MODELING AND ANALYSIS OF A DYNAMIC VOLTAGE REGULATOR

A Thesis

presented to

the Faculty of California Polytechnic State University,

San Luis Obispo

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Electrical Engineering

by

Timothy David Haskell

May 2013

© 2013

Timothy David Haskell

ALL RIGHTS RESERVED

COMMITTEE MEMBERSHIP

TITLE: Modeling and Analysis of a Dynamic Voltage Regulator

AUTHOR: Timothy David Haskell

DATE SUBMITTED: May 2013

COMMITTEE CHAIR: Dr. Taufik, Professor, EE Department

COMMITTEE MEMBER: Dr. Ali Shaban, Professor, EE Department

COMMITTEE MEMBER: Dr. Ahmad Nafisi, Professor, EE Department

ABSTRACT

Modeling and Analysis of a Dynamic Voltage Regulator

Timothy David Haskell

Increased government funding and incentives in recent years has led to an increase in the number of grid-tied renewable energy sources as their economic benefits become more renowned. Unfortunately, the outputs of these renewable resources are often highly variable, resulting in undesirable voltage disruptions that are harmful to sensitive loads. In addition to the energy variability of renewable energy sources, random voltage sags, swells and disruptions are already a major issue in power systems. Recent advances in power electronic devices have provided a platform for new solutions to the voltage support problem in power systems. One promising solution is the Dynamic Voltage Regulator (DVR), a series compensating device used to protect a sensitive load that is connected downstream from voltage sag or swell. For this thesis, the design, modeling, and analysis of a DVR system were performed using PSCAD software. Results from simulation demonstrate the DVR's effectiveness in protecting a sensitive load from load and source side voltage disturbances as well as regulate the load bus voltage to its rated value.

Keywords: Dynamic Voltage Regulator, Grid-Tied, Voltage Sag, Voltage Swell,
Voltage Support, Series Compensating Device

ACKNOWLEDGMENTS

This thesis would have remained a dream had it not been for my parents, Tim and Kim Haskell. Without their continuous love and support, I would not be the man I am today. They taught me to always work hard and to be dedicated, which were both necessary in the writing of this thesis.

Next, I would like to express my sincere gratitude to my advisor Dr. Taufik. His guidance and contagious passion for power engineering have helped me reach my goals as a student and mature as an individual.

I also owe a great deal of thanks to my friends, old and new, for always being there for me. I would especially like to thank my fellow student and friend, Ben Johnson. The countless discussions and seemingly endless work sessions we had are unforgettable. We got through it all together.

Finally, I would like to thank my girlfriend Tala Fatolahzadeh. Over the years, she has helped me through the thick and thin, and I am extremely thankful for the sacrifices that she has made so that I could achieve my goals.

Disclaimer:

SDG&E does not endorse or accept the conclusions or results of this study.

Table of Contents

LIST OF TABLES	vii
LIST OF FIGURES	viii
1 Introduction.....	1
1.1 Renewable Energy	1
1.2 Growing Market for Solar PV	2
1.3 Voltage and Power Quality Issues	5
1.4 Smart Grid.....	6
2 DVR Background	8
2.1 Voltage Regulation Significance.....	8
2.2 FACTS Controllers	9
2.2.1 Static VAR Compensator (SVC).....	9
2.2.2 Thyristor-Controlled Series Capacitor (TCSC).....	12
2.2.3 STATCOM.....	14
2.2.4 DVR.....	16
2.3 Summary of Existing DVR Models / Thesis Objective	17
3 DVR Design Requirements	19
3.1 Sinusoidal Pulse Width Modulation (SPWM) Inverter.....	19
3.2 PSCAD Inverter Model.....	22
3.3 Energy Storage System (ESS) and DC Link Capacitor	29
3.4 PSCAD ESS and DC Link Capacitor Modeling	31
3.5 PSCAD Low Pass Filter Design	33
3.6 PSCAD Series Injection Transformer Design.....	34
3.7 Complete DVR Design and Control Method	35
4 Tests and Results	48
4.1 Load Side Voltage Sag Protection	48
4.2 Load Side Voltage Swell Protection	52
4.3 Source Side Voltage Sag Protection	56
4.4 Source Side Voltage Swell Protection	61
4.5 Three-Phase Fault Protection	65
5 Conclusion	69
BIBLIOGRAPHY	72

LIST OF TABLES

Table 3.1: Comparison of Batteries and Capacitors	30
Table 3.2: Stored Energy Capacity Requirements by Application	31
Table 4.1: DVR Load Side Voltage Sag Correction with Added Load.....	51
Table 4.2: DVR Load Side Voltage Swell Correction with Added Load.....	55
Table 4.3: DVR Source Side Voltage Sag Correction with Added Load.....	60
Table 4.4: DVR Source Side Voltage Swell Correction with Added Load.....	64

