DEVELOPMENT OF D-STATCOM IN HARDWARE IN THE LOOP SYSTEM FOR VOLTAGE SAG MITIGATION

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DEDICATION

I would like to dedicate this thesis to

“ALMIGHTY ”

(Who gave me strength, knowledge, patience, and wisdom)

to my beloved “Parents”

(Their love, devotion, cares, sacrifices, and prayers helped me to achieve this dream)

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"Alhamdulillah", all praise to **ALLAH,** the most gracious and the most merciful, for all the strength and will be provided to the author in completing the research. Without "the mercy", the author is just an ordinary person who may not even understand what the research topic is all about.

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ABSTRACT

The problem of power quality (PQ) is of utmost concern today. The widespread use of electronic equipment such as adjustable speed drive (ASD), programmable logic controller (PLC), information technology equipment in power electronics applications such as energy-efficient lighting brings about a complete change in the nature of the electrical load. These loads are simultaneously major causes and major victims due to power quality problems. The most common types of power quality problems are voltage drops. The main causes of the voltage drop are due to a short circuit in the system, a switching operation, the starting of the large motor, a sudden increase in line loads, electrical fault on utility power lines caused by an animal, trees or other objects in contact with power lines. Therefore, this project is about to develop a Distributed Static Compensator (D-STATCOM) for voltage sag mitigation in hardware in the loop (HIL) with phase shift control technique for maintaining the bus bar-load voltage. It is because the intermittent switching of heavy loads results in voltage sag in the distribution line. The distribution line 400V and the D-STATCOM are modeled using MATLAB-SIMULINK software. In this work, the 6-pulse D-STATCOM configuration with IGBT has been designed. The HIL was develop using the low-cost microcontrollers which are the Arduino Mega 2560 and Raspberry Pi Type B2 with high accuracy response for high speed communication on mimic the real time response. In order to run the D-STATCOM in HIL and test the mitigation of sag, software design is first carried out to illustrate the use of D-STATCOM in mitigating voltage sag in a distribution line. The simulation results for software design proved that the D-STATCOM is capable of mitigating voltage sag as well as improving power quality of a system and the voltage sag 20% was corrected from 200V to normal voltage 245V. The D-STATCOM that has been modeled successfully and able to mitigate the voltage sag by using D-STATCOM in (HIL). At last the results have been analyzed and compared with the results which get in software.

ABSTRAK

Masalah kualiti kuasa (PQ) amat penting hari ini. Penggunaan elektronik yang meluas seperti pemacu kelajuan boleh laras (ASD), pengawal logik diprogram (PLC), peralatan teknologi maklumat dalam aplikasi elektronik kuasa seperti pencahayaan cekap tenaga membawa perubahan lengkap dalam sifat beban elektrik. Beban ini serentak menyebabkan utama dan mangsa utama disebabkan oleh masalah kualiti tenaga. Jenis-jenis masalah kuasa yang paling biasa adalah penurunan voltan. Penyebab utama kejatuhan voltan disebabkan oleh litar pintas dalam sistem, operasi penukaran, permulaan motor besar, peningkatan beban secara tiba-tiba, kerosakan elektrik pada talian kuasa utiliti yang disebabkan oleh haiwan, pokok atau objek lain bersentuhan dengan talian kuasa. Oleh itu, projek ini akan membangunkan Compensator Statik yang Didistribusikan (D-STATCOM) untuk pengurangan kendaran voltan dalam perkakasan dalam gelung (HIL) dengan teknik kawalan anjakan fasa untuk mengekalkan voltan beban bar bas. Ini kerana beban beralih sekejap-sekejap menyebabkan bebola voltan dalam talian pengedaran. Barisan pengedaran 400V dan D-STATCOM dimodelkan menggunakan perisian MATLAB-SIMULINK. Dalam kerja ini, konfigurasi 6-denyut D-STATCOM dengan IGBT telah direka. The HIL telah dibangunkan menggunakan mikrocontrollers kos rendah yang Arduino Mega 2560 dan Raspberry Pi Type B2 dengan respons ketepatan tinggi untuk komunikasi berkelajuan tinggi untuk meniru tindak balas masa sebenar. Untuk menjalankan D-STATCOM dalam HIL dan menguji pengurangan rompakan, reka bentuk perisian mula-mula dilaksanakan untuk menggambarkan penggunaan D-STATCOM dalam meredakan bebola voltan dalam satu barisan pengedaran. Keputusan simulasi untuk reka bentuk perisian membuktikan bahawa D-STATCOM mampu mengatasi kendalan voltan serta meningkatkan kualiti tenaga sistem dan bebanan voltan 20% diperbaiki dari 200V ke voltan normal 245V. D-

