means of number of cycles, energy density, power density, cost and etc. It has been widely used for a long time and considered as one of the mature technology currently. The commercial types of batteries are lead-acid, NiCd and sodium-sulfur batteries, while the advanced types of batteries are vanadium redox, Li-ion, advanced lead-acid as of now. From the study of (Weidenmo, 2012), BESS gives acceptable performance and cost in per kWh in the application of grid support. However, it was also pointed out that substantial large amount of funding is invested in research of lithium ion based BESS today due to the interest from the electric vehicles and mobile consumer products, thus there might be a different outlook in BESS technologies in near future (Ibrahim et al., 2008).

Another alternative from batteries is Supercapacitors (SC). They are characterized by longer life time which is counted in millions of cycles and maintenance is not necessary. Also, they are fit for high power output in short duration application because of their characteristic in low energy density and high power density (Bollen, 2011). Supercapacitor technology has a higher charge density over the conventional capacitor due to the double layers of electrochemical. It has been commercialized in the last two decade and used in the case where a high capacitance is needed (Ibrahim et al., 2008).

Flywheels system consists of a rotating mass that stores energy in the form of kinetic energy. The energy storing is achieved by increasing the rotational speed, and reducing the rotational speed can extract the energy. The speed control is done by AC generator connected which is connected at the DC-side of the grid via a AC to DC converter. They are having a similar feature as SC in terms of producing high power output within a short duration of time. However, SC is one tenth lower cost than a flywheel and having higher efficiency which up to 97% (Bollen, 2011).

The superconducting magnetic energy storage (SMES) enables the energy storage in the form of magnetic energy by conducting a current in closed loop which can last infinitely in ideal case. This can be achieved due to the lacking of electrical resistance nature of the SMES. The storing and extracting of energy can be controlled by its magnets which control the mount of flowing current in the loop. Similar to flywheel and SC, it has a feature in providing high power output in a short amount of time. As of now it has been used only in a special applications as shown in (Casazza et al., 2003).

The fuel cell technology produces and stores energy though an electrochemical reaction of a positively charged hydrogen ions with oxygen, instead of combustion method in conventional power generation methods. As such, it is similar to BESS technology since both of them rely on electrochemical reaction, but it allows continuous supply of electricity as long as it has continuous sources of fuel and oxygen. Fuel cell is considered a more environmental friendly technology due to the absence of combustion which decreases the gas emission. The working principle of fuel cell is as following description: The side of the cell houses the fuel is anode and the side with oxygen is cathode. The fuel is oxidized and producing electrons in anode, and they are passing through an external circuit to extract them from the system. The oxygen is reduced by the addition of the electrons which result of water byproduct. Such working principle is illustrated in diagram as shown below (Larminie et al., 2003)

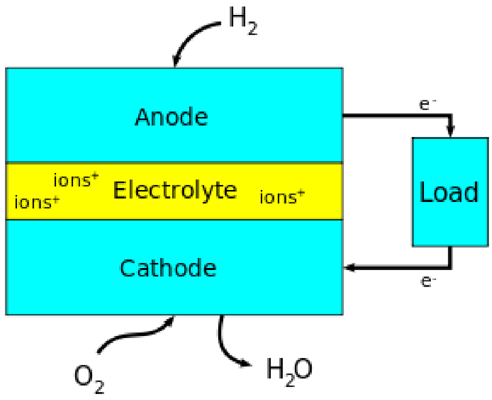

Figure 2.17 Fuel Cell Working Principle

The fuel cell can be used as energy storage by the above operation working reversely. Excess electricity is electrolyzing the water and carbon dioxide to produce fuel for consumption later. Such excess electricity is possible coming from grid in off peak hours for best utilization. There are different types of fuel cells design, such as Proton Exchange Membrane (PEM), Phosphoric Acid Fuel Cell (PAFC), Solid Acid Fuel Cell (SAFC) and etc., and rigorous amount of research on this technology is on-going currently to align the aim of green technology exploration (Liu and Li, 2009).

From the above review of different ESS technology, they are capable in supporting grid relevant application, and one of the applications is the ESS integration motivation to D-STATCOM in this study due to their capability in providing high output power in short duration of time. In this aspect, the energy and power density comparison among these technologies is as shown in the chart below (Liu and Li, 2009):

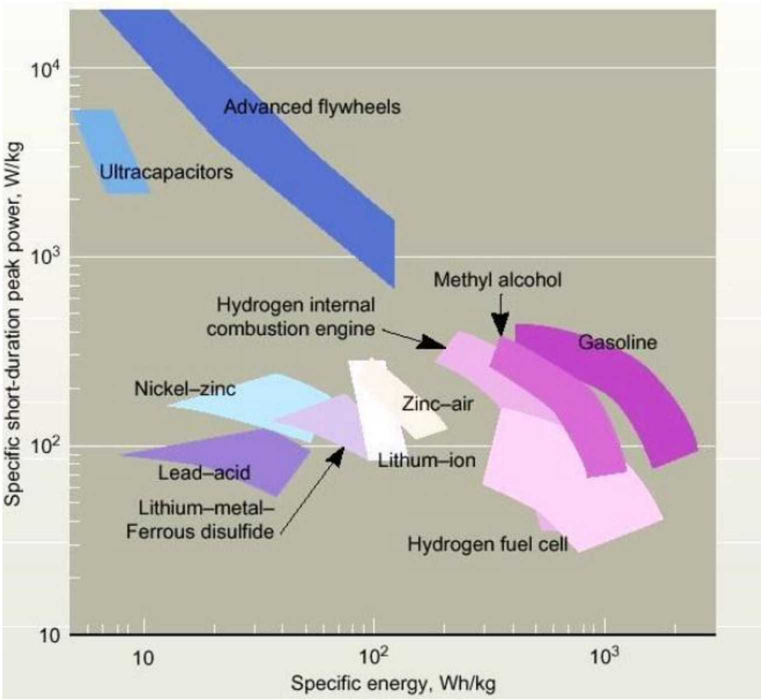

Figure 2.18 Energy Density and Power Density of ESS

From the comparison above, it can be seen that the Supercapacitor is able to perform better than electrochemical batteries and flywheel in terms of the capability of high output power burst. The SMES technology, which is not shown in the comparison above, is placed between Supercapacitor and flywheels. In the other hand, fuel cell technology as of now may be inferior to other ESS technologies in terms of output power burst as shown in the chart above, but they provide the best choice of technology in terms of environmental friendliness. Such feature matched the interest of this study in green technology exploration, thus it is the target to be investigated in this study. The investigation is intended to be carried out by using the mature and proven useful BESS technology as a reference to be compared when fuel cell was used as the ESS for the integration to D-STATCOM. Since both BESS and fuel cell were playing the same role in real compensation in D-

STATCOM, performance comparison between them is considered a reasonable and fair approach.

Since both BESS and fuel cell are relying on electrochemical reaction and the fuel cell technology is much younger than BESS, it was worthwhile to critically compare both of the technologies to validate the value in exploring fuel cell solution. These comparisons were summarized in below table form:

No.	Comparison Aspect	BESS	Fuel Cell
1	Electrode Run Down	The electrodes dissolve in the chemical reaction. When they're gone, the battery is dead	The electrodes are not consumed: As long as fuel is supplied, the cell will generate a voltage: it won't 'run down'.
2	Amount of Energy	The amount of energy the battery supplies is determined by the amount of chemicals in the battery	The amount of energy is determined by the amount of gas reactants.
3	Charging / Discharging	In some cases (re-chargeable batteries), the chemicals can be restored by reversing the current and restoring the original chemicals.	It can supply/store energy continuously as long as the fuel/excess electricity is injecting.
4	Environmental Friendliness	It does not contribute to green technology due to hazardous substance to the environment.	The chemical reaction is with water as byproducts, thus it is more environmental friendly.

Table 2.1 BESS versus Fuel Cell

Given the fuel cell is having advantage in the above aspects especially on the environmental friendliness, the study here is intended to explore the fuel cell solution for ESS integration. While the feature of different ESS technologies were reviewed in the above by correlating to D-STATCOM integration need, the following session reviewed in details on how ESS can be integrated in system structure viewpoint.

2.4.2 Integration of ESS into D-STATCOM

This session is aimed to review the system structure changes of a D-STATCOM which is intended to be integrated with ESS for the compensation capability enhancement. The block diagram below shows the overall system viewpoint of the ESS integration in D-STATCOM in the grid (Chakraborty et al., 2012):

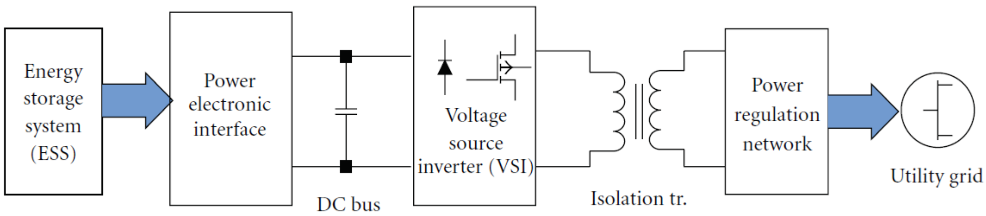

Figure 2.19 D-STATCOM with ESS Block Diagram

From the above block diagram, the ESS and power electronic interface is the additional portion needed to be connected for ESS integrated D-STATCOM compared to D-STATCOM alone. In such ESS integrated D-STATCOM configuration, the number of steady-state operation (real and reactive power copensation) is extended to different situations. These are capacitive mode with DC charge and discharge and inductive mode with DC charge and discharge. Therefore, four operating modes are available for the system to be operated in different needs. In the aforementioned, such ESS integration is intended to be an buffer in any dire or critical situation, such as tripping of other generators and etc., and its sizing is not intended to have huge cost spike to the D-STATCOM, thus generally the integrated ESS is able to provide sufficient energy to stabilize the power regulation until the faulty generator are brought back in service, and also stabilize any disturbances occuring in the system.

While the above diagram shows an overview of the system outline on how ESS to be integrated, the example here is further extending this integration by scoping it narrower for greater details (Saradva et al., 2016):

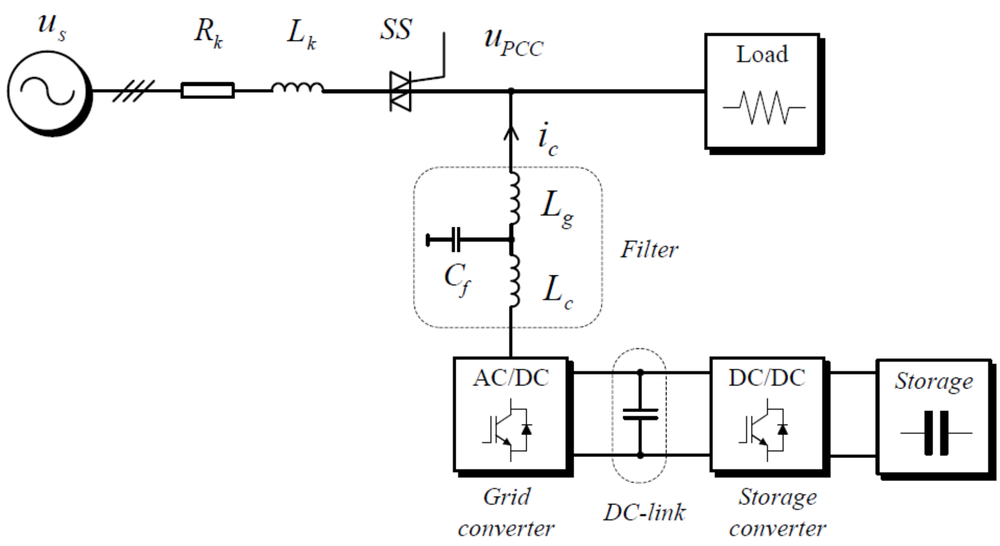

Figure 2.20 ESS integrated D-STATCOM Details

From the above block diagram, it can be seen that an ESS integrated D-STATCOM requires two converter: grid-tied AC to DC converter and ESS interface of DC to DC converter. The grid-tied AC to DC converter existed in usual D-STATCOM and operation has been reviewed earlier, but the DC to DC converter is the new system required if ESS integration is intended, and it is the “power electronic interface” block in Figure 2.19.

The ESS interface DC-DC converter is necessary to allow power flow in bidirectional and convert the stored energy into direct current exchanged with DC link capacitor of the grid-tied AC to DC converter. The ESS integrated is a low voltage storage, but it is intended to be used for PQ alleviation. As a result, this application requires a high voltage gain and flexible voltage of the ESS. In order to achieve such gain, this DC to DC converter is usually utilizing high frequency transformer (Montero et al., 2007).

In order to realize the above design requirements, there are several typical converter topologies used, these includes simple step up/step down or Dual Active Bridge Topology (DAB) and Three Phase Dual Active Bridge (DAB3). The diagram below shows the DAB topology of the DC to DC converter (Saradva et al., 2016):

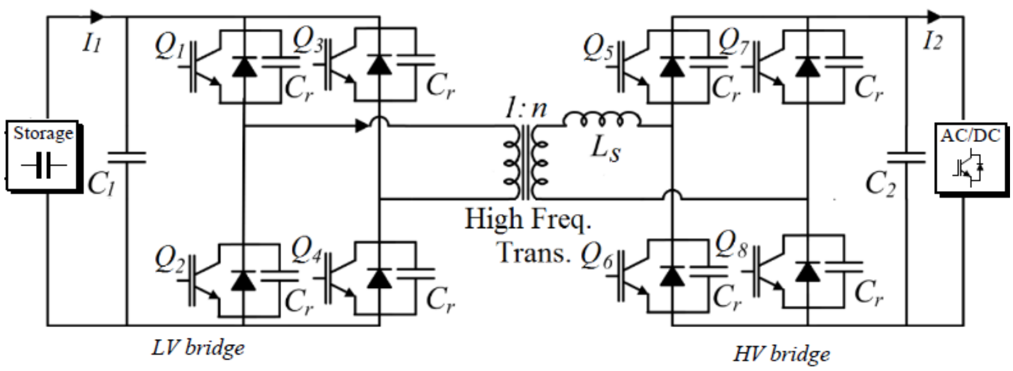

Figure 2.21 DAB Topology of DC DC Converter

From the above DAB topology diagram, there are two controlled H-bridges on low voltage (LV) and high voltage (HV) sides respectively. Also, the AC terminals are connected with high frequency transformer, while DC links are connected to ESS and AC to DC converter. This topology provides easy control of voltage gain via turn ratio of the tarnsformer and galvanic isolation between the grid and ESS. However, there is one drawback happening in this topology is that the DC to DC converter output power is limited by high current at the LV side.

The drawback from above mentioned in DAB topology can be addressed by DAB3 topology (De Doncker et al., 1991). The working principle of this topology is as follow: The H-bridges from DAB topology are replaced by three phase bridges in DAB3 topology, and they are connected to three phase transformer, and it is illustrated in below circuit diagram and its equivalent circuit (Saradva et al., 2016):

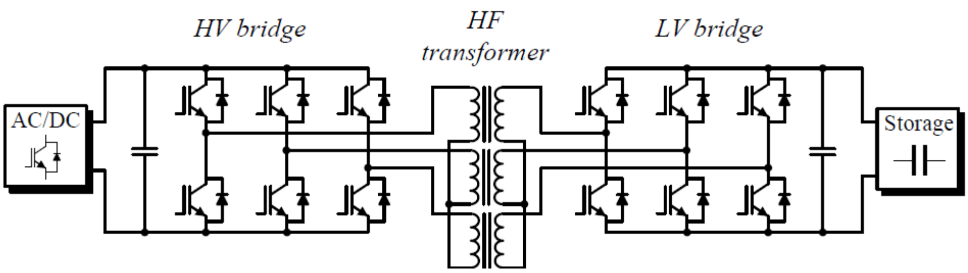

Figure 2.22 DAB3 of DC DC Converter

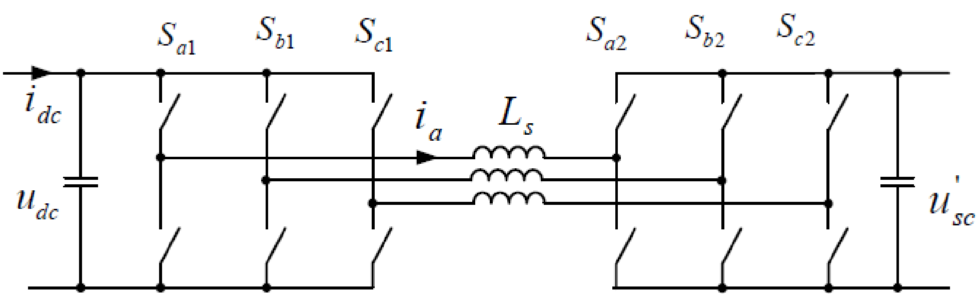

Figure 2.23 Equivalent Circuit of DAB3

DAB3 can be modulated by phase shift modulation technique. The bridges are modulated with constant duty cycle of 50% in constant frequency, and the signals of the three converter legs are shifted by 2Π/3 to create six step voltage at the AC terminals of the converter as shown below.