LIST OF FIGURES

Figure 1.1: Annual Investment in Renewable Energy Scenarios	2
Figure 1.2: Number of Annual U.S. Grid-Connected PV Installations (2002-2011)	3
Figure 1.3: Cumulative U.S. Grid-Connected PV Installations (2002-2011)	3
Figure 1.4: Timeline of Solar Cell Efficiencies	4
Figure 1.5: Smart Grid Functions Mapped to Benefits	7
Figure 2.1: Average Hourly Monetary Loss by Business Sector	8
Figure 2.2: SVC System Devices (without Harmonic Filters)	12
Figure 2.3: Basic TCSC Device.....	13
Figure 2.4: STATCOM.....	15
Figure 2.5: DVR System	16
Figure 3.1: PWM Signals in Linear Modulation Region	21
Figure 3.2: Basic Three-Phase Inverter	22
Figure 3.3: PSCAD Voltage Source Inverter.....	23
Figure 3.4: Single IGBT with RC Snubber and Clamping Diode	24
Figure 3.5: Triangle Wave Carrier Signal.....	24
Figure 3.6: Triangle Wave Carrier Signal Generator.....	25
Figure 3.7: Sinusoidal Wave Generators	26
Figure 3.8: Firing Pulse Generators	27
Figure 3.9: Phase A PWM Output Pulses.....	28
Figure 3.10: V_{ab} PWM Output Pulses.....	29
Figure 3.11: PSCAD Model of ESS and DC Link Capacitor	32
Figure 3.12: PSCAD LC Low-Pass Filter.....	33
Figure 3.13: PSCAD Model of Series Injection Transformers.....	35
Figure 3.14: PSCAD Calculation of Phase Voltages in Per Unit	37
Figure 3.15: PSCAD Modulation Index Calculations	39
Figure 3.16: V_{ab} , Filtered and Unfiltered.....	41
Figure 3.17: V_{ab} , Filtered	41
Figure 3.18: PSCAD Winding Voltage Ratings	43
Figure 3.19: PSCAD DVR Model	45

Figure 3.20: Test Circuit One Line Diagram	46
Figure 3.21: DVR Module	47
Figure 4.1: DVR Module Protecting Sensitive Load.....	48
Figure 4.2: Load Side Voltage Sag Setup	49
Figure 4.3: Load and Source Voltages During Load Side Voltage Sag (RMS, pu)	50
Figure 4.4: Source, Load, and DVR Phase Voltages During Load Side Sag	50
Figure 4.5: Phase A Load, Source, and DVR Voltages During Load Side Sag	51
Figure 4.6: Load Bus Voltage for Various Load Side Sag	52
Figure 4.7: Load Side Voltage Swell Setup.....	53
Figure 4.8: Load Voltage During Load Side Voltage Swell (RMS, pu).....	54
Figure 4.9: Source, Load, and DVR Phase Voltages During Load Side Swell	54
Figure 4.10: Phase A Load, Source, and DVR Voltages During Load Side Swell	55
Figure 4.11: Load Bus Voltage for Various Load Side Swell	56
Figure 4.12: Source Side Voltage Sag Setup	57
Figure 4.13: Load and Source Voltages During Source Side Voltage Sag (RMS, pu)	58
Figure 4.14: Source, Load, and DVR Phase Voltages During Source Side Sag	58
Figure 4.15: Phase A Load, Source, and DVR Voltages During Source Side Sag	59
Figure 4.16: Load Bus Voltage for Various Source Side Sag	60
Figure 4.17: Source Side Voltage Swell Setup.....	61
Figure 4.18: Load and Source Voltages During Source Side Voltage Swell (RMS, pu) .	62
Figure 4.19: Source, Load, and DVR Phase Voltages During Source Side Swell	63
Figure 4.20: Phase A Load, Source, and DVR Voltages During Source Side Swell	63
Figure 4.21: Load Bus Voltage for Various Source Side Swell	65
Figure 4.22: Three-Phase to Ground Fault Setup	66
Figure 4.23: Load and Source Voltages During Three Phase Fault (RMS, pu)	67
Figure 4.24: Source, Load, and DVR Phase Voltages During Three Phase Fault.....	67
Figure 4.25: Phase A Load, Source, and DVR Voltages During Three Phase Fault.....	68
Figure 5.1: Phasor Diagram of Pre-Sag Compensation	71

1 Introduction

This study analyzes the ability of a Dynamic Voltage Regulator (DVR) system to provide voltage support in a power distribution network. Additionally, this study examines the effectiveness of a DVR system in mitigating voltage swings and regulating voltage levels within acceptable limits. Energy production variability has become a major issue with the rise of renewable energy resources. As a result, there is a growing demand for equipment that can help reduce energy variability. A DVR system can be implemented to provide a dynamic response to voltage fluctuations.

1.1 Renewable Energy

In recent years, it has become evident that the global energy demand has risen and will continue to rise. Additionally, the world has become more knowledgeable of the harmful environmental effects and scarcity of fossil fuels. As a result, there has been a major push for the creation of clean, reliable, and renewable energy resources [1]. The renewable energy industry spent \$260 billion in 2011, which is a large increase from \$40 billion in 2004. Of the \$260 billion spent, \$127 billion was dedicated to solar photovoltaic, \$84 billion to wind power, and most of the rest was put towards solar thermal power and offshore wind power [2]. Figure 1.1 shows a list of several projections for the world's annual investment in renewable energy resources. Although some may be more optimistic than others, the general consensus is that the funding for the research and development of renewable energy resources will continue to increase for many years to come.

Figure 1.1: Annual Investment in Renewable Energy Scenarios [2]

1.2 Growing Market for Solar PV

Solar energy is among the most widely used renewable energy sources because it is clean, safe for the environment, and easily accessible. Additionally, the process of using photovoltaic (PV) systems to convert solar energy into electrical energy to meet consumer demands has proven to be efficient and reliable [3]. For these reasons, the solar market has become a vital part of the U.S. economy. The growing emphasis on solar PV systems has allowed prices to decrease, and people can now afford to buy and install grid-connected PV systems on their homes. In the last decade, grid-connected installations have become the most common type of PV installation. Figure 1.2 shows an increasing trend in the number of installations of grid-connected (grid-tied) PV systems in the U.S. for each year from 2002 to 2011. Following this same trend, Figure 1.3 shows a large increase in the total capacity of grid-connected PV in the U.S. from 2002 to 2011 [4].