STATCOM yang telah dimodelkan dengan jayanya dan mampu mengurangkan bebanan voltan dengan menggunakan D-STATCOM dalam (HIL). Pada akhirnya keputusan telah dianalisis dan dibandingkan dengan hasil yang diperolehi dalam perisian.

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CHAPTER 1

INTRODUCTION

1.1 Background

Power quality analysis is an important aspect of recent research activities. Power is generated by using conversion energy generation where a huge amount of electric power generated from a power plant is generally far away from the load center where it is transported to the consumer via the transmission line. Transmission of electric power from the power generation point to the consumption point is combined with weather fluctuation, load fluctuation, demand fluctuation, etc., to lower power quality. Industrial and commercial power consumers are becoming increasingly sensitive to power quality problems [1].

Poor electric power quality has many detrimental effects on power system equipment and consumer load. These effects are extremely dangerous and will not be visible until the equipment fails. Even if the failure of the equipment does not occur, loss and heating occur in the equipment, eventually shortening the life of the equipment [2]. Power quality problem is described as the deviation in voltage, current and frequency from its nominal value in a power system. Various power quality problems such as voltage drop, fluctuation, undulation, harmonic distortion, unbalance and transient phenomena, etc. may have impact on customer devices which will cause malfunctions and loss of production [3].

Voltage drop out of all power quality problems is the most common obstacle faced by consumers. These problems are due to the rapid advancement of the past technology, the equipment used to control the industrial process is inherently

mechanical, it was quite tolerant to voltage disturbance. Today, however, most devices are electronically controlled, such as PLC, automatic speed drive which requires pure supply voltage without ripple and turbulence [4]. Voltage drop is defined as a decrease in root mean square (RMS) voltage exceeding half a period and, in the period, less than 1 minute, it is in the range of 0.1 to 0.9 per unit (pu). Voltage drop is caused by a grid or grid failure (in most cases, a parallel feeder failure). There is a problem with the installation of consumers. Connection of heavy load and activation of large motor [5]

In order to mitigate the sag in voltage, several mitigation techniques are used, where Distribution Static Synchronous Compensator (D-STATCOM) is presented with different control strategy. D-STATCOM is a shunt-connected device that generates a balanced set of 3-phase sinusoidal voltage or current at the fundamental frequency. D - STATCOM consists of IGPT, voltage type inverter such as MOSFET, DC link capacitor, and controller. D-STATCOM has been proved to be a device that can solve the power quality problem in the distribution system [6].

In order to perform the test of the mitigation voltage using D-STATCOM device, the D-STATCOM prototype was needed. As is known, physical prototypes are expensive and may spend more time to build to reduce project costs. Hardware-In-The-Loop (HIL) simulation has been widely used when reducing the use of physical prototypes and saving time over conventional tests. Hardware-In-The-Loop (HIL) is a low-cost simulation platform technology that represents a mathematical algorithm (called "plant simulation") of all relevant dynamic systems in hardware. HIL uses REAL-TIMEWORKSHOP® which is an automatic code generation extension function of MATLAB® tool chain. This is one of the standard tools for modeling and offline simulation in the field of controller design. This allows the control system to more easily process the controlled model and to more conveniently and time-effectively test the control system [7].

The aims of this project are to mitigate the voltage sag at busbar which load been connected by using D-STATCOM in Hardware in the Loop (HIL) by consuming the Raspberry pi and Arduino mega 2560 as the platform. The simulation model of the project was created using MATLAB SIMULINK. To archive cost-effective simulation tests, we used Raspberry Pi as a real-time simulator. The main part of the project is

host (personal computer), MATLAB Simulink software, Raspberry Pi (interface) and Arduino (as PI controller) as shown in Figure 1.1. At the end the results that been collected from this configuration are been collected in real time which can be observed in the host.