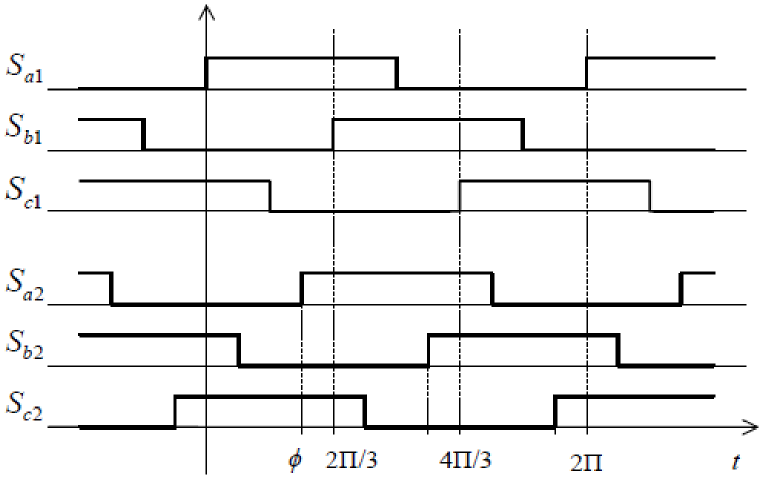

Figure 2.24 Phase Shift Modulation

Referring to the DAB3 equivalent circuit in Figure 2.23, it can be seen that the voltage across the inductor depends on the DC voltages of both LV and HV sides and the phase shift between bridges. Different output voltage and current waveforms can be achieved for ϕ<Π/3 and ϕ>Π/3 as shown in below:

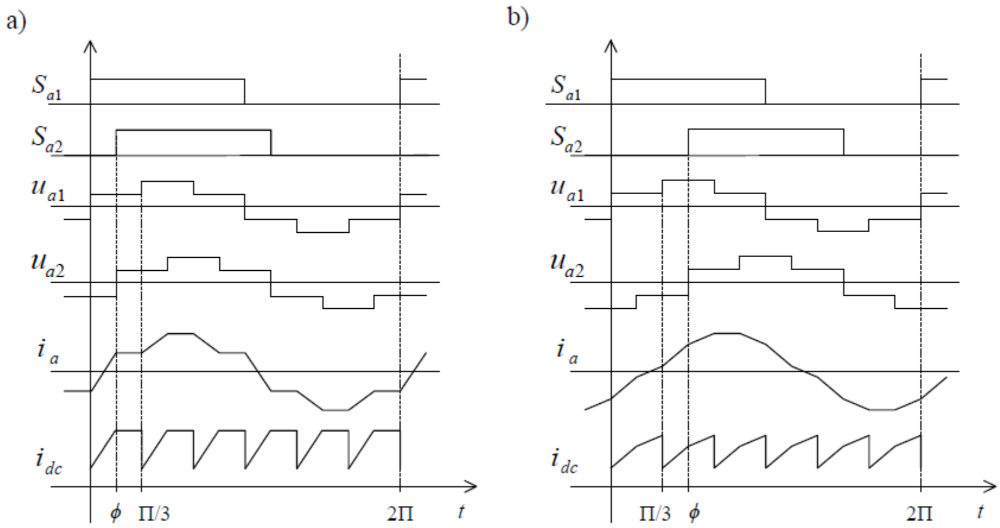

Figure 2.25 Waveform at Different Phase Shift

Similarly, referring to the DAB3 equivalent circuit in Figure 2.23, the real power flow in the DAB3 converter can be calculated with the expressions below at different phase shift:

$$P = \frac{u_{dc} u'_{sc}}{f L_s} \frac{\Phi}{2\Pi} \left(\frac{2}{3} - \frac{\Phi}{2\Pi} \right), \qquad \Phi \leq \frac{\Pi}{3} \tag{5}$$

$$P = \frac{u_{dc} u'_{sc}}{f L_s} \frac{\Phi}{2\Pi} \left(\frac{\Phi}{2\Pi} - \frac{\Phi^2}{2\Pi^2} \right), \qquad \Phi \geq \frac{\Pi}{3} \tag{6}$$

From the above working principle review, the DAB3 topology exhibits many advantages over the single phase DAB topology which is as shown in the list below (De Doncker et al., 1991):

- Lower DC current ripple
- Better usage of high frequency transformer
- Higher efficientcy under the same modulation method (switches do not turn off at maximum current)

In this session, the details in realizing the ESS integration to D-STATCOM were reviewed in several aspects, these include the overall D-STATCOM system design changes from without ESS to ESS integrated, the need and working principle of the additional interface, which is DC to DC converter, and its relevant converter topologies to enable the real power flow to be happened in the D-STATCOM. Several research works on ESS integration with D-STATCOM have been carried out worldwide aimed to achieve the great benefits from simultaneous and independent real and reactive power compensation, and these works were critically reviewed in the next session in order to validate the value of this study.

2.5 Relevant Research Work

Recalling from the earlier introduction, it is known that STATCOM is actually more mature in development than D-STATCOM since it has been widely used and developed for a long time, thus the idea and research works done for integrating ESS into STATCOM is relatively more than D-STATCOM. Although the study is targeted in D-STATCOM, it is still worthwhile to review what research works have been carried in STATCOM since both of them are having the similar motivation. The following shows series of research works done for ESS integrated STATCOM:

The researchers (Qian and Crow, 2002) demonstrate the real and reactive power flow regulation by using a cascaded converter based STATCOM that integrated with BESS. (Yang et al., 2001) also perform investigation on similar STATCOM integrated BESS system on the improvement of transient and dynamic stability. A different approach was illustrated in the research work of (Shim et al., 2013), which is integrating a bank of super capacitors for energy storage system (SCESS) into STATCOM for real power compensation in the RE system to reduce grid swing. On the other hand, (Bhaskar et al., 2014) proposed a fuel cell integrated STATCOM system for enhancing the voltage stability of the power system and shows that the fuel cell is capable to alleviate power system stability problem. For a similar fuel cell system, (Rahman et al., 2013) developed the grid-connected system in MATLAB/SIMULINK and analyzed the system transient stability.

From the above research works, it can be seen that there is a wide range of different research works carried out in discussing different type of ESS integrated into STATCOM, and many aspects have been covered including transient and dynamic stability, voltage stability, real and reactive power regulation and etc. Such great amount of research works in discussing ESS integrated D-STATCOM is not realizing as of now, which provides research opportunity to address this gap. The examples below show a number of the research works discussing D-STATCOM:

From the study of D-STATCOM in these seven group of researchers (Twining et al., 2003, Masdi et al., 2009, Lee et al., 2013, Hill, 1997, Haque, 2001, Giroux et al., 2001, Babaei et al., 2010), they were having a common aspect, which is utilizing the reactive compensation capability of D-STATCOM in alleviating voltage issues in distribution network, such as voltage sag, voltage swell, voltage fluctuation and etc., but they are different in the aspect of control strategy, such as adaptive controller with stationary frame, predictive control, Digital Signal Processing (DSP) control and so on. Taking in the aspect of ESS integrated D-STATCOM, (Zhengping et al., 2008) demonstrated a successful study in voltage regulation and voltage sag mitigation as well with a 125 kVA D-STATCOM integrated with SC ESS in a distribution network. The work also suggested that integrated SC ESS helps to maintain the D-STATCOM DC voltage to be constant which can avoid overcurrent and tripping off of the D-STATCOM when there is a system fault, such as three-phase fault, single-line to ground fault and line-line fault happened as it is intended to keep D-STATCOM being affected from the system faults. On the other hand, (Baran et al., 2008) attempted to smooth intermittent power output of a large wind farm to 1/2h dispatching of the wind farm by using a BESS integrated D-STATCOM which capable to provide both real and reactive power compensation. Furthermore, the study from (Saradva et al., 2016) integrated BESS into D-STATCOM for real and reactive power compensation to mitigate voltage drop due to resistance in distribution line and the inductive load respectively. Lastly, (Joseph et al., 2016) demonstrated the SMES sourced multilevel D-STATCOM for harmonics mitigation.

Due to the maturity of BESS technology in the field, there are greater amount of works done on its integration to D-STATCOM, and it has been proven useful when it comes to PQ alleviation. However, BESS technology comes with several drawbacks, such as short life span, hazardous to environment, voltage and current limitation (Ibrahim et al., 2008). While there is a lesser amount of research works carried out regarding fuel cell integration, and with the motivation in exploring green and sustainable energy source as a solution, this study is attempted to close these gaps and fulfill the motivation by using fuel cell as the ESS to be integrated with D-STATCOM for the operation enhancement. The performance of BESS integrated system serves a reference to compare with the proposed fuel cell integrated solution to quantify the effectiveness of this attempt.

2.6 Approach of the Work

The aforementioned literature review and introduction were all intended to find out the best approach of this study that can best address the research questions and objectives. By looking at all of these review in overall viewpoint, this session scoping them down and concluded the best fit approach of this work which serves as the foundation of the entire research methodology direction of this work, and it is as shown below:

- A solar powered distribution level hybrid power system model is intended to be developed to create a context that is applicable to both Malaysia and global aspect.
- PQ problems of the developed hybrid power system in the aspect of voltage parameters are intended to be identified which can induce the opportunity to bring in D-STATCOM in addressing these problems.
- A D-STATCOM is intended to be developed using the commonly and proven useful IRPT converter topology that can extract the reactive power compensation from the D-STATCOM in order to address the voltage problems identified earlier.
- The same D-STATCOM system is intended to be enhanced by integrating ESS with relevant design upgrade (such as additional DC to DC converter design) hoping to achieve real and reactive power compensative together to address the

identified PQ problem better. BESS will be used to perform such integrate first to serve a performance reference.

- Similarly, the same system will be integrated with fuel cell, and its performance will be compared to BESS integrated system to quantify its effectiveness since it is an innovative act.

Bearing in mind with the above best fit research approaches to achieve the study objectives, the research methodology of this work was aligned and it was discussed in the next coming chapter.

CHAPTER 3

METHODOLOGY

By aligning with the derived research approaches resulted from the literature review previously, the research methodology of this work is able to be identified and it is as shown in the sequence below:

- Development of D-STATCOM model with IRPT topology
- Formulation of solar powered hybrid power system model and identification of its PQ issues (voltage)
- Utilization of D-STATCOM in the system for PQ issues (voltage) alleviation
- Modification of D-STATCOM to ESS integrated (BESS and fuel cell) for compensation enhancement

The above methodology was carried out by using MATLAB/SIMULINK with the Simscape Power Systems toolbox. The models used for the analysis in this study are using (MathWorks, 2009a) as reference and they were modified to fit the objectives and aspects of this study. The desired outcomes required to be produced from each of these methodologies to achieve the study objectives were highlighted in each session as shown below, and the actual outcomes were discussed in the next chapter.

3.1 Development of D-STATCOM model

The model of D-STATCOM with IRPT converter topology was developed as shown below and it was used as the base system for further analysis later on:

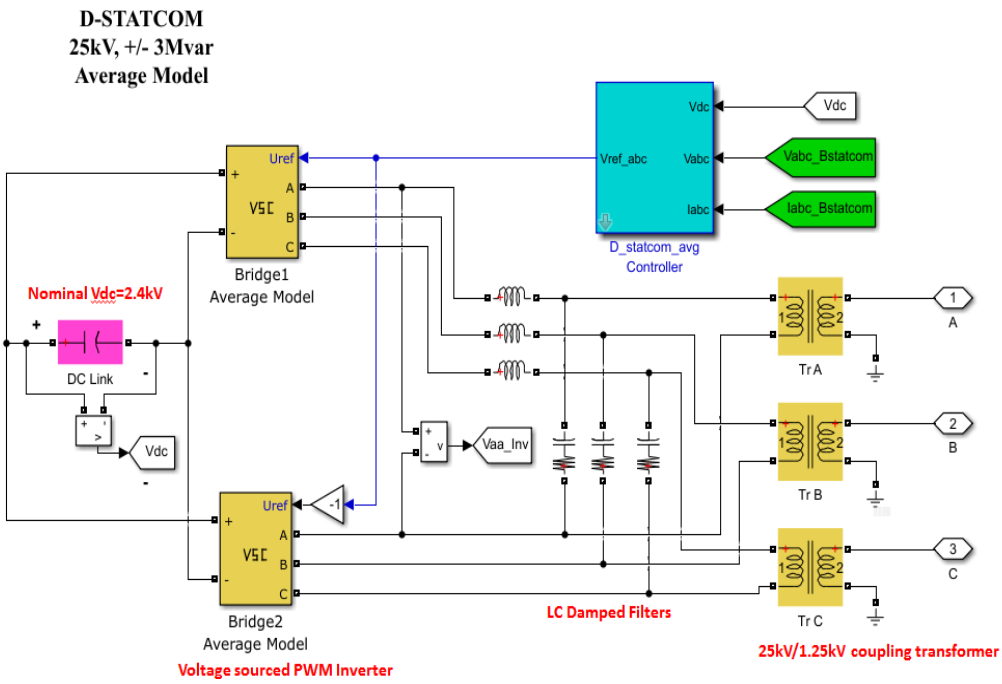

Figure 3.1 D-STATCOM Model in SIMULINK

The model diagram above shows the components involved for the developed D-STATCOM model. It is intended to regulate 25 kV distribution network and with a rating of 3 MVar of reactive power. The DC terminal of the VSC is placed with a DC link capacitor that acted as a voltage source for the inverter at 2.4 kV and the rating of the capacitance is 1000 microfarard. The two bridges that form the PWM inverter are IGBT switches model with a switching frequency of 1.68 kHz. It is noted that the harmonics resulted from the switches is not visible in this model, because this is an average model without harmonics visibility, and it is not affecting the study since the voltage regulation is the major concern in here. Output terminals of the inverter are connected with LC damped filters, and the quality factor is 40 at 60 Hz resulted from the resistances that connected in series with the capacitors. Lastly, the 25 kV/1.25 kV coupling transformers are connected to ensure proper coupling between inverter output and network with correct voltage translation.

Regarding the controller of the inverter as shown in model diagram above in blue colour, it consists of several functional blocks which are as shown in the below list. As mentioned earlier, the controller of the inverter in this model is based on the concept of IRPT topology.

- Phase Locked Loop (PLL)
- Measurement Systems for d-q axis computation
- Inner current regulation loop
- Outer voltage regulation loop and
- DC Voltage controller (V_{dc}=2.4 kV)

The desire outcome of this step is to validate the voltage regulation capability of D-STATCOM by its reactive power compensation and it will serve as the basis for further analysis in the next steps. As such, this developed D-STATCOM has to be integrated into a simplified power system connected with load so that the voltage regulation can be tested out. The simplified power system model for such purpose is as shown below (refer to APPENDIX C for clearer view).