Figure 1.2: Number of Annual U.S. Grid-Connected PV Installations (2002-2011) [4]

Figure 1.3: Cumulative U.S. Grid-Connected PV Installations (2002-2011) [4]

A major factor in the recent growth of residential PV installations is the decreased price. Looking at price data from 2011, the total set-up cost for a residential PV installation dropped by 14% from 2010 to 2011 [4]. This drop in cost is largely influenced by a reduction in non-module costs, such as installation labor, marketing, overhead, inverters, and other parts of the manufacturing process [5]. However, in addition to a drop in manufacturing cost, solar panels have become more efficient. Constructed by the National Renewable Energy Laboratory (NREL), Figure 1.4 shows an increase in efficiency for several solar cells technologies [6].

Figure 1.4: Timeline of Solar Cell Efficiencies [6]

1.3 Voltage and Power Quality Issues

In an ideal world, power distribution companies should have a system in place that provides their customers with a smooth sinusoidal voltage with a fixed amplitude and frequency. However, power systems, especially at the distribution level, are composed a number of non-linear loads that negatively affect the power quality of the grid. The impact of these non-linear loads is growing [7].

The large influx of grid-tied renewable energy sources in recent years has greatly impacted power quality and total system operation. Unfortunately, the output power for most renewable energy sources is highly variable. Wind generators only produce rated power when the wind is blowing. Similarly, the efficiencies of solar PV installations are affected by the presence of clouds. The randomness associated with these energy sources results in voltage fluctuations and a decrease in power quality, both of which have profound effects on the overall system [8].

In addition to the rise of non-linear loads, there will always be random sags, swells, and surges on utility lines that affect power quality. Surges, spikes, sags, swells, harmonic distortions and momentary disruptions are examples of voltage fluctuations that can be harmful to a system. Voltage sags are the most common type of occurrence affecting power quality. They are usually caused by external factors such as storms and animals, but they can also be caused by internal factors like heavy loading and grounding problems. Voltage sags can do damage to electronic devices, as most are supposed to be operated in a specific and constant voltage range. Some of the more sensitive devices in industry include variable frequency drives, robotics, programmable logic controllers, controller power supplies, and control relays. In order to protect expensive devices like

these from harmful voltage variations and maintain power quality for the electrical grid, new management strategies and devices are being implemented [9].

1.4 Smart Grid

As the electrical grid has become more and more complex in the 21st century because of increasing energy demands, new strategies are needed to manage power flow and power quality. One such strategy is the design and implementation of a Smart Grid, which allows the exchange of electricity and information between the utility and the customer. According to the government's website on Smart Grid technology,

Like the internet, the Smart Grid will consist of controls, computers, automation, and new technologies and equipment working together, but in this case, these technologies will work with the electrical grid to respond digitally to our quickly changing energy demand.

The Smart Grid aims to increase the efficiency of electricity transmission as well as provide faster energy support after power disturbances. Another target of the Smart Grid is the smoother integration of residential wind and solar energy production systems [10].

A larger summary of the key functions of the Smart Grid and their respective benefits can be seen in Figure 1.5. The four major benefits of the Smart Grid are listed as economic, reliability, environmental, and security benefits. The reliability benefit includes an improvement in both power interruption and power quality. The Smart Grid introduces a method of “self-healing” by monitoring and responding to disturbances before they damage sensitive equipment or degrade power quality [11]. Currently, a number of Smart Grid devices are being implemented to regulate voltage, protect sensitive loads and improve power quality. These devices will be discussed in the following chapters.

Benefits			Functions														Energy Resources		
			Fault Current Limiting	Wide Area Monitoring, Visualization, and Control	Dynamic Capability Rating	Power Flow Control	Adaptive Protection	Automated Feeder Switching	Automated Islanding and Reconnection	Automated Voltage and VAR Control	Diagnosis & Notification of Equipment Condition	Enhanced Fault Protection	Real-Time Load Measurement & Management	Real-time Load Transfer	Customer Electricity Use Optimization	Distributed Generation	Stationary Electricity Storage	Plug-in Electric Vehicles	
Economic	Market Revenue	Arbitrage Revenue															•		
		Capacity Revenue															•		
		Ancillary Services Revenue															•		
	Improved Asset Utilization	Optimized Generator Operation		•													•		
		Deferred Generation Capacity Investments												•	•	•	•		
		Reduced Ancillary Service Cost		•					•			•		•	•	•	•		
		Reduced Congestion Cost		•	•	•								•	•	•	•		
	T&D Capital Savings	Deferred Transmission Capacity Investments	•	•	•	•								•	•	•	•		
		Deferred Distribution Capacity Investments			•							•	•	•	•	•	•		
		Reduced Equipment Failures	•		•						•	•							
	T&D O&M Savings	Reduced Distribution Equipment Maintenance Cost							•										
		Reduced Distribution Operations Cost							•										
		Reduced Meter Reading Cost										•							
	Theft Reduction	Reduced Electricity Theft										•							
		Energy	Reduced Electricity Losses							•			•	•	•	•	•		
		Electricity Cost Savings	Reduced Electricity Cost											•	•	•	•		
Reliability	Power Interruptions	Reduced Sustained Outages					•	•	•		•	•			•	•	•		
		Reduced Major Outages		•					•			•	•						
		Reduced Restoration Cost					•	•		•	•								
	Power Quality	Reduced Momentary Outages									•						•		
Reduced Sags and Swells											•					•			
Environmental	Air Emissions	Reduced CO ₂ Emissions				•		•		•			•	•	•	•	•		
		Reduced SO _x , NO _x , and PM-2.5 Emissions				•		•		•				•	•	•	•		
Security	Energy Security	Reduced Oil Usage (not monetized)						•		•		•					•		
		Reduced Widescale Blackouts	•	•															