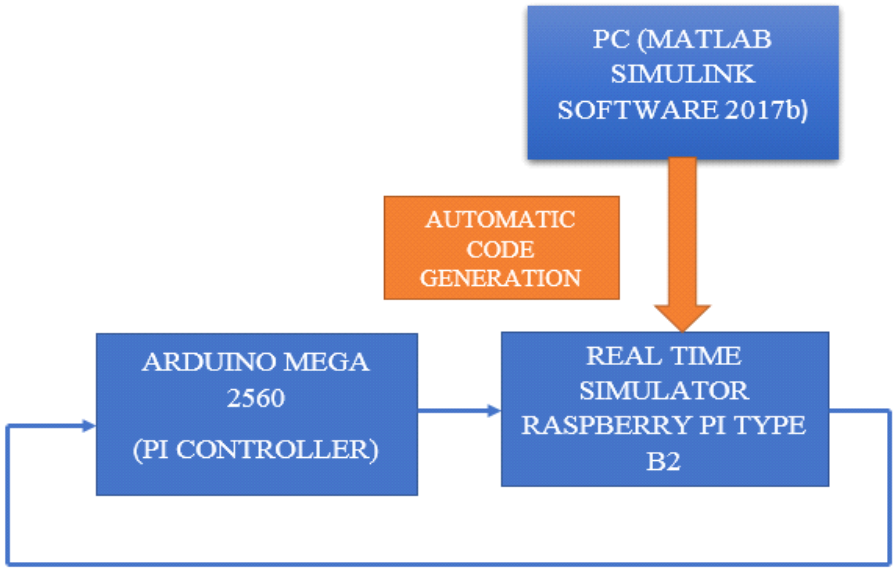

Figure 1.1: Block diagram of overall process system

1.2 Problem statement

There are various parameters that determine the power quality of the distribution system, where voltage sags are more frequent PQ problems than end users face [8]. The voltage sag is the rms amplitude reduction in the AC voltage at power frequency from half of a cycle to a few seconds duration. It has a very bad influence on the operation of Adjustable Speed Drives (ASD), computers, induction motor and process control systems. Voltage drop is caused by faults on the transmission or distribution network (in most cases, a parallel feeder failure). There is a problem with the installation of consumers. Connection of heavy load and start-up of large motor [9]. In order to mitigate the voltage sag which created by intermittent switching of heavy load at bus bar connection. Hardware in the loop (HIL) technique for D-STATCOM with control strategy was used to inject the reactive current at bus bar load.

1.3 Objective of the project

The aim of this project is to model D-STATCOM in real time for voltage sag mitigation during load changes caused by the fault. This project is conducted to achieve the following objectives:

1) To design D-STATCOM with phase shift control strategy for mitigating the voltage sag.
2) To develop a hardware in loop (HIL) system by using low-cost microcontroller.
3) To validate the hardware in loop (HIL) in voltage sag mitigation.

1.4 Scope of the study

The scope of this project is to have a 400V distribution system with R load and fault connected. This project required to develop the Hardware In the Loop process using the low-cost microcontroller.

1) Use a microcontroller (Raspberry pi) with (REAL-TIME WORKSHOP) as to implement a real-time hardware simulation such as software.
2) Design and implementation for 400V distribution line with load and created sag by using resistive heavy load of 12kW.
3) Development of D-STATCOM for Hardware-in-loop simulation by using Raspberry Pi and Arduino microcontrollers.
4) Analysis performance of D-STATCOM in hardware in the loop for mitigation voltage sag at distribution line

1.5 Project outline

In **chapter** 1, the background of voltage sag in power network is discussed and problem statement is identified. This is followed by the project objectives and scope of project. In **chapter 2**, the literature view discusses the impact sag voltage on the

equipment and sensitive loads and the applied technique to mitigate the sag in voltage at distribution grid also D-STATCOM was discuss, related works on D-STATCOM cancellation. And hardware in the loop the methodology is presented in **chapter 3**. This covers the project research frame work and steps in carrying out the project work. The block diagram of the system design, Simulink designs and system parameters are presented. In **chapter 4**, the simulated results in (software and hardware in the loop) are presented and discussed. Two case studies are considered: 1) test system in software design, 2) test system in hardware in the loop and. Finally, **chapter 5** concludes the report and further works are discussed.