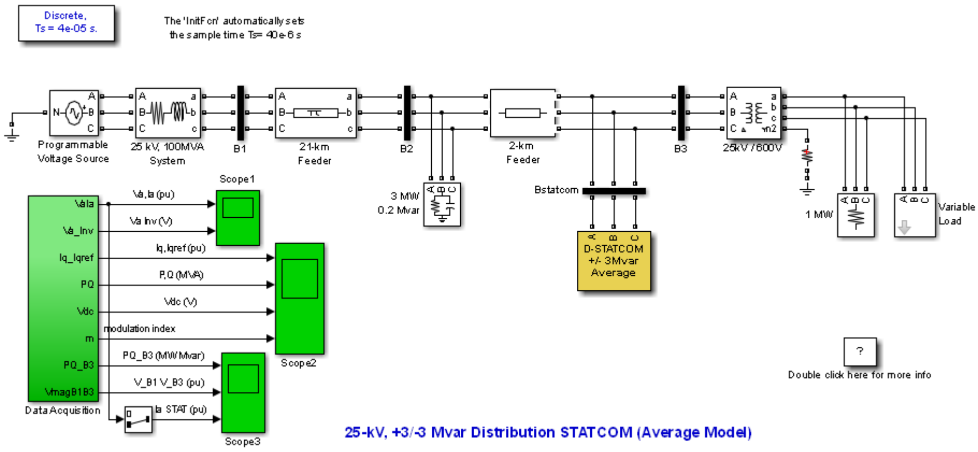

Figure 3.2 Simplified Power System for D-STATCOM Testing

In this power system that aimed for D-STATCOM voltage regulation testing, there is a 21 km feeder and a 2km feeder transferring power from the programmable voltage source to the loads at bus B2 and bus B3. The bus B2 is having a shunt capacitor for correcting the power factor. 600 V load is located at bus B3 coupling via a 25 kV/600V coupling transformer. The base voltage value in this power system is 25 kV, which is the desired value for the regulation of D-STATCOM, thus 1 p.u. is equivalent to 25 kV. To validate the voltage regulation capability of the D-STATCOM, two test cases were carried out in this power system as shown below:

1. Voltage Source Variation

   In this power system, the programmable voltage source is programmed at 1.077 p.u. in order to get bus B3 maintaining at 1 p.u. (omit loading effect here). Any variation from 1.077 p.u.of the source can induce bus B3 running out of 1 p.u. Hence, in order to validate the voltage regulation act from D-STATCOM, 0.2 s, 0.3 s, and 0.4 s were programmed to be faulty by raising the source voltage by 6%, dropping it by 6% and restoring to nominal value of 1.077 p.u.

Desired outcome at this test case is:

The voltage at bus B3 is able to be kept at 1 p.u. regardless the source voltage variation.

2. Load Variation (Voltage Flicker)

   In this test case, voltage regulation of D-STATCOM to counter load variation is intended to be tested out. The source voltage variation in previous case is removed by programming it to be constant at 1.077 p.u, and the 600 V load at bus B3 via 25 kV/600 V coupling transformer is programmed to be a variation load at a frequency of 5 Hz, 0.9 power factor and apparent power drawn varies at 1 MVA to 5.2 MVA. Such situation similar to an arc furnace load, and it would produce voltage flicker at bus B3, thus voltage regulation from D-STATCOM compensation act can be observed. The amount of voltage variation should be significant before turning on the D-STATCOM compensation and otherwise when D-STATCOM is turned on for regulation.

   Desire outcome of this test case:

   When the D-STATCOM has been turned on for compensation, it should be able to mitigate the voltage flicker by reducing the amount of voltage variation of bus B3 compared to case before turning on.

The voltage regulation mode of D-STATCOM can be turning on and off by the user interface as shown in the below snapshot:

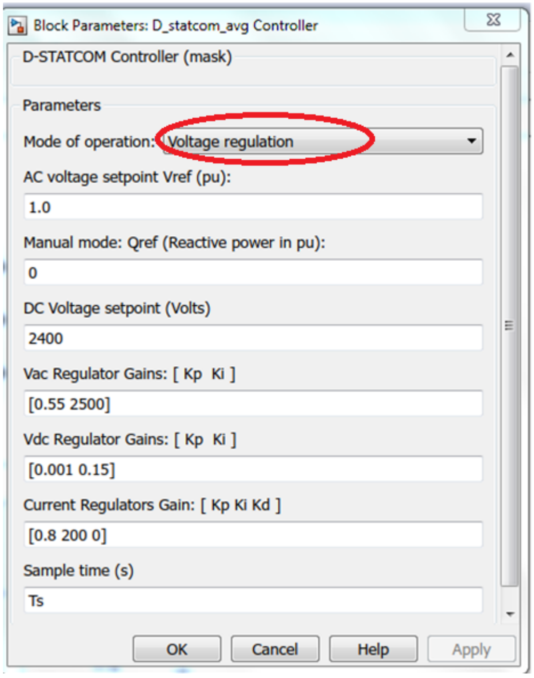

Figure 3.3 Voltage Regulation Mode of D-STATCOM

If the desired outcomes stated in the above two test cases were achieved, then it indicates that the D-STATCOM model developed is workable in voltage regulation with mere reactive power compensation. The results of these test cases were presented in the next chapter.

There is another aspect required to be highlighted on the simplified power system model here is that it acts as a reference that can be further extended by actual hybrid power system in the later modeling. It means the programmable ideal voltage source used here can be replaced by actual hybrid generators such as Solar PV system, and the loading here can be replaced by utility grid with load connection. These are illustrated in the below diagram in red circle.

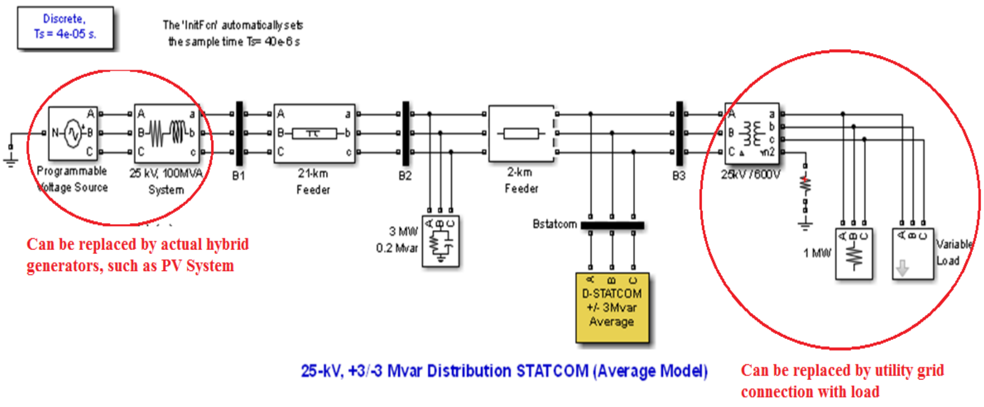

Figure 3.4 Replaceable Simplified Power System

3.2 Development of Hybrid Power System

A 100 kW PV system is intended to be developed as the representation of hybrid power system and it is connected to a 25 kV grid, which serves an opportunity for a 25 kV regulating D-STATCOM in possible alleviation of PQ. The model of such system is as shown below (refer to APPENDIX D for clearer view):

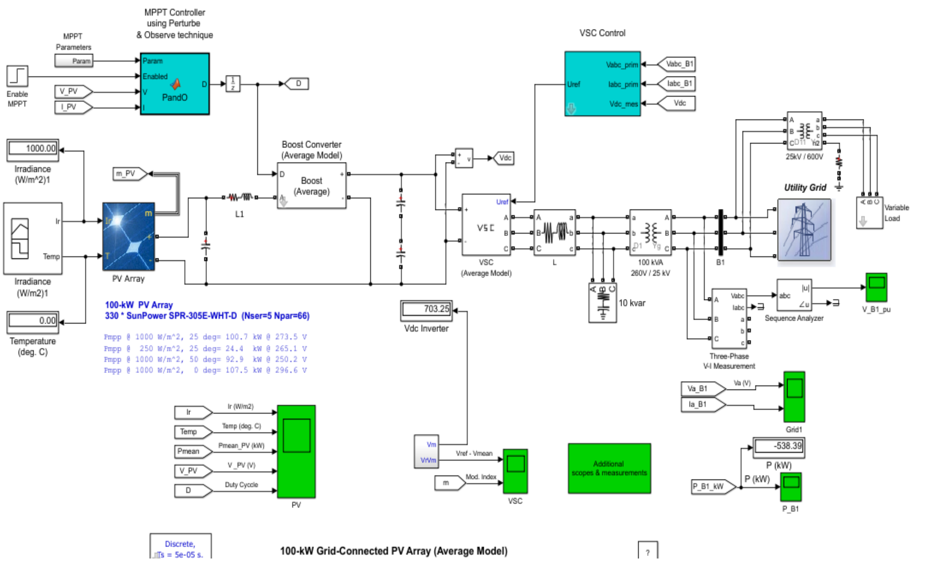

Figure 3.5 Hybrid Power System Model

By referring to the above diagram, the components of the grid-connected hybrid power system with PV system are listed as below, and it is sequenced from the component from left side of the diagram to right side:

- 100 kW PV Array
- DC to DC Boost Converter
- Three Level Three Phase VSC
- 10 kVar Capacitor Bank
- 100 kVA 260V/25 kV Three Phase Coupling Transformer
- Utility Grid

Since the aspect of the study is focusing on the operation of D-STATCOM, the details operation principle for every single component in the hybrid power system as shown in the above list were not included here. Instead, the functions of these components and interaction among them in overall system standpoint were described and reviewed as follow: The PV array used is able to deliver a maximum 100 kW at the standard sun irradiance, which is 1000 W/m^2. The PV panel is a 330 SunPower modules with the part number SPR-305E-WHT-D and having a rated power of 305.2 W under standard test conditions (STC), which are 1000 kW/m^2, 25 degree Celsius and Air Mass (AM) 1.5 solar spectrum. This array consists of 66 strings of 5 series connected PV modules in parallel and the manufacturer specifications for one module is as per snapshot below. Also, there are two inputs that allow user to program the operating temperature and sun irradiance, which is as highlighted in below diagram:

Number of series-connected cells : 96
Open-circuit voltage: Voc= 64.2 V
Short-circuit current: Isc = 5.96 A
Voltage and current at maximum power : Vmp =54.7 V, Imp= 5.58 A

Figure 3.6 PV Module Manufacturer Specifications

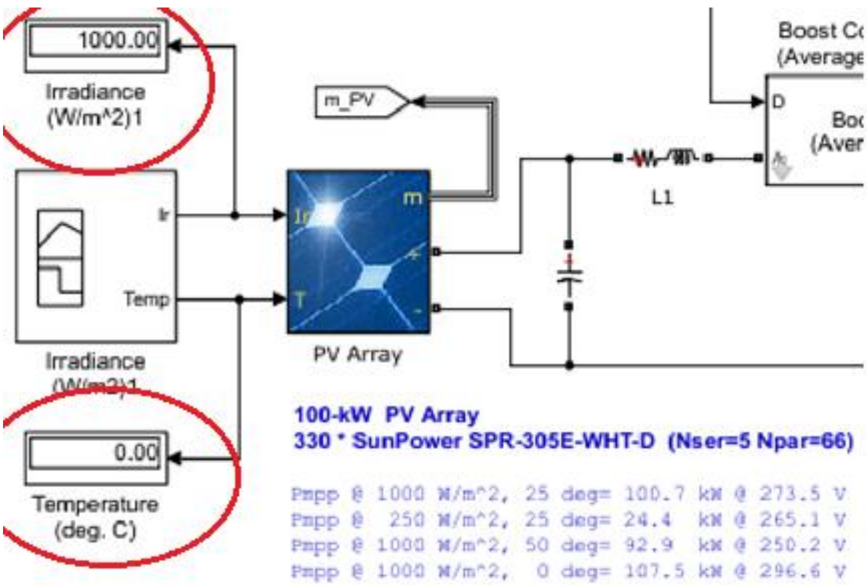

Figure 3.7 Temperature and Irradiance Inputs of PV Array

These temperature and sun irradiance inputs were programmed with a series of variation in different point of time in order to simulate a practical operating environment with changing of temperature and sun irradiance and also to obtain a practical PV array behavior in varying delivered output power due to such practical operating environment. The variation range of the sun irradiance and temperature programmed are from 250 W/m^2 to 1000 W/m^2 and 0 degree Celsius to 50 degree Celsius.

As a result due to the varying operating environment, the real power delivered from the PV system and the natural PV voltages are expected to be changing over different point of time, and these power output is recorded in the later chapter. The snapshot below shows the corresponding PV power output under different temperature and irradiance profile:

Figure 3.8 Different Output Power and Voltage of PV

Apart from the PV array, the DC to DC Converter functions as converting the fluctuating natural PV voltage which is 273 V at maximum power to a constant 500 V DC. The Maximum Power Point Tracking (MPPT) controller is used to extract the maximum power from the different I-V curve of the PV array due to sun irradiance variation. This can be done by deriving the best operating point of voltage and current which can result in delivering maximum output power, and such derivation can be achieved by various MPPT algorithms. The MPPT algorithm used in here is “Perturb and Observe (P&O)” and the detail of this algorithm is as shown in APPENDIX E. From the derived voltage point by MPPT, the switching duty cycle of the DC to DC converter is adjusted to achieve this voltage point since it is the best input voltage point to the DC to DC converter that can produce the maximum output power. Next, the boosted 500 V DC output of the DC to DC converter is going into a three level three phase VSC for converting to 260 V AC. This output AC voltage from VSC is designed to be at unity power factor, because PV system is intended to deliver only in real power form. This VSC adopted IRPT converter topology which requires d-q axis computation and a PLL control for synchronizing with the system voltage. A 10 kVar capacitor bank is used for harmonics filtering that resulted from VSC. To ensure proper interface and coupling between the different voltage level produced from VSC (260 V) and the grid (25 kV), a 100 kVA 260V/25kV coupling transformer was used, and finally it is connected to the utility grid that represents a 25 kV distribution feeder and 120 kV equivalent transmission system.

The objective of this step is to identify the relevant voltage stability issue in the 25 kV grid, which is bus B1 in this developed hybrid power system. Again, since 25 kV grid is the bus that was intended to be regulated, the base voltage value is 25 kV thus 1 p.u. is equivalent to 25 kV. As such, there is only one test case in this step as shown below:

1. Voltage Problem Identification

Under the varying output power from the PV array and the variation of the load in bus B3, the voltage of 25 kV grid is expected to varies from 1 p.u. The variation of the load is programmed at the point of time in 3 s to 4 s.

Desire outcome:

Significant voltage level fluctuation from its steady state value shall be observed during the duration of 3 s to 4 s and identify if there is other voltage problem.

From the derived voltage problem in this session, the next step is attempted to apply the counter measure by utilizing the reactive power compensation from developed D-STATCOM in earlier step.