Figure 1.5: Smart Grid Functions Mapped to Benefits [11]

2 DVR Background

2.1 Voltage Regulation Significance

One of the most important requirements of a power system is to maintain a constant voltage within a permissible set of ranges. As discussed previously, voltages are largely affected by variations in load, making them difficult to regulate. Varying the voltage level results in larger system losses and decreases in efficiency, both of which are undesirable [12].

Power quality problems can also be very costly for both the utility and the customer. According to the Contingency Planning Research Company's annual study of the effects of power quality, blackouts and power disruptions can cause customers to suffer financially. Figure 2.1 shows the average monetary loss per hour due to power quality issues resulting in downtime and data loss [13].

Figure 2.1: Average Hourly Monetary Loss by Business Sector [13]

Fortunately, problems with voltage stability and power quality can be alleviated with proper voltage regulation. Several different types of flexible ac transmission system (FACTS) devices are used to regulate voltage, some better than others, and a few of the more mainstream ones are discussed in the following sections.

2.2 FACTS Controllers

FACTS controllers are static electronic controllers used to increase power quality in distribution systems with a voltage rating between 1 and 38 kV [14]. The first generation of FACTS controllers are thyristor based, whereas the second generation controllers are converter based. Generally speaking, FACTS controllers can be imcategorized into 4 different types: series controllers, shunt controllers, combined series-series controllers, and combined series shunt controllers [15]. The research portion of this thesis covers a mixture of both first and generation FACTS controllers.

2.2.1 Static VAR Compensator (SVC)

Static VAR compensators (SVCs) are well known FACTS controllers that are connected in shunt with a load in order to provide voltage support and control reactive power [15]. The control of reactive power is associated with voltage support, which is to say that controlling voltage in a power system is achieved by either absorbing or generating reactive power. In an ac power system, capacitors generate reactive power and inductors absorb reactive power. This is important because SVCs are composed of static VAR generators (SVGs), which are semiconductor power circuits that use thyristors along with inductors and capacitors to produce a variable reactive output.

Currently, the four most common types of SVGs are the thyristor-controlled reactor (TCR), the thyristor-switched capacitor (TSC), the fixed-capacitor, thyristor-controlled reactor (FC-TCR) type VAR generator, and the thyristor-switched capacitor, thyristor-controlled reactor (TSC-TCR) type VAR generator [16].

The TCR type VAR generator is composed of a fixed inductance and bidirectional thyristor switches. The current in the inductor can be varied by introducing a delay angle α to the firing pulses given to the gate of the thyristors. For maximum inductance, the α is set to zero so that the thyristors are always conducting. If α is adjusted to 180 degrees, the thyristors are always off, so the device doesn't draw any current. TCRs introduce an inductive impedance to the system, meaning that the current through the reactor lags the system voltage [16]. So, this device can be adjusted to absorb a certain amount of reactive power.

TSC type VAR generators are composed a capacitor, bidirectional thyristor switches, and a small reactor used to protect the device from large surge currents. The thyristors are controlled similarly to those in the TCR type VAR generators, except in this case the capacitance is dictated by the delay angle α . A zero degree firing angle will introduce the maximum capacitance to the system. Additionally, the current through the capacitor will lead the system voltage [16].

As the name implies, the FC-TCR type VAR generator is composed of a fixed capacitor in parallel with a TCR. It is common knowledge that ac systems are usually composed of inductive loads that create an undesired non-unity power factor. The fixed capacitor in the FC-TCR is used for power factor correction, as it is shunted near the inductive load in order to supply reactive power. However, loads are almost never fixed,

so the ability to absorb reactive power in addition to supplying it is very important. This is why the FC-TCR includes the parallel TCR branch. The parallel TCR allows a controllable amount of VAR to be absorbed from the system. The combination of the fixed capacitor in parallel with the TCR allows for more adjustability and better system reactive power control [16].

The TCR and TSC can be placed in parallel to form the TCR-TSC type VAR generator. The combination of the two controllable branches allows for an even more dynamic and accurate reactive power compensation [16].

The four SVG types discussed can be used in SVC controllers to produce the net reactive power needed by the load on a continuous basis. Figure 2.2 shows the three physical system devices used in SVC controllers. In addition to the TCR, the TSC and the fixed capacitor, a step-down transformer is used in an SVC to “step” the system voltage down to the 1 to 38 kV range discussed previously [16].

Although the SVC provides voltage support and reactive power control, one of the major disadvantages of the SVC is the harmonics that it produces at lower frequencies due to the switching thyristors. This in turn results in the need for heavy filtering, which takes up a lot of space and adds to the cost of the controller [17].

Figure 2.2: SVC System Devices (without Harmonic Filters)

2.2.2 Thyristor-Controlled Series Capacitor (TCSC)

The thyristor-controlled series capacitor is one of the most common FACTS controllers in modern power systems. TCSCs are series compensation devices that possess the ability to quickly adjust line impedance in order to control the flow of power, improve stability, and increase the amount of transferrable power in a system. As seen in Figure 2.3, a basic TCSC is composed of a fixed capacitor in parallel with a TCR. TCSCs have four modes of operation depending on what net series reactance is needed on the line. These four operating modes are thyristor-blocked mode, thyristor-bypassed mode, and thyristor conduction mode in either the inductive or capacitive regions.