1.6 Summary

In this chapter, introduction to the project has been presented. This includes the background of power quality problems and voltage sag, problem statement, project objectives, and the scope of the project.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Literature review is a vital part of the research, it was similar an overall analysis or research on all comparations of existing project in selected fields. In this part, all problems related to this project are concluded and the details of this project will be explained. The relevant discussion, contradiction, problem or knowledge is explained in this part. Other main reasons to study and solve problems already highlighted from previous research projects.

2.2 Voltage sag theory

In past, mechanical tools were applied to control on the industrial processes, which was low sensitive to the problems of voltage. Nowadays more sensitive equipment's are used which controlled in it electronically like PLC. They demand a pure supply voltage without any annoyance or ripple. Due to the high sensitivity of these devices' voltage sag considers as source of problems for electronic equipment [10].

Voltage sag is the most frequent and one of the main power quality (PQ) problems that exist in power systems. According to IEEE standard 1159-1995, a voltage sag is defined as a reduction in root mean square (rms) voltage between 10% and 90% pout the power frequency for durations of 0.5 cycle to 1 minute as shown in Table 2.1. [11]. Moreover, voltage sags are being classified by their duration as shown in Table [2-1].

Table 2.1: Classification of voltage sag according to IEEE

Type of voltage Sag	Voltage Magnitude	Time Duration
Instantaneous	0.1 – 0.9 per unit	0.5 – 30 cycles
Momentary	0.1 – 0.9 per unit	30 cycles – 3 seconds
Temporary	0.1 – 0.9 per unit	3 seconds – 1 minute

Voltage sag is caused by faults and short-circuit generally allied to bad weather conditions (i.e. lightning strokes, storms, wind, etc.), transformer energizing, motor starting, overloads and other load variations

Figure 2.1: Waveform when voltage sag accrues

Many methods have been developed to preventing or reducing the effect of voltage sags in distribution systems (Traditional, Uninterruptible Power Supplies and FACTS). Traditional methods included Transformer Tap Changers and SCR switched units, Servo-Variance technology and Ferro-Resonant Transformers (constant voltage transformers).

In some cases, and in some applications, these traditional technologies can work well, but in many cases, they are designed to solve problems other than voltage sags. Uninterruptible Power Supply (UPS) technology has been available for over 20 years and is ideally suited for applications such as high-speed data processing where all power supply fluctuations, more importantly continuous protection against any power interruption is essential is. Industrial UPS units are widely used to protect

electronic process control equipment and to enable orderly shutdown of processes, but large UPS systems accompanying large UPS systems for high power electrical equipment such as high horsepower drives. It is not economical to install with banks. 12].

Currently, The Flexible AC Transmission System or called (FACTS) devices is the best and famous method to solve the problem of voltage sag. FACTS devices like SVC, DVR and STATCOM, are well-improved perfect technologies which have been moderately widely applied in power systems around the world to make the power system more stability [13].

2.3 Distribution static compensator (D-STATCOM)

Reactive power is the main cause of distribution grid loss and various power quality problems. A voltage source converter (VSC) is used with the filter in the distribution grid to compensate reactive power and mitigate power quality problems. VSC is a highly effective system controller used to provide reactive power compensation at the transmission level, but it does not meet modern deployment requirements because of limited bandwidth, higher number of passive elements, increased size and loss, and slower response time [14].

In order to provide reactive power compensation at the transmit level another compensation system has been proposed which uses a combination of VSC and active power filter. Distribution Static Compensator (D-STATCOM) is a flexible AC transmission system (FACTS) controller that can absorb reactive power or send it to power grid. The Distribution Static Compensator (D-STATCOM) have been proposed to compensate reactive power and imbalance due to various loads of the distribution grid. The Distribution static compensator is based on VSC principle. D-STATCOM injects current into the system to compensate for voltage drop and power factor. Distribution Static Synchronous Compensator (D-STATCOM) is an effective means of maintaining voltage stability and improving the power quality of the distribution grid [15].