3.3 Utilization of D-STATCOM for PQ Alleviation

In this step, the voltage problem identified earlier is intended to be alleviated by the D-STATCOM which has been validated for its voltage regulation capability. Hence, it is integrated into the power system as shown in the red highlighted area below (refer to APPENDIX F for clearer view):

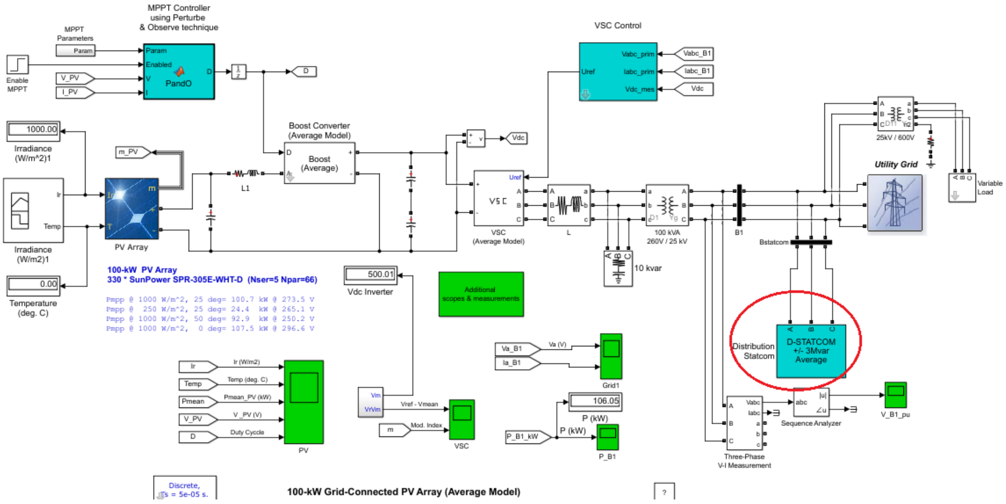

Figure 3.9 Utilization of D-STATCOM in Hybrid Power System

Since this step is aimed to observe the voltage regulation effectiveness of reactive power compensation from the developed D-STATCOM, the test case and desire outcome is straightforward, and it is as shown below:

1. Voltage Regulation by D-STATCOM

   The voltage problem identified in previous step should be mitigated by D-STATCOM

   Desired outcome:

   The 25 kV grid voltage variations should be significantly reduced by D-STATCOM compared to the case of absent in D-STATCOM. It can be observed during the variation loading period of 3 s to 4 s. Relevant waveforms should be shown in order to demonstrate the operation of the compensation from D-STATCOM, such as output voltage of D-STATCOM, leading/lagging current circulating to the grid, reactive power injected and etc.

When the above desired outcome is achieved, it indicates that the reactive power compensation of D-STATCOM is proven good, it can then be modified for ESS integration in order to obtain simultaneous real and reactive power compensation feature.

3.4 Modification of D-STATCOM for ESS Integration

While the previous step validated the usefulness of D-STATCOM in voltage regulation with mere reactive power compensation, this step is aimed to enhance D-STATCOM for real and reactive power compensation simultaneously for better performance in voltage regulation. To fulfill this aim, the existing D-STATCOM model has to be modified so that it can integrate with BESS and fuel cell. Such modification requires addition DC to DC converter which serves as an interface between ESS and DC link capacitor of the D-STATCOM as mentioned in previous review, and it is illustrated graphically in the below diagram to highlight the required modifications:

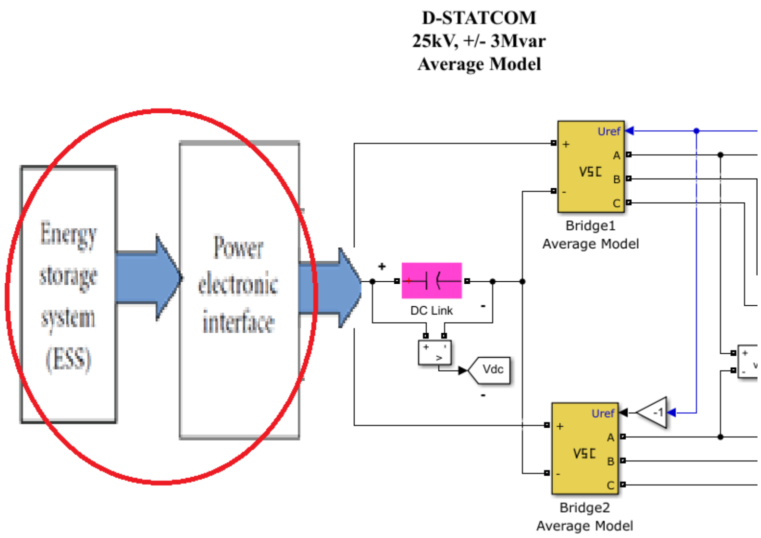

Figure 3.10 Modification of D-STATCOM for ESS

As mentioned previously, the effectiveness of fuel cell integrated D-STATCOM is intended to be carried out by comparing to the mature and proven useful BESS integrated D-STATCOM. Also, in order to test the modified D-STATCOM in real power compensation capability, the condition that demands real power compensation in the hybrid power system has to be created. Based on these concerns, the test cases and desire outcomes of this step can be derived as below:

1. Existing D-STATCOM Modification

   The existing D-STATCOM model has to be modified to two different models: The first one is BESS integrated model, and the second one fuel cell integrated model. These two models are needed because the fuel cell system performance required to be compared with BESS system.

   Desire outcome:

Successful modifications of the existing D-STATCOM model to BESS and fuel cell integration that can be integrated into the hybrid power system and running simulation without any error are expected.

2. Compensation Enhancement (Real and Reactive Power)

   The load connected at 25 kV grid is programmed to be overloaded at selected period of time so that the grid voltage at this period is not stable at 1 p.u. This condition requires real power compensation from D-STATCOM to regulate the voltage, and the modified D-STATCOM model can be tested in this case.

   Desire outcome:

   The fuel cell integrated D-STATCOM can provide real and reactive power compensation to regulate the voltage. Also, such voltage regulation ability is expected having no significant differences from the voltage regulation done by BESS integrated D-STATCOM by comparing the regulated voltage waveforms resulted from both.

From all of the above test cases and desire outcomes in each step, the corresponding results and discussion were presented in the next chapter.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter is aimed to present the results obtained from the test cases derived from the research methodologies in the previous chapter and verify if the results are able to meet the desired outcomes stated earlier in order to achieve the objectives of this study. As this chapter linked directly with the previous chapter in the form of derived test cases, the results here are presented by putting the same test case title and discussions of the obtained results were made under the test case title for the ease of reference.

4.1 Development of D-STATCOM model

This step consists of two test cases as stated earlier, which are 1. Load Variation (Voltage Flicker) and 2. Voltage Source Variation. The results from these cases were presented as below:

1. Voltage Source Variation

This test case programmed three steps of source variation by raising the source voltage by 6%, dropping it by 6% and restoring to nominal value of 1.077 p.u. These variations happened at 0.2 s, 0.3 s, and 0.4 s, and as a result the grid voltage is fluctuating accordingly in these points of time. Such variation induces D-STATCOM for voltage regulation by reactive power compensation, and the results were as shown below:

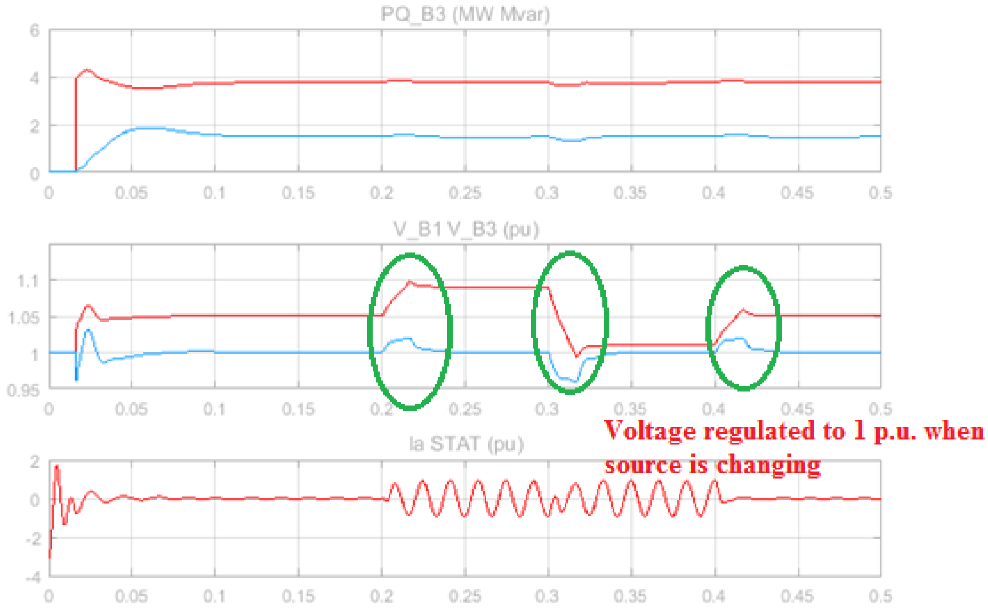

Figure 4.1 Voltage Regulation Waveform of D-STATCOM

Referring to the above diagrams, the green highlighted area shows the successful voltage regulation from D-STATCOM. The source voltage, V_B1 (red colour waveform) is changing at the faulty timing (0.2 s, 0.3 s, 0.4 s) as stated earlier and the grid voltage bus B3, V_B3 (blue colour waveform) is regulated to 1 p.u. at these points of time. The PQ_B3 waveform shows the real power (P, red colour) and reactive power (Q, blue colour) at the grid bus B3, and it indicates a reception of reactive power injected from D-STATCOM at Q waveform. Lastly, the Ia STAT waveform is a current waveform showing the injected current from D-STATCOM to the grid for the attempt of voltage regulation, and it indicates the reactive power compensation is successful.

To further display the operation of reactive power compensation in D-STATCOM, the grid voltage, grid current, and the D-STATCOM inverter voltage waveforms were presented in the diagram below:

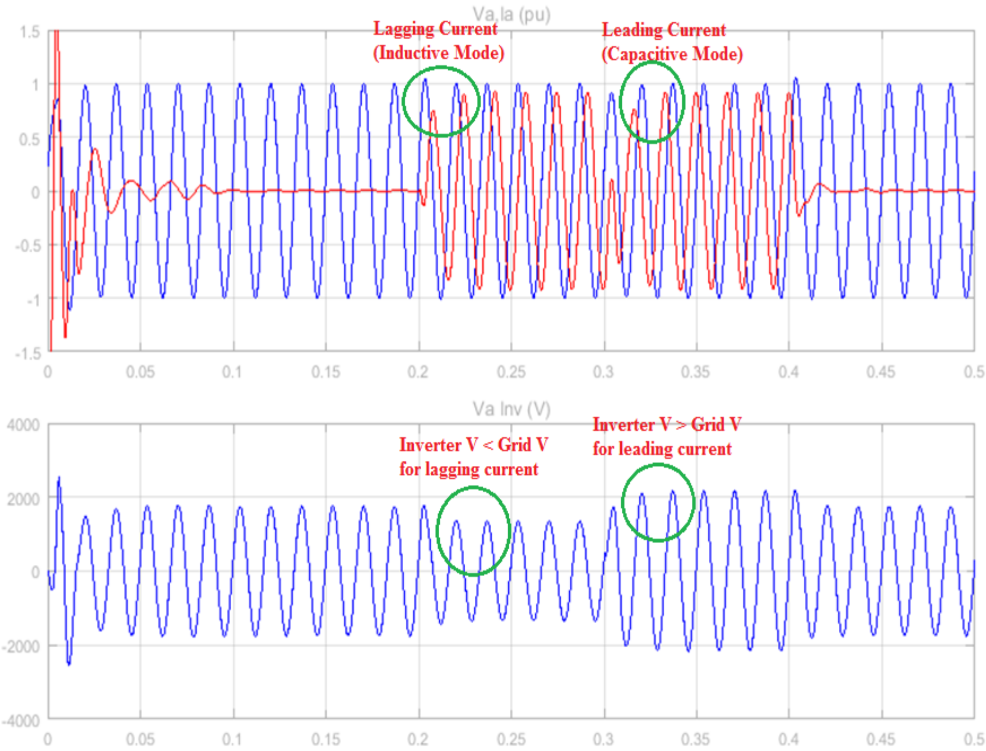

Figure 4.2 Voltage and Current Waveform of D-STATCOM Compensation

Referring to the waveforms above, the leading and lagging current were successfully injected at different point of time for the desired corresponding reactive power compensation. For example, the grid voltage was raised at 0.2 s due to source voltage was raised, thus the D-STATCOM behaved in inductive mode by injecting lagging current to the grid to absorb the reactive power and regulate the voltage back to nominal value of 1 p.u (as shown in V_a I_a waveform in green circle). Also, referring to the voltage waveform of the D-STATCOM inverter (as shown in V_a_inv, second graph), the inverter voltage is tuned lower than grid voltage to produce the desired lagging current. The reverse of this fashion applied to 0. 3 s for the leading current injection resulted from the inductive mode of D-STATCOM as highlighted in the green circle in above graph due to the drop of grid voltage and the need of supplying reactive power.

Further waveforms were obtained to display the operation of D-STATCOM in deeper level, such as DC Link capacitor voltage, modulation index and power absorption or production, and they are as shown below:

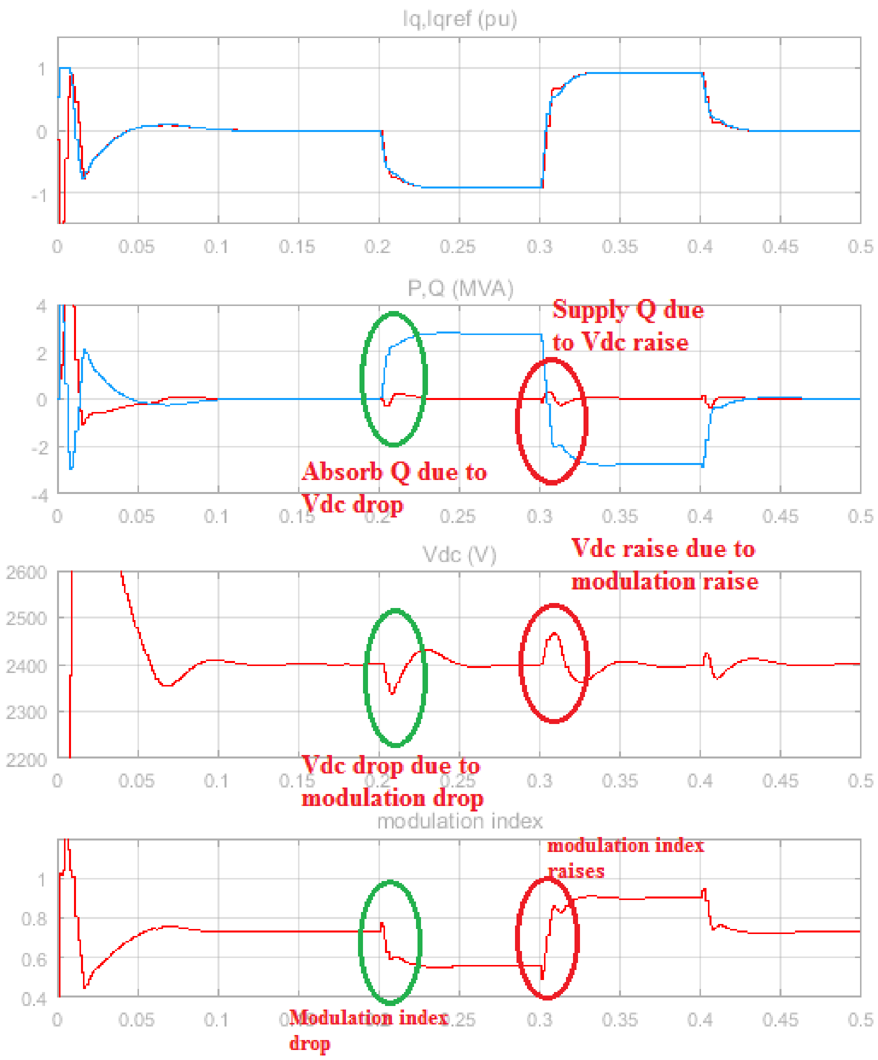

Figure 4.3 Internal Waveforms of D-STATCOM

The above diagrams show the corresponding action DC Link capacitor voltage and modulation index based on the reference parameters from I_q ref. The first waveform I_q ref shows the grid voltage condition to the D-STATCOM inverter at the faulty timing. The second waveform shows the real and reactive power absorption or production of the D-STATCOM. The third waveform shows the DC voltage of the DC terminal of the inverter. Lastly the fourth waveform shows the modulation index of inverter. Based I_q reference information as shown in the first waveform, and considering the point of time at 0.2 s which needs an absorption of reactive power for voltage regulation purpose, the modulation index was reduced to reduce the DC voltage of the input terminal DC Link capacitor in the inverter. The drop of such DC voltage induced the drop in magnitude of the output voltage of the inverter, and thus the D-STATCOM absorbed the reactive power (indicated as positive in the second graph, PQ waveform). These were highlighted in green circle in the above. The reverse of this fashion applied to 0.3 s which was highlighted in red circle for supplying reactive power, Q.