Starting from a zero degree firing angle, the equivalent series impedance of the TCSC is inductive. The firing angle can be increased to create a capacitive reactance, but a region near parallel resonance is prohibited. In parallel resonance, the reactance of the capacitor is equal to the reactance of the reactor, so in theory the equivalent TCSC reactance becomes infinite [18].

Figure 2.3: Basic TCSC Device

In terms of FACTS controllers, some consider the TCSC controller to yield the best results in terms of performance and flexibility in power distribution systems. A typical transmission line has inherent inductance, and a TCSC controller can be tuned to provide a series capacitive reactance that reduces the overall reactance of the line. In this application, the lower line reactance lowers the voltage drop across the line and increases the allowable transferable power capability of the system. So, TCSC controllers have the ability to control power flow, reduce loss, and provide voltage support. Limitations do exist, however, as TCSCs must be operated within the allowable ranges of the firing

angle α even when the voltage is dynamic. This means that the line reactance needed from the TCSC is variable, not static, so the operating limitations of the controller must always be considered [19].

2.2.3 STATCOM

Another common FACTS controller is the static synchronous compensator (STATCOM). STATCOMs are shunt devices used to control reactive power flow, regulate voltage, and thus improve voltage quality without the use of reactive energy components. The most common STATCOMs are usually composed of an inverter with a capacitor on the dc side, a coupling transformer, and a control system. The reactive power output of the STATCOM is determined by the difference in magnitude between the ac system voltage and the ac voltage outputted by the voltage source converter (VSC). The amplitude of the STATCOM's output voltage is controlled by varying the magnitude of the dc voltage across the capacitor. So, the output voltage can be adjusted to make the STATCOM act like a capacitive or inductive load by either generating or absorbing reactive power, respectively. If the amplitude of the STATCOM's output voltage is adjusted to be smaller than the magnitude of the system voltage but in phase with it, then the STATCOM acts like a capacitive load [20]. A diagram of a STATCOM can be seen in Figure 2.4.

Figure 2.4: STATCOM

STATCOMs are proven to improve power quality and provide dynamic voltage response. However, just like any other FACTS controllers in industry, STATCOMs have a few downsides. For example, the VSCs used in STATCOM controllers create large switching losses that decrease its efficiency. Additionally, the performance of a STATCOM device decreases significantly with the addition of negative sequence components in the system. This is a problem because more control circuitry must be implemented in this case, which adds to the complexity and price of the controller [21].

2.2.4 DVR

One of the most effective devices used for voltage regulation and improving power quality is the dynamic voltage regulator (DVR). A DVR is a series compensation device composed of an energy storage system (ESS) with a dc link, an inverter, a filter circuit, and a series voltage injection transformer. A simple diagram of a DVR system including these components can be seen in Figure 2.5 [22].

Figure 2.5: DVR System [22]

DVRs are power electronic devices that, much like STATCOMs, use a VSC to output an ac voltage. However, in the case of the DVR, both the active power and the reactive power can be controlled independently. Additionally, DVR systems are bidirectional, so they can either absorb or generate active and reactive power. This bidirectional functionality can be achieved because of a DVR's ability to inject a series voltage of desired magnitude and phase. DVR systems are primarily placed upstream to a sensitive load in order protect them from supply side disturbances. In addition to their real and reactive power control, DVR systems are known to provide a fast response to system disturbances and consume zero real power during steady state. One disadvantage of DVR systems is the injection of harmonics into the system from the VSC, which requires filtering [22].

2.3 Summary of Existing DVR Models / Thesis Objective

Existing models of dynamic voltage regulators have been created to simulate their ability to effectively protect a critical load from supply side disturbances. Most of the contemporary models have been performed in MATLAB (Simulink), but there is very little modeling of a DVR system in PSCAD. PSCAD is a very powerful modeling tool that allows power electronics based devices to be simulated in and interact with power systems. Most DVR models do not have the ability to control active and reactive power flow in addition to providing dynamic voltage regulation. So, although maintaining a constant voltage is important to critical loads and sensitive devices, improving power quality is a desired feature of a DVR system.

This thesis will contain the design, modeling and analysis of an effective DVR system using PSCAD software. Developing a complex and scalable model will serve as a useful tool for future analysis and placement of DVR systems. Once the basic functionality of the DVR system has been verified, the device model will then be applied to a larger radial system. The research, design, testing and analysis of the DVR model are discussed in the following chapters.

3 DVR Design Requirements

The primary purpose of a DVR is to protect sensitive loads that are connected downstream from voltage sag or swell. Additionally, a DVR can regulate the bus voltage at the load terminal. The DVR model discussed in this thesis will abide to the IEEE1547 standard of regulating the protected load's bus voltage to within 5% of nominal value.

As mentioned previously, a DVR system is composed of four major components: an inverter, a filtering circuit, an energy storage system with a dc link capacitor and a series injection transformer. This chapter discusses the design decisions made for each of these four major components and their roles in an effective model of a DVR system.