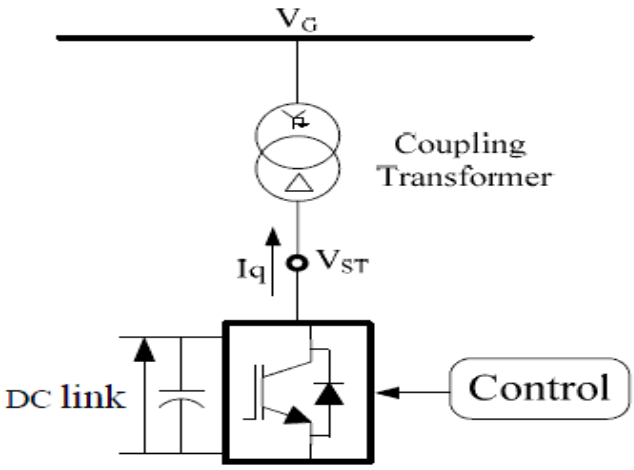

Figure 2.2: Block diagram of D-STATCOM [15]

Distribution Static Synchronous Compensator (D-STATCOM), have been developed to support problems of power quality and make the system more stable. If an error occurs in a distribution grid, voltage sag suddenly appears on the adjacent load. The D-STATCOM, was install in a sensitive load, returns the line voltage to its nominal value within a response time of a few milliseconds, thus prevent power interruption to the load [16].

The static synchronous compensator (STATCOM) is a voltage source converter based on a FACTS controller. This is mainly a shunt controller used to regulate the voltage by generating reactive power. STATCOM not allows to exchange the real power with an AC system it allows for exchanging the reactive power between DC side and AC on the transformer sides. The reactive power is varied by varying the magnitude of the converter output voltage [17].

2.4 Basic structure of DSTATCOM

Distribution Static Compensator (DSTATCOM) is a shunt-coupled reactive power compensation device which be used to improve the PQ of a power system. This device can be installed close to or directly on the load bus of the distribution grid, to treat voltage sag and reduce the number of sensitive equipment failures [18].

The major structure of DSTATCOM are consists of three main part a DC energy storage device (DC capacitor or DC source), inverter module (IGBT, thyristor, etc.) and coupling transformer. The basic unit of DSTATCOM is a voltage source

inverter (VSI) which converts the DC voltage in the storage device to the AC voltages. These voltages are in coupled to the distribution grid via the reactance of the coupling transformer. The VSI is used to compensate the voltage during the sag state [19].

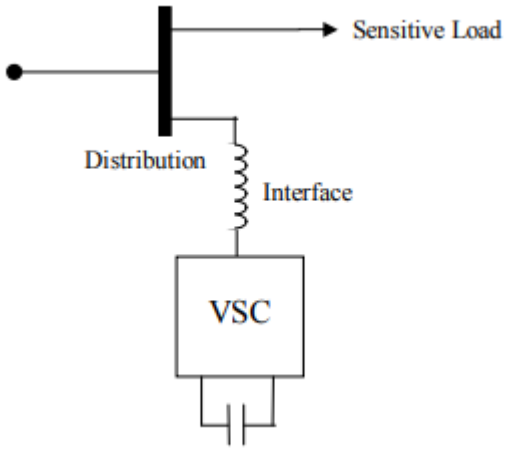

Figure 2.3: Structure of D-STATCOM [19]

2.5 Operation of D-STATCOM

DSTATCOM is a solid-state device that can control phase angle and voltage magnitude. For this reason, it can be treated as a voltage control source, also can be viewed as a controlled current source**.** The D-STATCOM consists mainly of a DC voltage source behind the inverter which that using IGBTs and coupling transformers. An IGBT inverter with a DC voltage source can be consider as an inconstant voltage source. Distributed power systems can also be modelled as voltage sources [20]. From the diagram of DSTATCOM are shown in Figure 2.4. The controller regulates the flowing of reactive current between the distribution grid and the compensator so that the phase angles between the output voltages of DSTATCOM (Vi) and the voltage power grid (Vs) are equal to each other. The power system voltage (Vs) is dynamically adjusted so that DSTATCOM absorbs or generates the demand reactive power at point connection [21].