From all of the above waveforms obtained, the operation of this developed D-STATCOM model in regulating the voltage due to variation of source can be concluded as below (considering at 0.2 s):

When the source voltage is increase, the grid voltage is increased. As a result, I_q ref is decreased to indicate the need of reactive power, Q absorption of D-STATCOM to reduce the grid voltage. To achieve the absorption, the modulation index is decreased, which induced DC voltage (V_{dc}) of inverter decreased as well. Finally, due to the effect of the reduced V_{dc} , the output voltage of the inverter (V_a_inv) is decreased and it is lower than grid voltage in magnitude, which allows lagging current to be injected into the grid (inductive mode), then the reactive power, Q is able to be absorbed by D-STATCOM to regulate the grid voltage to nominal value at 1 p.u.

The above operation was in reverse fashion for 0.3 s. At this rate, it can be concluded that the desired outcomes of this test case was achieved. The second test case results are as follow:

2. Load Variation (Voltage Flicker)

As mentioned previously this step is aimed to test the D-STATCOM voltage regulation under the continuous variation of load which induced a continuously change of voltage (voltage flicker) from nominal value. The results of this step are done by comparing the voltage variation before turning on D-STATCOM and after turning on D-STATCOM for voltage regulation mode. These results are presented side by side for the ease of comparison, which is as shown below:

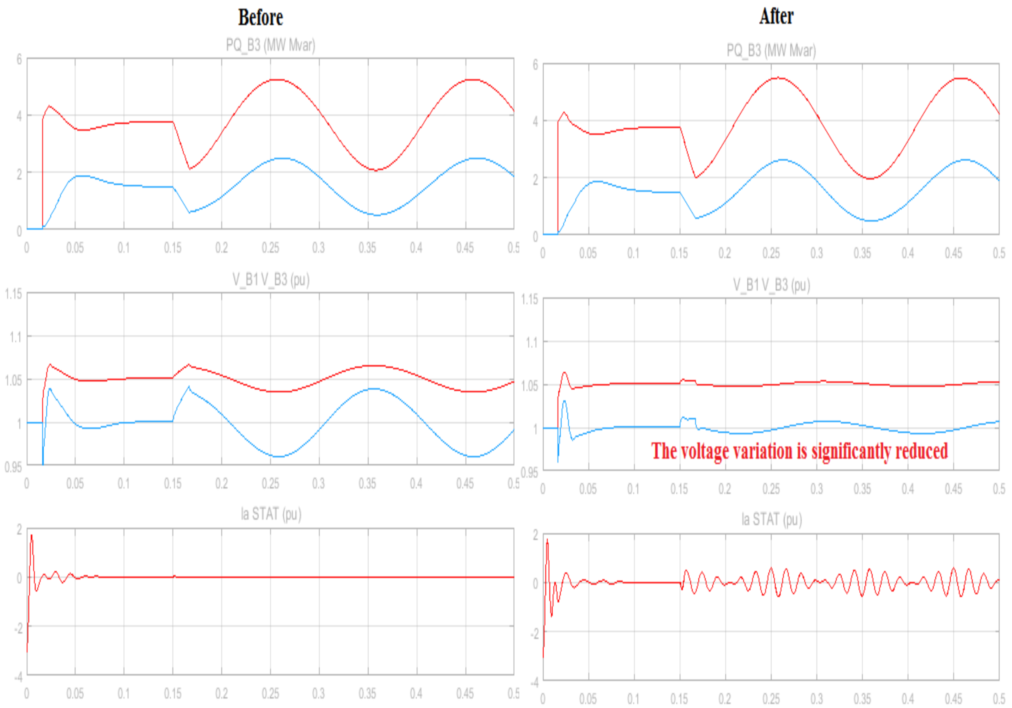

Figure 4.4 Before and After D-STATCOM Turning On

Referring to the above comparison graph, the first graph shows the real and reactive power drawn by the load, and they remained unchanged before and after turning on the D-STATCOM since power drawn is solely depending on load which has is not affected by D-STATCOM, thus it shows a proof that both cases of before and after turning on D-STATCOM are under the same loading effect. In the second graph which shows the source voltage (V_B1) and grid voltage (V_B3), it is obvious that the grid voltage variation was significantly reduced from ± 4% (before turning on D-STATCOM) to ±0.7% after turning on D-STATCOM voltage regulation mode. In the third graph (Ia_STAT), it further shows that there is no injected current from the D-STATCOM to the grid before turning on the D-STATCOM, and current is injected into the grid after turning on the D-STATCOM for voltage regulation purpose. Such results obtained were fully meeting the desired outcomes of this step.

Similarly, further waveforms were obtained to further observed the operation of the D-STATCOM during this test case. One of the examples is the output waveforms of D-STATCOM, and they are putting side by side for the ease of comparison in before and after turning on of D-STATCOM:

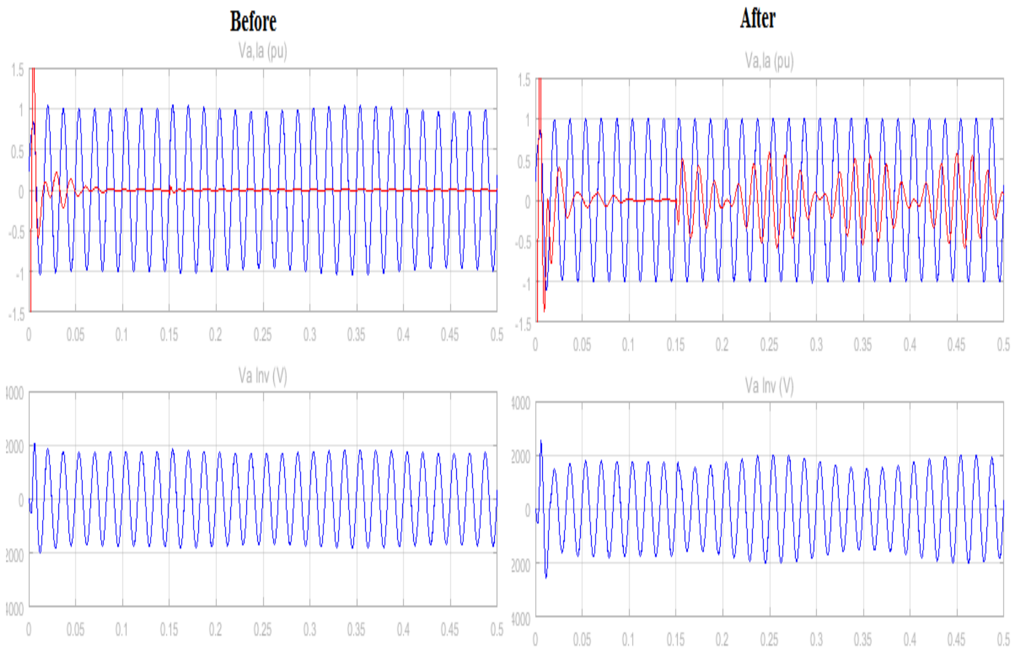

Figure 4.5 Before and After Turning On D-STATCOM

As shown in the above comparison, there is no injected current (I_a, (red colour) and no changes of the inverter output voltage magnitude (V_a_inv, blue colour) before turning on the D-STATCOM. After turning on the D-STATCOM, the injected current and inverter output voltage are changing continuously to mitigate the continuously changing load. The internal parameters of the D-STATCOM, such as modulation index, DC voltage of the inverter and etc., were compared in the same fashion as well and it is as shown below:

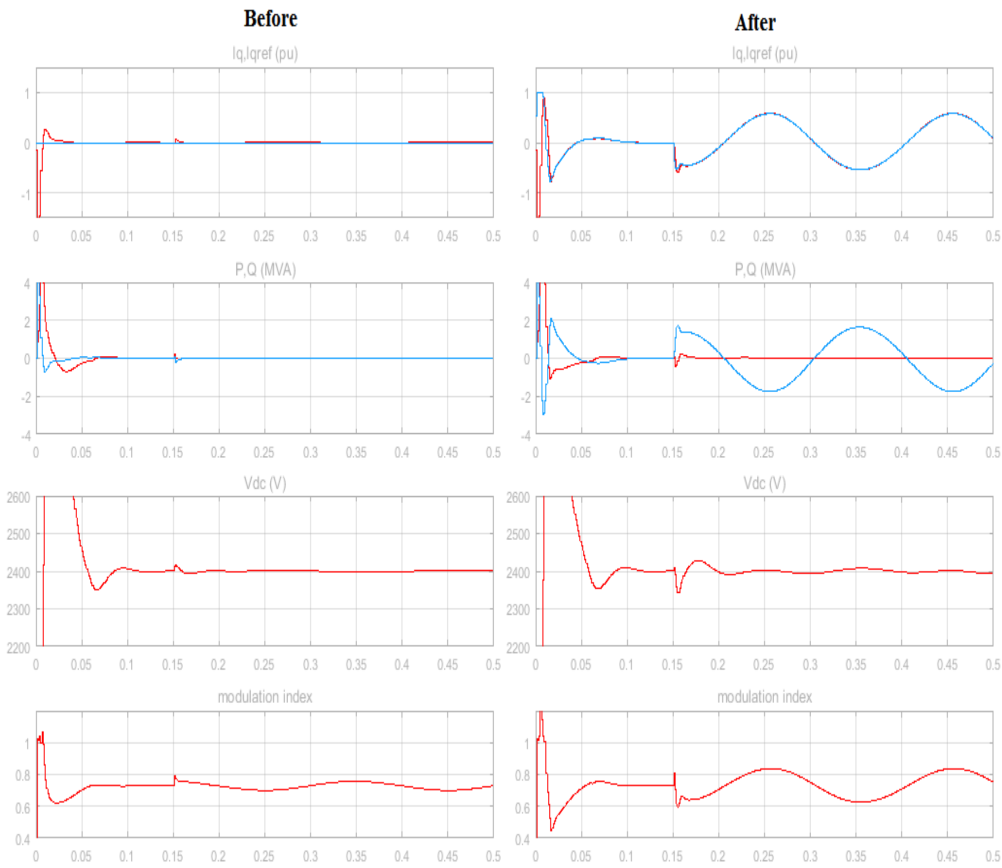

Figure 4.6 Before and After of Internal Parameters of D-STATCOM

Similarly, there is no any action in all of the parameters before turning on the D-STATCOM as shown in the above comparison. In contrast, modulation index (fourth graph), DC voltage of the inverter (third graph), reactive power exchange (second graph in blue waveform) and the reference I_q (first graph) were changing continuously as well to regulate the grid voltage. These operations were behaving in the same mechanism as mentioned in the previous test case.

As a conclusion from all of the results obtained in this test case, it can be derived that the developed D-STATCOM is able to meet the desired outcomes by mitigating the continuous voltage variation. As all of the desired outcomes from these two test cases were successfully achieved, it can be concluded that the developed D-STATCOM model is proven useful in voltage regulation aspect and can be used for the further analysis in the later stage which dealing with the actual interested hybrid power system.

4.2 Development of Hybrid Power System Model

The aim of this step is to identify the voltage problem of the formulated hybrid power system that made of PV system earlier. Also, in the aforementioned, the PV system is going to delivered varying output power due to the constant change in the temperature and sun irradiance profile of the operating environment. The result of the output power delivered from this system and relevant waveforms which can describe the behavior of such formulated system are as shown below:

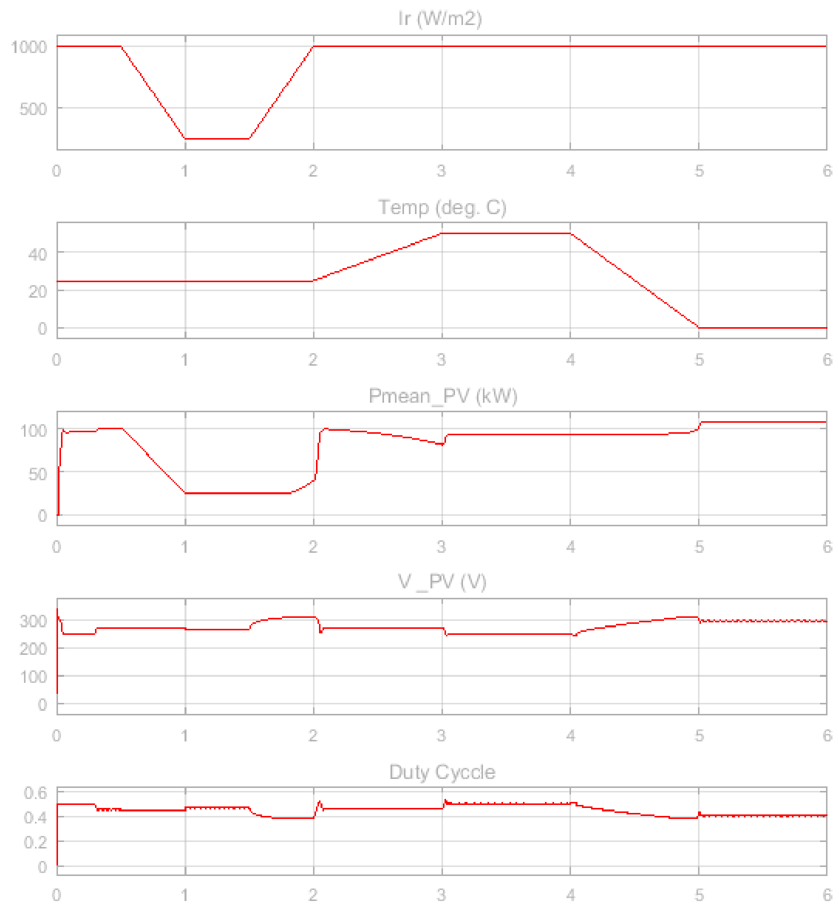

Figure 4.7 Output Power and Waveforms of Hybrid Power System

Referring to the above results, several discussions were made as follow: The first and second graphs are the sun irradiance and the temperature profile that programmed which defined the operating environment. Under such profile, the third graph, which is the output power delivered by the PV array (P_{mean}_PV) is varying over time and these variation are matching to what have been specified in manufacturer datasheet under corresponding temperature and sun irradiance as shown previously in Figure 3.8 . The fourth graph shows a varying PV natural voltage behavior over time and such variation is due to the switching duty cycle is changing over time as shown in the fifth graph. The duty cycle is changing because the MPPT controller is adjusting the operating voltage of the PV to the best value that can provide maximum power under different temperature and sun irradiance profile.