3.1 Sinusoidal Pulse Width Modulation (SPWM) Inverter

The DVR voltage source inverter is based on sinusoidal pulse width modulation (SPWM). Sinusoidal pulse width modulation involves the comparison of a reference waveform (modulating signal) to a triangular wave of a much higher frequency (carrier wave) in order to produce a desired output voltage. If the modulating signal is larger than the carrier wave, meaning that the amplitude of the sinusoidal wave is greater than the triangular wave, then a positive dc voltage is produced at the output of the inverter. If the magnitude of the triangle wave exceeds the magnitude of the sinusoidal wave, then a negative dc voltage or ground is applied to the output of the inverter. The result of this logic is a series of pulses that require filtering in order to obtain the desired waveform from the inverter. The ratio of the amplitude of the modulating signal to the amplitude of the triangular carrier wave is called the modulation index (m_a) [23].

$$m_a = \frac{A_m}{A_c} = \frac{A_{sin}}{A_{tri}} \quad (3.1)$$

The output voltage of the inverter is a function of the dc input voltage and the modulation index. Linear modulation occurs when $0 \leq m_a \leq 1$, and this is the desired region of operation because the output will be a linear function of m_a and the inverter's dc input voltage. If the modulation index is increased beyond a value of 1, then over modulation occurs. In the case of over modulation, the output no longer possesses a linear relationship to the modulation index and the dc input voltage [24]. Figure 3.1 shows the relationship between the modulating (input) signal, the triangle wave (oscillator) carrier signal and the output signal (V_o) for SPWM in the linear operating region [25]. In order to prevent high frequency components from propagating to the output of the inverter, it is necessary to choose a rather large carrier frequency. In power systems, a common range for carrier frequencies is 2-15 kHz [23]. Additionally, it is common practice to choose a switching frequency that is an odd triple multiple of the modulating frequency in order to minimize harmonics. Even order harmonics create small dc components that are undesired in ac systems [15].

Figure 3.1: PWM Signals in Linear Modulation Region [25]

In a three-phase ac system, a three-phase inverter must be used to create three sine waves of desired amplitude and frequency from a dc input. Figure 3.2 shows an example of a basic three-phase inverter. The dc link capacitor will be discussed in a later section. Figure 3.1 is an example of the generation of a single phase of a desired output signal using a unipolar switching method. The switching is unipolar for this single phase because the output is switched from $+V_{dc}$ to 0, unlike bipolar switching where the output varies from $+V_{dc}$ to $-V_{dc}$ [24]. One advantage of unipolar switching over bipolar switching is that the output voltage does not have to switch as far instantaneously during a switching transition (less dv/dt), which results in less noise and smaller switching losses. Additionally, the set output pulses generated from unipolar switching contain undesired harmonic components at much higher frequencies than those generated by bipolar switching, which requires less filtering [24].

Figure 3.2: Basic Three-Phase Inverter

3.2 PSCAD Inverter Model

The PSCAD model of the inverter for the DVR system can be seen in Figure 3.3. A three-phase SPWM voltage source inverter topology with unipolar switching was used in the design. The sinusoidal pulse width modulation technique was chosen because of its ubiquity in modern inverter designs. Additionally, PWM is commonly used in high power applications and consumes very little power. Using the three-phase inverter, only two switches per phase (a total of six switches) were needed to switch each output from $+V_{dc}$ to 0 V. The dc voltage source and capacitor will be discussed more in later sections, but it can be noted that the dc input voltage used for the voltage source inverter model was chosen to be 12 kV.

Figure 3.3: PSCAD Voltage Source Inverter

Insulated-gate bipolar transistors (IGBTs) were used as switches in the design of the DVR voltage source inverter in Figure 3.3. IGBTs were chosen because they have larger current and voltage ratings than MOSFETs as well as a small “on-state” voltage drop. Figure 3.4 shows a close-up of one of the IGBTs used in the inverter. An RC snubber circuit and a clamping diode are put in parallel with the IGBT. The purpose of the RC snubber circuit is to alter the IGBT’s switching trajectory in order to reduce switching losses [15]. The function of the parallel diode is to clamp the unfiltered output pulses of the inverter just after a switching transition. While performing an initial simulation of the inverter, it was found that the output pulses would spike to a value beyond the dc input voltage during an on transition for the upper IGBTs (referring to Figure 3.3). The addition of parallel clamping diodes eliminated these spikes.

Figure 3.4: Single IGBT with RC Snubber and Clamping Diode

The carrier signal was chosen to be a triangular wave with a frequency of 5220 Hz. This frequency lies in the desired range of 2-15 kHz for switching devices in power systems. Further, the switching frequency of 5220 Hz represents the 87th harmonic of the modulating frequency, which is an odd multiple of the third harmonic frequency (29th multiple of 180 Hz). This design choice was made to minimize injected harmonics from the inverter. Figure 3.5 shows the actual model of the triangle signal that is used in the PWM scheme, while Figure 3.6 shows the settings for this carrier switching signal. A duty cycle of 50% is desired in the carrier signal for SPWM in order to create the desired output signal. Finally, the triangle wave has a maximum level of 1 and a minimum level of -1, which is also common in SPWM.