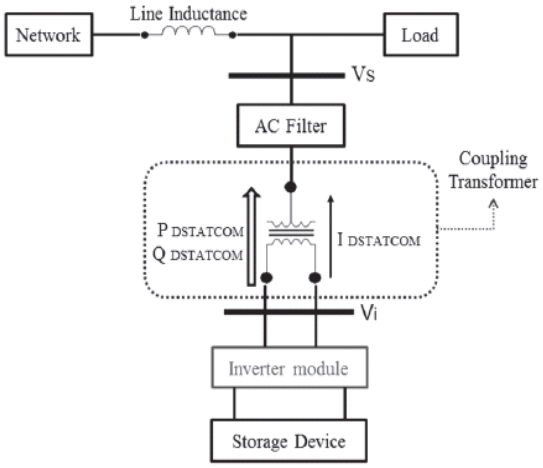

Figure 2.4: Operation of D-STATCOM [21]

The active power (P_{DST}) and reactive power (Q_{DST}) that flow through the reactance of the coupling transformer X_{Trx} can be estimated using the following equations:

$$P_{DST} = \left[\frac{|V_S||V_i|}{X_{Trx}}\right] * Sin(\delta) \quad (2.1)$$

$$Q_{DST} = \left[\left[\frac{|V_S||V_i|}{X_{Trx}}\right] * \cos(\delta)\right] - \left[\frac{|V_S|^2}{X_{Trx}}\right] \quad (2.2)$$

Where, δ is the phase angle between $V_{invrter}$ (V_i) and V_{system} (V_S) the expressions presented in (2.1) and (2.2) show that the basic operation of D-STATCOM varies depending upon Vinverter. The operation modes of this device are as follows [24]:

1) If V_{system} equal to $V_{invrter}$, the reactive power exchange is zero and the DSTATCOM does not generate or absorb reactive power.
2) When V_{system} greater than $V_{invrter}$, the current flows from DSTATCOM to the power system. In this state, the system sees the compensator as capacitance and DSTATCOM generates reactive power.
3) When V_{system} smaller than $V_{invrter}$, the current flows from the power system to DSTATCOM. In this condition, the system sees the compensator as inductance connected to its terminals and the DSTATCOM absorbs reactive power.

4) When the phase angle equal to zero the active power exchange is zero. This can be achieved with the control stage.

2.6 Related works on D-STATCOM to mitigate voltage sag

M.H. Hague from School of Electrical and Electronic Engineering Nanyang Technological Universities, Singapore presents the research under title "Compensation of Distribution System voltage sag by DVR and D-STATCOM" [21].

The study of this article characterizes the technology to correct the voltage sag in a distribution grid by using two power electronics support devices called D-STATCOM and DVR. DVR injects voltage in series with the system voltage and D-STATCOM injects current into the system to compensate for voltage sag. The steady state performance of both DVR and D-STATCOM are determined and compared for voltage sag of different values. The minimum apparent power injection required to correct for a given voltage sag by these devices is also determined and compared. The maximum voltage sag that can be compensated without putting active power on the system is also determined. Simulation results showed that DVR can compensate for instantaneous voltage sag with much lower apparent power compared to D-STATCOM.

Paper wrote by L. S. Patil and Ms. A. G. with research title "Application of D-STATCOM to Mitigate Voltage Sag Due to DOL Starting of Three Phase Induction Motor"[38]. In this research paper, the model of Distribution STATCOM has been designed in MATLAB/Simulink to veirfy its ability for mitigation of voltage sag due to DOL starting of induction motor. This paper summarized with brief introduction about voltage sag problem then the characteristics of voltage sag, basic structure and operation of D-STATCOM. The model was simulated in two cases, first without D-STATCOM and the second with it. The results obtained in both the cases are analyzed. According to the results which carryout from simulation on this analysis the capability of D-STATCOM to mitigate the voltage sag due to DOL starting of IM is validated.

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