Apart from the waveforms that shows the PV array behavior in this model, it is interested to confirm the current drawn in the grid is matched with the trend of the output power delivered from the PV array. Such confirmation can further ensure the PV array is delivering the power only in unity power factor, which means it supplies power only in real power form. This is the design nature and intention of a grid connected PV system. The current drawn at the grid and the PV array output power were compared side by side in the diagram below (first graph is I_a, grid current and second graph is PV output power, P_{mean}_PV) and it can be concluded that such confirmation is achieved since the both of the changing trend are the same:

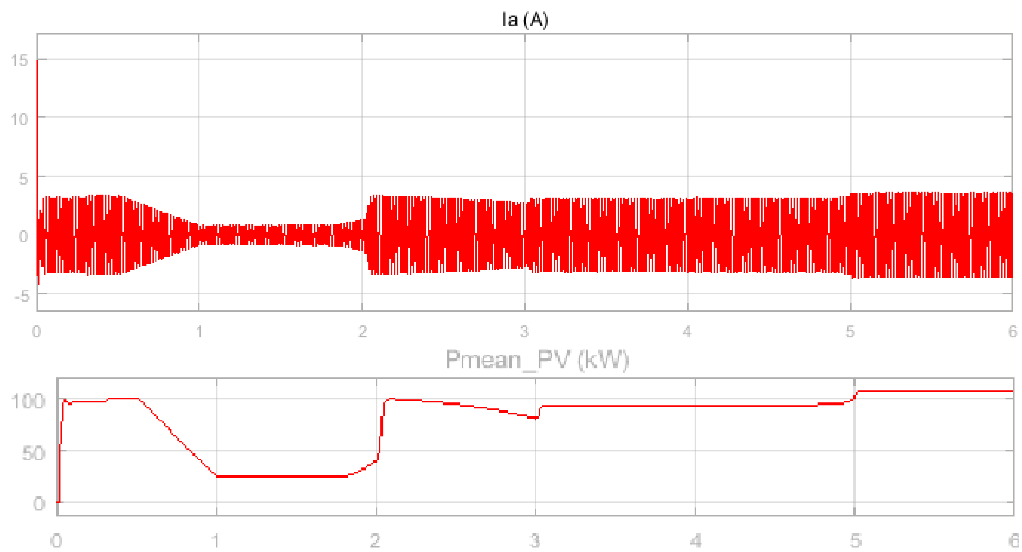

Figure 4.8 Grid Current and PV Output Power

From the above waveforms obtained, it can be concluded that the PV system model used in this hybrid power system is behaving within expectation since it matched the known and specified nature of PV in delivering different output power over time under the varying temperature and sun irradiance in operating environment. At this rate, the test case of this step which is identifying the voltage problem mentioned earlier can be carried out and the result is as shown below:

1. Voltage Problem Identification

Apart of the varying output power delivered from the PV system, there is a variable load drawing constant change of current from the grid at the period of time in 3 s to 4 s. In the combination of the above effects, the hybrid power system was modeled and the waveform of the grid voltage in 25 kV network (equivalent to 1 p.u.) is as shown below:

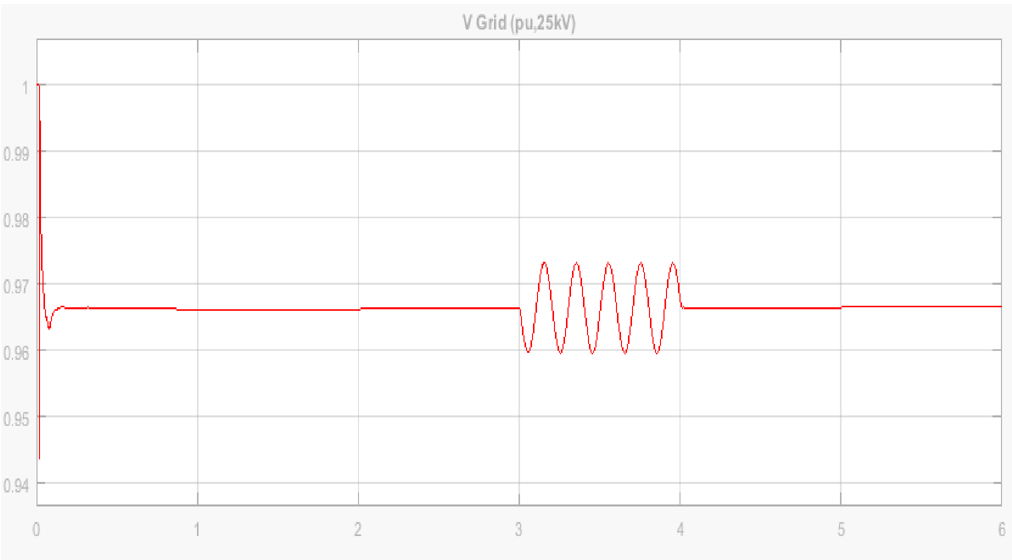

Figure 4.9 Grid Voltage Instability in Hybrid Power System

From the above grid voltage waveform, the voltage problems in this hybrid power system due to the mentioned effects can be concluded as the two points below:

1. The grid voltage is not stabilized at nominal 1 p.u., instead it is at 0.967 p.u.
2. There is a significant fluctuation of ±1.4% in voltage during the period of 3 s to 4 s due to the variable loading during this period of time.

At this rate, the desired outcomes for this step were met since the voltage problems of this hybrid power system were able to be identified as shown in the above list. It paves a way for the D-STATCOM to be utilized in this system for mitigating these identified voltage problems. The results of this D-STATCOM utilization are in the following session.

4.3 Utilization of D-STATCOM

Since this step is aimed to utilize D-STATCOM in alleviating the two voltage problems identified previously, the desired outcomes of this step can be further derived to more specific terms as shown below:

1. To regulate the grid voltage from 0.967 p.u.to nominal value of 1 p.u.
2. To reduce the amount of fluctuation (±1.4%) in the grid voltage during the period of time between 3 s to 4 s.

Based on the above expected outcomes, the results of the voltage regulation by D-STATCOM were presented below to verify if these expected outcomes were achieved.

1. Voltage Regulation of D-STATCOM

In order to check the effectiveness of the D-STATCOM in voltage regulation, the results were presented as shown below by comparing the grid voltage waveform before and after the D-STATCOM (in p.u.) regulates the voltage.

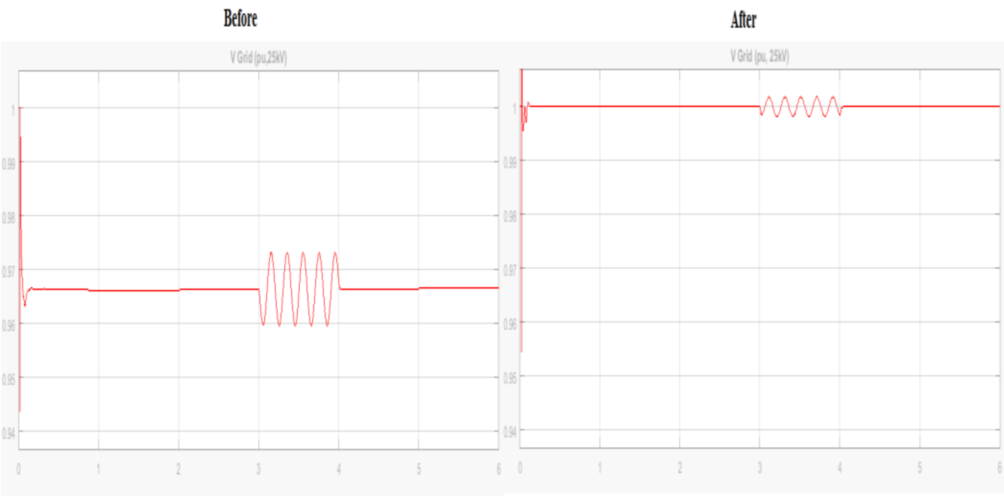

Figure 4.10 D-STATCOM Voltage Regulation in Hybrid Power System

From the above comparison result in grid voltage waveform as shown above, the observations below can be made after the D-STATCOM was turned on:

1. The grid voltage was stabilized to 1 p.u. (from 0.967 p.u.) after turning the D-STATCOM.

2. The degree of fluctuation in grid voltage during the period of 3 s to 4 s was significantly lesser after D-STATCOM was turned on, which is from ±1.4% to ±0.3%.

From the above results, it can be seen that the desired outcomes for this step were achieved. Hence, it can be concluded that the D-STATCOM developed is effective in alleviating the voltage problem in hybrid power system with reactive power compensation. Further waveforms were obtained and as shown below to demonstrate the compensation activity of D-STATCOM when it is trying to regulate the problematic grid voltage.

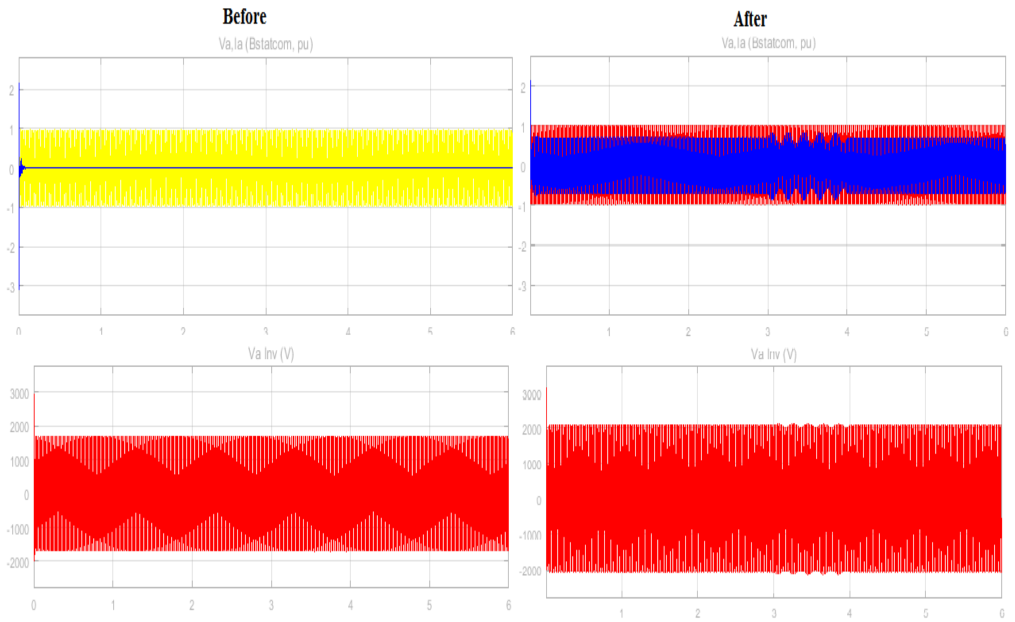

Figure 4.11 Grid and Inverter Voltage Comparison

The waveforms above are presented in comparison form with before and after D-STATCOM turned on in phase basis. The first graph shows the grid phase voltage and current. Before the D-STATCOM was turned on, it can be seen that there is no injected current into the grid as shown in blue colour waveform in the graph of left side. After the D-STATCOM was turned on, reactive current was injected into the grid as shown in blue colour waveform in the graph of right side. The injected current is needed in the entire 6 s period because it needs to stabilize the grid voltage from 0.967 p.u. to 1 p.u, and also the injected current is fluctuating in the period of 3 s to 4 s to compensate the variation of load in this period. In the second graph, it shows the inverter output voltage of the D-STATCOM. It can be seen that the magnitude of the inverter output voltage does not change at all before the D-STATCOM was turned on, because it does not need to inject compensating current into the grid. In contrast, due to the need of injected current after the D-STATCOM was turned on, there are changes in the inverter output voltage in order to inject the current, and it is more significant during the 3 s to 4 s period since it is regulating the variation of voltage.

The grid phase voltage and current waveform after the D-STATCOM was turned on as shown above were zoomed for a clearer view, and it was separated to two zone: The first zone is in the time period of 3 s to 4 s, and the second zone is the other time out of these 3 s to 4 s. The second zone in here was selected to be 1 s to 1.5 s, and any period of time as long as it is not the same time selected in the first zone, because the rest of the time is exhibiting the same behavior in the grid voltage and current. These are as follow:

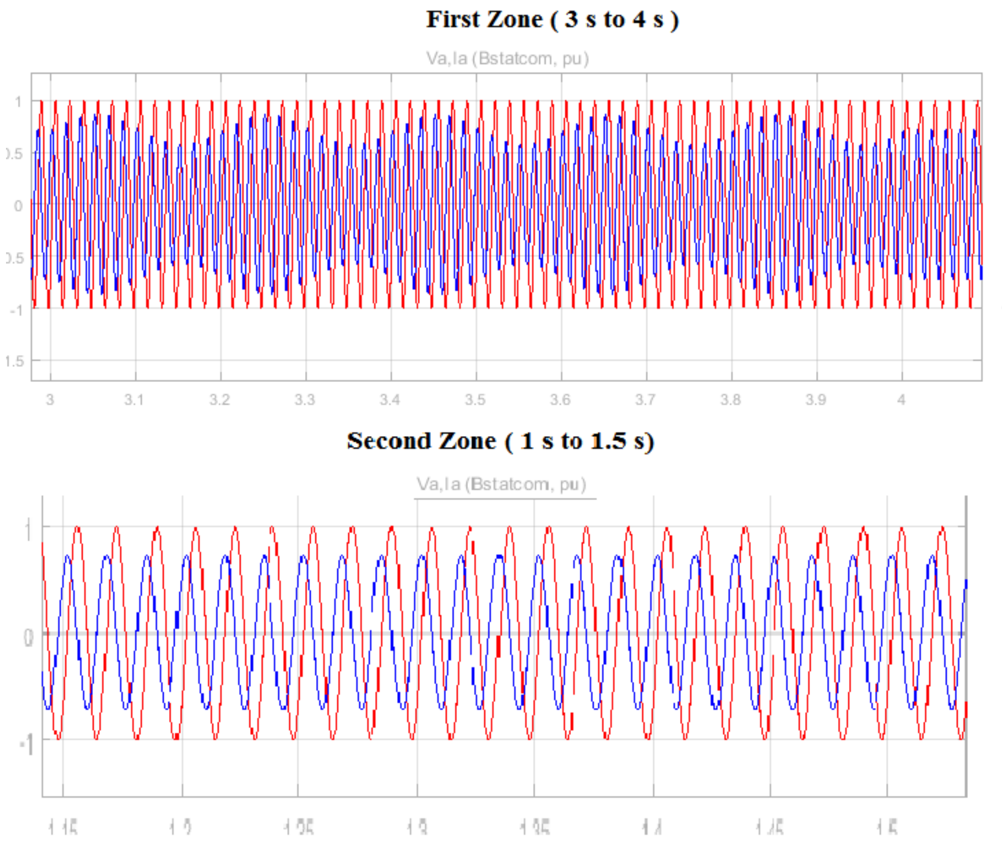

Figure 4.12 Zoom in of Grid Voltage and Current

As shown in the above waveforms, specifically on the first zone which is the period of 3 s to 4 s that having great fluctuation of grid voltage due to variable loading, it can be seen clearly that the injected current to the grid is also fluctuating in order to regulate the voltage to nominal value, and the result shown earlier proves that the grid voltage fluctuates in significant lesser degree (±0.4%). On the other hand, the second graph which is having the period out of 3 s of 4 s (1 s to 1.5 s in here), the injected current is constantly in leading phase with the grid voltage (inductive mode). This is because the grid voltage requires to be stabilized to 1 p.u. from 0.967 p.u. and it is achieved by supplying of reactive power from D-STATCOM.