Figure 3.5: Triangle Wave Carrier Signal

Figure 3.6: Triangle Wave Carrier Signal Generator

The desired output of an SPWM based inverter is a set of pulses with a fundamental frequency of 60 Hz with adjustable amplitude. The set of pulses for each phase of the three-phase inverter are generated by comparing three sinusoids to the triangular carrier specified in Figures 3.5 and 3.6. The generation of three sinusoids in PSCAD consists of using a “SIN” block and specifying the magnitude, frequency and phase of each sinusoid. In conventional SPWM, the three sinusoidal generators are all given the same magnitude in order to create a balanced three phase output. However, in this design the sine wave generators for each phase can be given a different magnitude if an unbalanced output voltage is desired. Further, the desired phase for the sinusoidal

wave generators is specified for phase A, and then shifted +240 degrees and +120 degrees for phases B and C, respectively. Figure 3.7 shows the PSCAD model for the sine wave generators. The phase input to the sine wave generator is also the phase of the eventual filtered sine wave. The magnitude input to the sine wave generators, the modulation index, controls the magnitude of the output voltages. The inverter is designed to operate in linear modulation mode, which means that the magnitude of the modulation index ranges from 0 to 1 for all three phases.

Figure 3.7: Sinusoidal Wave Generators

Figure 3.8 shows the PSCAD model for the generation of the firing pulses which are input to the gates of the IGBTs. For each phase, the magnitude of the modulating sine wave is compared to the magnitude of the triangle wave carrier signal using comparators. If the modulating sine wave's magnitude is greater than the magnitude of the sine wave, then the top IGBT for that respective phase turns on and produces a voltage at the output. Additionally, when the top IGBT conducts it implies that the

bottom IGBT associated with that phase is not conducting (off). Similarly, when the triangle wave's magnitude exceeds the magnitude of the sine wave, the bottom IGBT is turned on and zero volts appear at the output of the inverter.

Figure 3.8: Firing Pulse Generators

The output of the inverter is a set of pulses for each phase. In the linear modulation region, the fundamental frequency component of the output voltage varies linearly with the modulation index. Specifically, the peak output voltage value of the fundamental frequency for each phase can be calculated as followed [15]:

$$(\hat{V}_{ph})_1 = m_a \frac{V_{dc}}{2} \quad [V] \quad (3.2)$$

The fundamental component of the output voltage in rms line-to-line can then be calculated by using the following formula [15]:

$$(\tilde{V}_{LL})_1 = \frac{\sqrt{3}}{\sqrt{2}} m_a \frac{V_{dc}}{2} = 0.612 m_a V_{dc} \quad [V] \quad (3.3)$$

In order to verify the operation of the inverter, a simple test was preformed where the modulation index was set to 0.25 for phases A, B and C. The unfiltered set of pulses generated by the inverter for phase A can be seen in Figure 3.9. As expected, the unfiltered pulses transition between $+V_{dc}$ and 0 V, which is characteristic of the unipolar switching technique. It is important to note that the input voltage of the inverter, V_{dc} , was chosen to be 12 kV. Since the pulses range from $+V_{dc}$ to 0 V for each phase when measured from ground, it is often desired to use the line-to-line voltages V_{ab} , V_{bc} and V_{ca} to obtain an output voltage that ranges from $+V_{dc}$ to $-V_{dc}$. Figure 3.10 shows the line voltage V_{ab} , which is created when the set of pulses at the output of phase B is subtracted from the set of pulses at the output of phase A. When filtered, the voltage V_{ab} will yield a sinusoid with zero dc offset, which is why its importance is emphasized in this section.

Figure 3.9: Phase A PWM Output Pulses

Figure 3.10: V_{ab} PWM Output Pulses

3.3 Energy Storage System (ESS) and DC Link Capacitor

Two major components in a DVR system are the energy storage system (ESS) and the dc link capacitor. A DVR system must be able to not only respond quickly to a disturbance but also provide voltage support for long durations if necessary. The dc link capacitor is an energy storage device that supplies short pulses of high power in order to provide a dynamic response [26]. Additionally, the dc link capacitor is used to supply a constant input current to the inverter [27]. The ESS of a DVR is often composed of a battery which provides the active power necessary to protect against longer interruptions. Energy storage devices can be divided into 3 different categories depending on the necessary power capability: Small devices (<10 MW), medium devices ($10 - 100$ MW) and large devices (≥ 100 MW). Batteries have a wide range of capacities ranging from a

few watts to a few megawatts, meaning that they are included in the small and medium ESS categories. Table 3.1 shows a comparison between typical capacitors and batteries with respect to their energy and power density, life cycle count, and discharge times [26]. It can be seen that typical batteries possess large energy densities and long discharge times, meaning that they can supply energy for long periods of time before losing charge. Capacitors, however, have a much larger power density than batteries along with a very small discharge time. This means that they can quickly supply a large amount of energy, but only for a short amount of time [26]. Thus, Table 3.1 shows that a battery and a capacitor can be used to supplement each other in order to meet the power and energy demands for a DVR.

Table 3.1: Comparison of Batteries and Capacitors [26]

Device	Energy Density (Wh/L)	Power Density (W/L)	Cycle Life (cycles)	Discharge Time (seconds)
Batteries	50 – 255	155	$1 - 10^3$	> 999
Capacitors	0.04 – 5	$10^5 - 10^8$	$10^5 - 10^6$	< 1.01

In general, the size of an energy storage device is dependent on the application. Table 3.2 shows the typical energy storage requirements for power grid leveling, power quality, and custom devices [26]. For a DVR system, the energy storage capacity must be large enough to meet the requirements for power quality and custom devices for a few seconds and a few cycles, respectively. This essentially means that the DVR's dc link capacitor must have a storage capacity of 0.11 – 11 MJ with a discharging time period of a few seconds [26].