Apart from the grid voltage and current aspect as shown above, the internal parameters of D-STATCOM, such as I_q*ref*, reactive power, V_{DC} and modulation index, were compared in the form of before and after D-STATCOM turned on as well. These are as shown below:

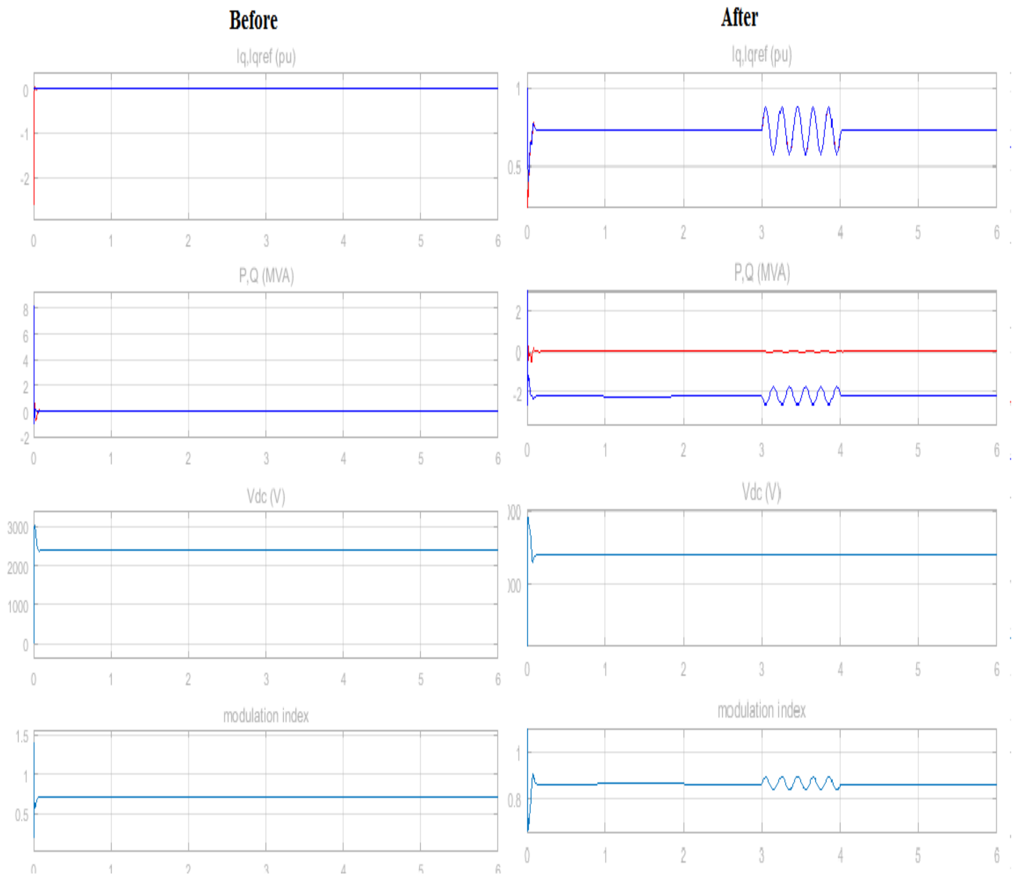

Figure 4.13 Internal Parameters Comparison of D-STATCOM

From the above comparison, it can be seen that all of the parameters are not changing throughout the entire period when D-STATCOM was turned off. In contrast, these parameters show changes after it was turned on. Based on the information from the $I_q$ref (first graph) derived which indicates the need of compensation, the modulation index (fourth graph) was reacted accordingly by increasing the index value. As a result, the DC voltage of the D-STATCOM inverter, V_{DC} (third graph) was increased that can cause the increase in inverter output voltage to behave in inductive mode by injecting leading current. This is proven valid in the reactive power waveform (second graph) in blue colour because it is in negative value which can indicate the supply of reactive power due to inductive mode. All of these responses for the parameters were meeting expectation.

As a conclusion from all of the results above, it can be concluded that the developed D-STATCOM is able to provide effective voltage regulation since all of the desired outcomes of the test cases were met. The step here is considered successful at this stage. As mentioned previously, the model at this rate is still in the standpoint of reactive power compensation alone which has been proven here, it can be now extended further to find out the enhancement possibility (real power compensation) for the D-STATCOM by integrating it with ESS via modification of the D-STATCOM structure. These results are as shown in the next session.

4.4 Modification of D-STATCOM for ESS Integration

As introduced earlier, the step here is aimed to modify the D-STATCOM in order to achieve the integration with BESS and Fuel Cell. The effectiveness in real and reactive power compensation in alleviating the voltage problem is intended to be compared between BESS and fuel cell. The results are as shown below in the respective case title.

1. Existing D-STATCOM Modification

The diagram below shows the modification done for the D-STATCOM to integrate with BESS in red highlighted:

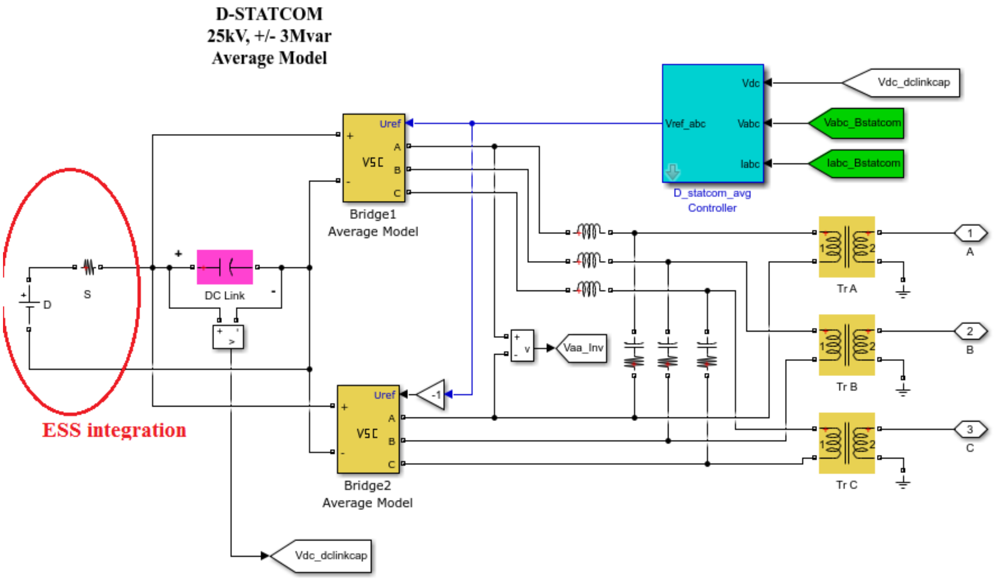

Figure 4.14 BESS Integrated D-STATCOM Model

As shown in above diagram, the BESS is modeled by a source with internal resistance and it is connected to the DC link capacitor of the inverter. The BESS is having the nominal voltage which is the same with the DC voltage of the input terminal (2.4 kV). To ensure such modification to the D-STATCOM does not impose unforeseen behavior and still maintaining its reactive power compensation ability, this ESS integrated D-STATCOM was retested in the simplified power system model as shown in the earlier test step (Figure 3.2), and it demonstrated the same outcome in session 4.1. Hence, it was good to continue for real power compensation test case, which is as shown in the following.

2. Compensation Enhancement (Real and Reactive Power)

In order to test out the real power compensation of the BESS integrated D-STATCOM, the hybrid power system has to be modified to create a need in drawing real power for alleviating the voltage problem. Hence, the load in the system was programmed to be overloaded which lead to voltage drop in the time period of 2 s to 2.5 s. Similarly, in order to investigate the effectiveness of the real power compensation in regulating the voltage drop, the results were presented in comparison form of before and after turning on the real power compensation in the grid voltage waveform. This is as shown below:

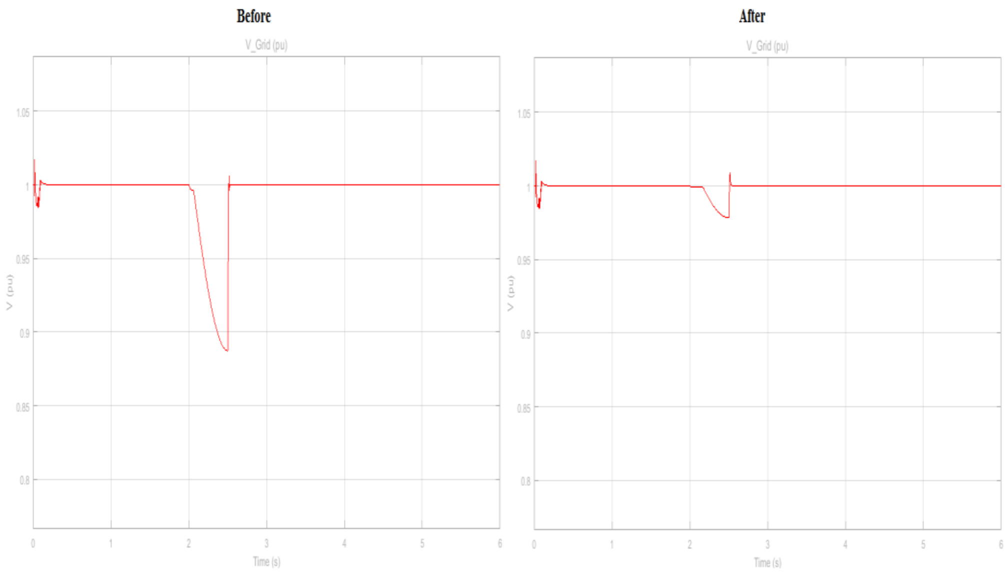

Figure 4.15 Before and After for BESS Integrated D-STATCOM

From the above result shown, there is a significant voltage drop by 12% due to overloading effect during the period of time in 2 s to 2.5 s before turning on the compensation mode of D-STATCOM. Since there is a restriction of size in the comparison diagram above, the below diagram shows a clearer view of the voltage drop:

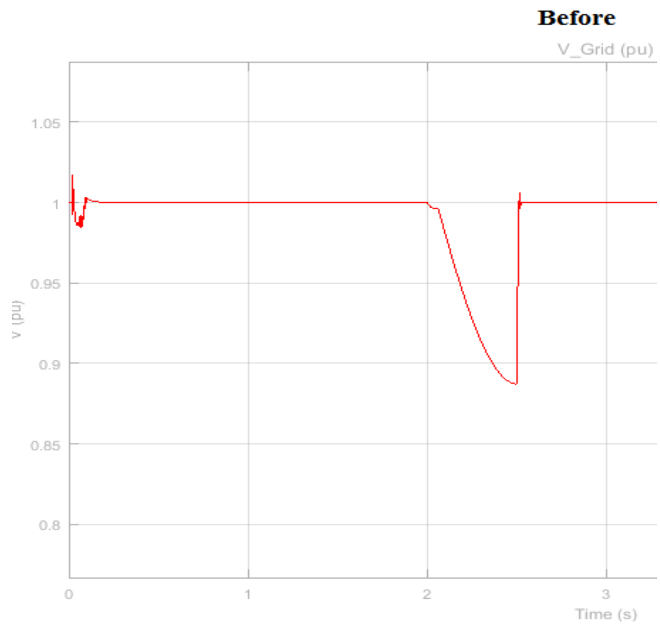

Figure 4.16 Voltage Drop of 12% Due to Overloading

By observing the grid voltage waveform after the compensation of D-STATCOM was turned on, the voltage drop was significantly reduced to 3.7%. Similarly, the clearer view of such voltage improvement is as shown in the diagram below:

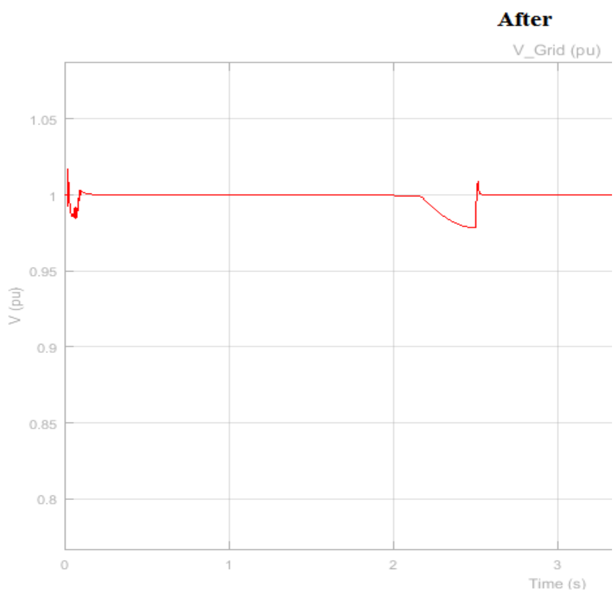

Figure 4.17 Voltage Drop Improvement to 3.7%

From the above result obtained, it can be concluded that the BESS integrated D-STATCOM is effective in voltage regulation with the enhanced operation in real power compensation because it provided real power which required by the grid due to the overloading condition which resulted voltage drop. Such performance of BESS integrated system serves a reference to the fuel cell integrated system which has the same role with BESS.

The fuel cell selected to be integrated with D-STATCOM is with the PEM type of fuel cell, which is as shown below (MathWorks, 2009a):

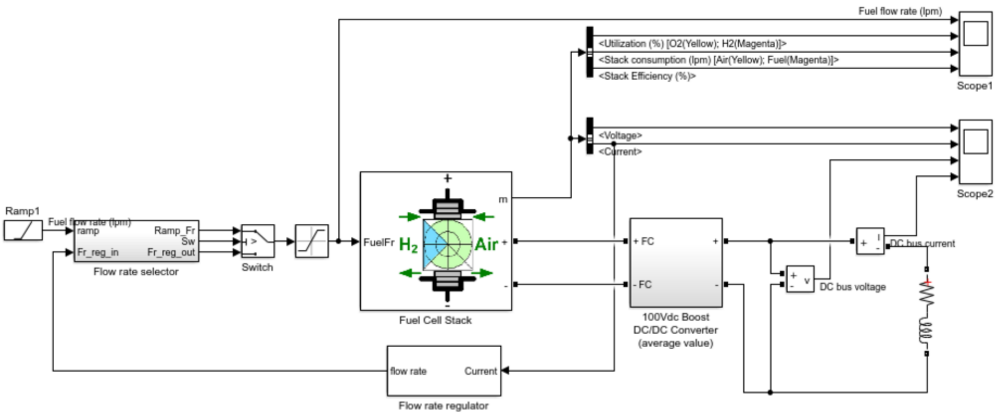

Figure 4.18 PEM Fuel Cell Model

The PEM fuel cell model as shown in the above consists of three components which are:

1. Fuel Cell Stack
2. Flow Rate Regulator
3. 100 V_{DC} DC to DC Converter
4. Fuel Rate Selector
5. 6 kW RL Load

The descriptions of these components are as follow: The PEM type fuel cell stack is having a nominal voltage of 45 V_{DC} and nominal power of 6 kW and it is loaded equivalently 6 kW by a RL load with 1 s time constant. The flow rate regulator is functioned to set the optimal flow rate under different loading to maintain the nominal fuel utilization and efficiency of the system. The Flow Rate Selector is functioned to set the fuel flow rate input. The DC to DC converter is boosting the changing voltage of the fuel cell output due to varying fuel flow rate to a constant 100 $V_{DC.}$

This fuel cell stack system is required to be modified in due to two problematic design aspects:

- Insufficient Output Power

  6 kW is too less to be used in D-STATCOM for compensation purpose.

- DC voltage is too low

  ESS which used to integrate with D-STATCOM requires 2.4 kV to match with its DC input terminal, because the D-STATCOM inverter is voltage sourced inverter operating based in nominal 2.4 kV DC input.

This PEM fuel cell stack system is required to be modified to address the above stated problems in order to be suitable for used in the integration, thus the possible actions needed are derived as below:

- Increasing the output power

One possible action to increase the fuel cell output power is stacking the fuel cell stack in parallel to increase its output current.

- Increase the DC voltage to 2.4 kV_{DC}

  Since the DC to DC converter used in here is only able to boost the voltage from nominal 45 V_{DC} to 100 V_{DC} which is way too less from the target 2.4 kV_{DC}, this DC to DC converter has to be replaced or redesigned in order to boost the output voltage.

When the above actions are completed, it has to be validated its functionality before integrating into D-STATCOM to ensure sufficient output power and output DC voltage are reached. Given both BESS and fuel cell are playing the same role in D-STATCOM, the performance in compensating with real power for the grid to address voltage problem should not differ significantly. The fuel cell integration work was suggested in the future enhancement in order to achieve the comparison with BESS.

CHAPTER 5

CONCLUSION AND FUTURE RECOMMENDATIONS

Hybrid power system is the result of the future trend in grid transformation that greatly promotes renewable energies, and they have posed challenges in the stability and security at distribution level in the form of PQ problems. The potential voltage problems were critically analyzed and demonstrated in this study, such as voltage flicker and voltage drop, by modeling a 25 kV grid tied PV sourced hybrid power system. PV sourced hybrid power system was selected in this study because it is one of the potential RE that can be developed in Malaysia as well as in the world. Shunt compensation is one of the effective approaches that can alleviate the voltage problems raised and this study contributed in-depth analysis on its effectiveness in voltage regulation. The study proposed D-STATCOM as the shunt compensator to alleviate the voltages problem in the developed hybrid power system due to its advantages in terms of functionality and cost. The D-STATCOM model with IRPT converter topology was developed and the voltage problems were effectively alleviated by its reactive power compensation. Besides, the study extended the research work further by enhancing the operation D-STATCOM via ESS integration to the system so that it can have independent and simultaneous real and reactive power compensation. Such enhancement can provide better flexibility to the D-STATCOM operation. In the aspect of exploring environmental friendly solution, the study proposed the innovative PEM fuel cell technology to be the ESS for the integration and the fuel cell model was developed in this study. On the other hand, the BESS integrated D-STATCOM model was developed as well and it was proven to be useful in this study on mitigating the grid voltage drop. Such performance was intended to be compared with the fuel cell integrated D-STATCOM hoping to prove this innovative and greener solution is able to provide the similar performance as the mature BESS technology. The future enhancements of this work were suggested accordingly in below to further extend the value of this research:

- Modification of the proposed PEM fuel cell model

  The proposed fuel cell model is at maximum output power of 6 kW, which can be too low to be used in real power compensation in case of overloading condition in the hybrid power system. The output power can be increased by stacking the cell in parallel so that the output current can be increased without affecting the output voltage level.

- Increase the DC voltage to 2.4 kV_{DC}

  The DC to DC converter in the fuel cell model is only able to boost the voltage from nominal 45 V_{DC} to 100 $V_{DC,}$ but the DC terminal of the D-STATCOM is at 2.4 kV_{DC}. As such, this DC to DC converter has to be replaced or redesigned in order to boost the output voltage from 45 V_{DC} to 2.4 kV_{DC}. Reference design is required to be investigated.

- Functional validation of fuel cell integrated D-STATCOM before integrating to hybrid power system

  To ensure the modification done on the D-STATCOM due to fuel cell integration does not affect its original reactive power compensation capability, it can be tested out first in the simplified power system model proposed as shown in APPENDIX C. Such validation is recommended so that it is easier for troubleshooting in case there is any error or unexpected performance delivered when integrating the modified system in the interested hybrid power system.

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APPENDICES

APPENDIX A – Clark Transformation

The below equation shows the Clark Transformation, which convert abc to dq0 (Akagi et al., 1984):

abc is converted to αβ

$$\begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \times \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix}$$

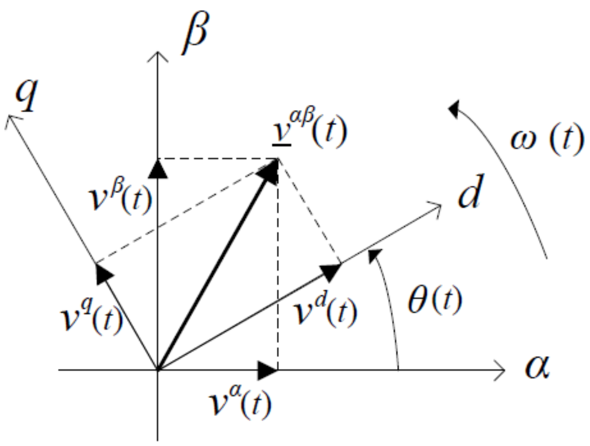
αβ is converted to dq

$$\begin{bmatrix} f_d \\ f_q \end{bmatrix} = \begin{bmatrix} \cos(\phi) & \sin(\phi) \\ -\sin(\phi) & \cos(\phi) \end{bmatrix} \times \begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix}$$

Therefore abc is directly converted to dq

$$\begin{bmatrix} f_d \\ f_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos(\phi) & \cos(\phi-\gamma) & \cos(\phi+\gamma) \\ -\sin(\phi) & -\sin(\phi-\gamma) & -\sin(\phi+\gamma) \end{bmatrix} \times \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix}$$

Relationship of αβ-frame and dq-frame is as shown in the figure below:



APPENDIX B – Inverse Clark Transformation

The below equation shows the Inverse Clark Transformation, which convert dq0 to abc (Akagi et al., 1984):

dq is converted to αβ

$$\begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} = \begin{bmatrix} \cos(\phi) & -\sin(\phi) \\ \sin(\phi) & \cos(\phi) \end{bmatrix} \times \begin{bmatrix} f_d \\ f_q \end{bmatrix}$$

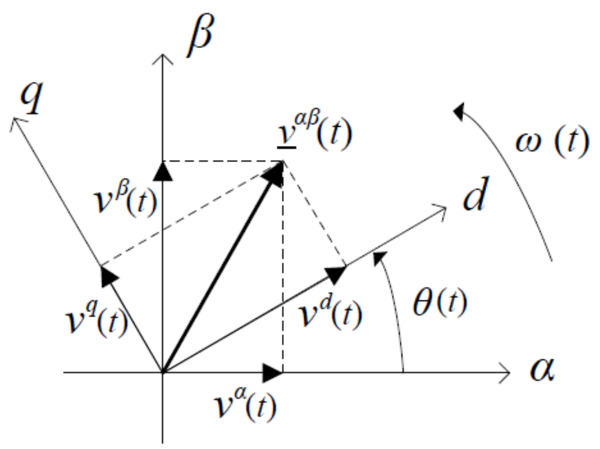
αβ is converted to abc

$$\begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \times \begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix}$$

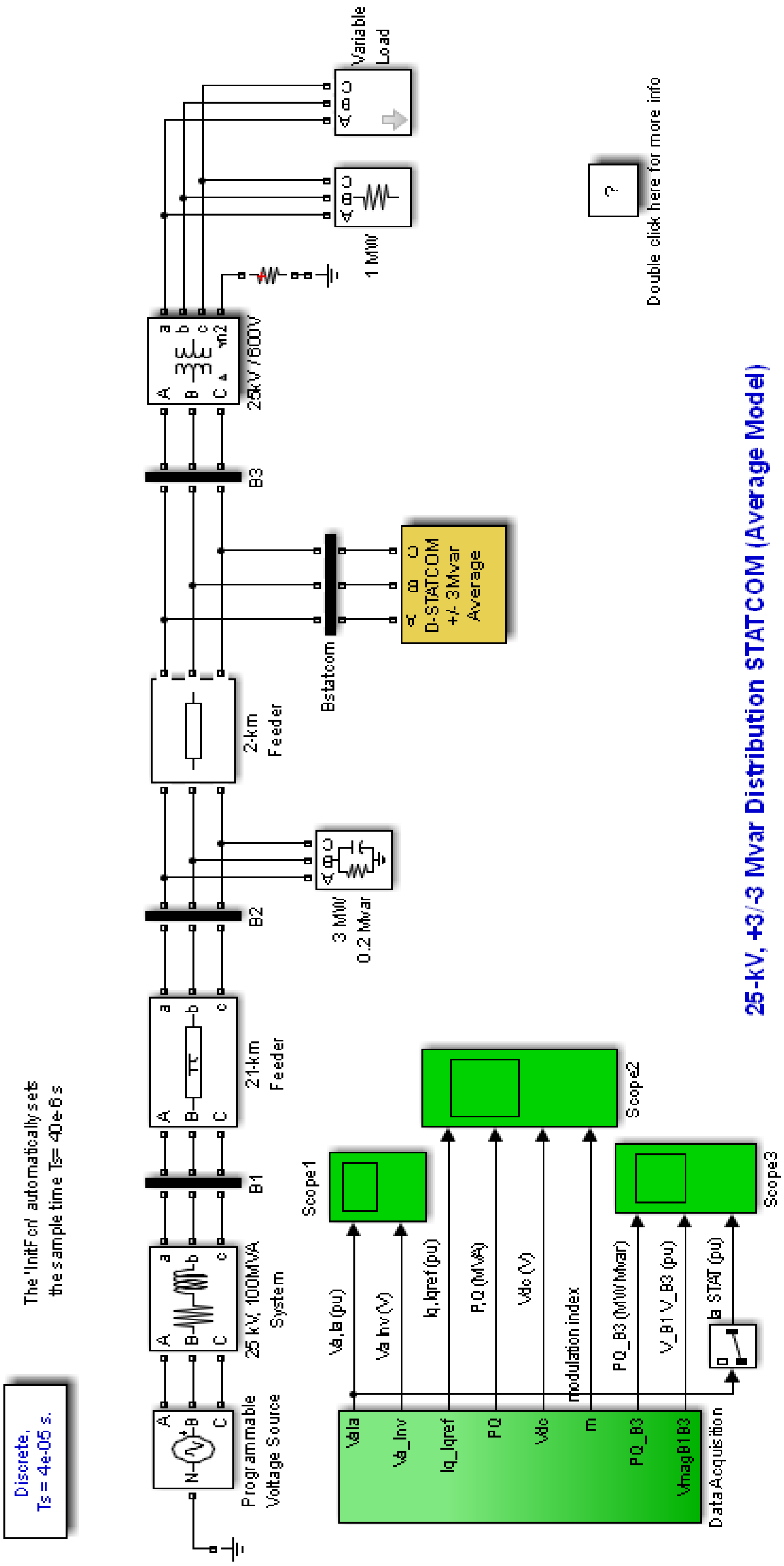
dq is directly converted to abc

$$\begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} = \begin{bmatrix} \cos(\phi) & -\sin(\phi) \\ \cos(\phi-\gamma) & -\sin(\phi-\gamma) \\ \cos(\phi+\gamma) & -\sin(\phi+\gamma) \end{bmatrix} \times \begin{bmatrix} f_d \\ f_q \end{bmatrix}$$

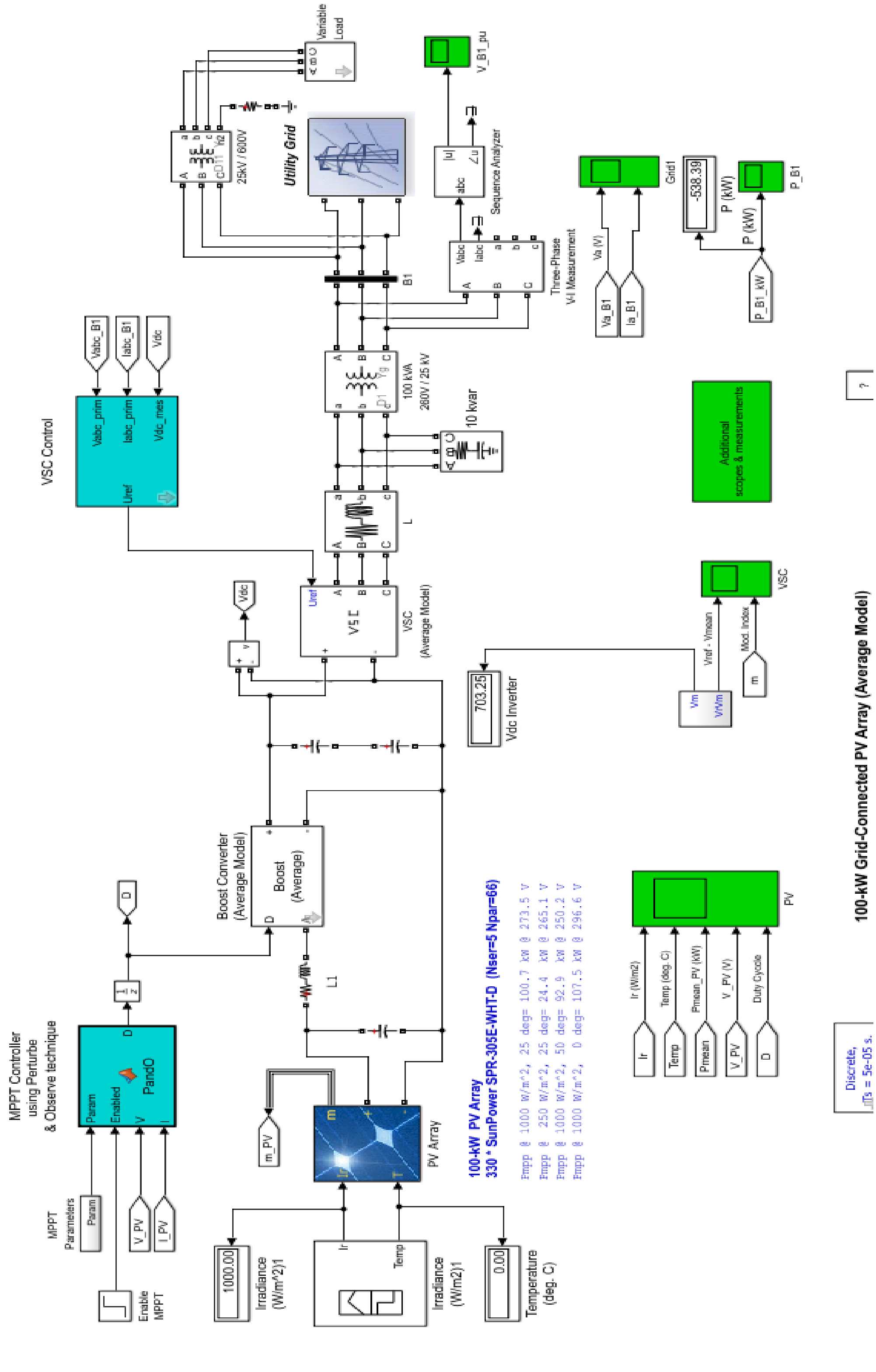
Relationship of αβ-frame and dq-frame is as shown in the figure below:



APPENDIX C – Simplified Testing Power System



APPENDIX D – Hybrid Power System



APPENDIX E – Perturb and Observe in MPPT

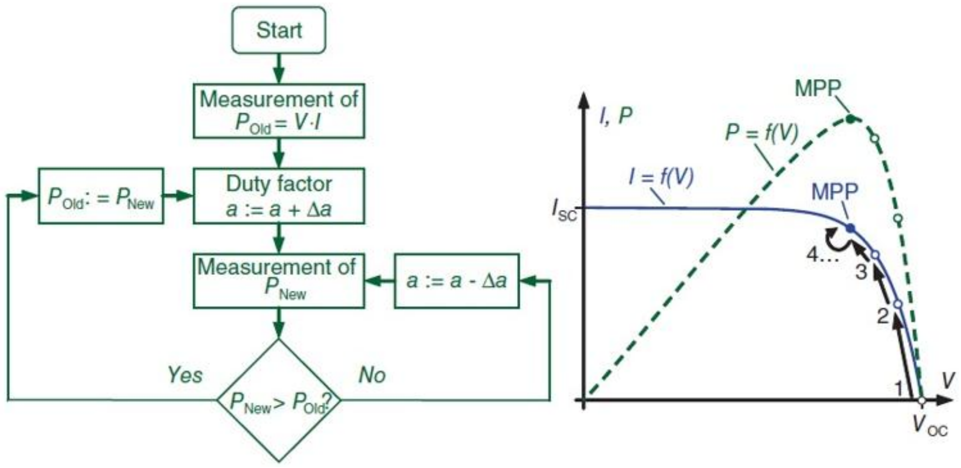


Figure F.1 Perturb and Observe in MPPT

The above diagram (Elgendy et al., 2012) and flow chart demonstrate the P&O algorithm in MPPT. This algorithm perturbs the PV array voltage periodically (observe the point 1 to point 2, point 2 to point 3 and vice versa in the graph) and the corresponding output power is compared with the previous perturbed voltage. The perturbation causes the power of the PV array varies from time to time. When the output power is increasing due to this perturbation, then the perturbation is continued in the same direction. Such process persists until the next perturbed power is greater than previous perturbed power, then the perturbation will reverse the direction. When the condition is stable and the maximum power point is fixed, the perturbation will oscillate around this maximum power point and hence the corresponding operating voltage that gives maximum output power from the PV array is obtained. The above explained algorithm is illustrated in chart form as shown in above. In order to maintain the maximum power point, the perturbation step is needed to be remained small.

APPENDIX F – D-STATCOM in Hybrid Power System