Table 3.2: Stored Energy Capacity Requirements by Application [26]

Application	Stored Capacity	Discharge Period
Power Grid Leveling	11 MJ – 201 GJ	Few Sec. – Few Days
Power Quality	0.11 – 11 MJ	Few Sec.
Custom Devices	0.11 – 11 MJ	Few Cycles

3.4 PSCAD ESS and DC Link Capacitor Modeling

The PSCAD modeling for the energy storage system and dc link capacitor can be seen in Figure 3.11. The dc input device or ESS is modeled as an ideal dc voltage source. The dc voltage source models a battery with the characteristics discussed previously in section 3.2. An ideal voltage source was chosen to provide a constant dc input voltage to the inverter. The input voltage V_{dc} was chosen to be 12 kV, which is a typical value for DVR systems. In fact, DVRs are commonly installed in substations with voltage ratings ranging from 11 kV to 69 kV [27]. The ideal voltage source will provide any active power required in simulation, meaning that it is capable of supplying an infinite amount of energy for an infinite amount of time. A constant dc input voltage source made it easier to verify the effectiveness of the DVR system in regulating voltage and improving power quality.

Figure 3.11: PSCAD Model of ESS and DC Link Capacitor

The size of the dc link capacitor was chosen in accordance to Table 3.2 of the previous section. The dc input capacitor is needed to supply a large amount of energy for a short period of time in response to a system disturbance. According to the power quality and custom devices applications listed in Table 3.2, this means that the DVR's dc link capacitor must provide between 0.11 and 11 MJ with a discharge time of a few cycles. To derive the capacitance needed to produce this amount of energy, the relationship between voltage, capacitance, and energy stored must be noted. The equation for the energy stored in a capacitor (J) in terms of charge (C) and voltage (V) is shown in Equation 3.4. Additionally, the energy stored in a capacitor (J) is written as a function of capacitance (F) and voltage (V) in Equation 3.5 [26].

$$E = 0.5qV \quad [J] \quad (3.4)$$

$$E = 0.5CV^2 \quad [J] \quad (3.5)$$

Since values for the energy stored in the capacitor and the voltage across the capacitor are known, Equation 3.5 can be rewritten to solve for the dc link capacitance. The value for the energy stored was chosen as 0.72 MJ, which falls in the range of 0.11 MJ to 11 MJ, and the voltage across the capacitor is V_{dc} (12 kV). The dc link capacitance was calculated to be 10 mF.

$$C = \frac{2E}{V^2} = \frac{(2 * 0.72E6)}{(12000)^2} = 10 \text{ mF} \quad (3.6)$$

3.5 PSCAD Low Pass Filter Design

The output side of the DVR's inverter is connected to an LC low pass filter in order to reduce harmonics created by the PWM voltage waveform. The PSCAD model of the LC low pass filter is shown in Figure 3.12. The unfiltered voltages are generated by the inverter, filtered, and then passed to the injection transformers. The delta configuration of the inverter was selected so that the series injection transformers could be connected in a wye configuration.

Figure 3.12: PSCAD LC Low-Pass Filter

For an LC low pass filter, the cutoff frequency is chosen to eliminate the most low order harmonics of the output voltage waveform [28]. The cutoff frequency attenuates the harmonics generated by the PWM inverter, which occur near the switching frequency of 5220 Hz. Equation 3.7 shows that the cutoff frequency or resonant frequency is dependent on the filter capacitance and filter inductance [29]. The filter inductance was chosen to be 100 uH. The capacitor value should be chosen so that the resonant frequency is less than one third of the inverter switching frequency [29]. Accordingly, a filter capacitance of 1 mF was chosen to create a resonant frequency of 503 Hz, which is less than one third of the switching frequency ($f_s/3 = 1740$ Hz). This calculation is performed below using Equation 3.8.

$$\omega_n = \frac{1}{\sqrt{L_f C_f}} \quad \left[\frac{rad}{s} \right] \quad (3.7)$$

$$f_n = \frac{\omega_n}{2\pi} = \frac{1}{2\pi\sqrt{L_f C_f}} = \frac{1}{2\pi\sqrt{(100E-6)(1E-3)}} = 503.3 \text{ Hz} \quad (3.8)$$

3.6 PSCAD Series Injection Transformer Design

In order to inject the three phase voltages created by the voltage source inverter, the DVR uses three single-phase injection transformers shown in Figure 3.13. Three single-phase transformers are typically used in a three-phase DVR system [30]. Each single-phase transformer is rated for 60 Hz, 3 MVA, and an rms voltage rating of 12.47 kV on the primary winding. The secondary side (low voltage side) of each transformer is connected in a wye configuration in order to maximize the output voltages produced by

the inverter [30]. The primary side (high voltage side) of each transformer is kept in an open configuration so that the voltages of each phase can be injected in series with the line.

Figure 3.13: PSCAD Model of Series Injection Transformers

3.7 Complete DVR Design and Control Method

The complete model of the DVR system includes the four major components introduced in the previous sections. The DVR system is series connected between a sensitive load and an upstream power system. For this model, the “source” side refers to the input of the DVR, which is upstream from the sensitive load, whereas the “load” side refers to the output of the DVR, which is directly connected to the sensitive load. The DVR model employs an in-phase compensation strategy in which the DVR injects a voltage in phase with the source voltage. The magnitude of the load voltage is corrected in the case of sag or swell, but the pre-fault load phase angle is not maintained [31]. In-

phase compensation requires both active and reactive power, which is supplied by the DVR's energy storage system and dc link capacitor respectively.

The control method requires voltage measurements at both the source and load side of the DVR. Voltage measurements are made using voltmeters, which measure the instantaneous load and source voltages (with reference to ground) for each phase separately. Each phase voltage is measured so that a separate modulation index can be calculated for each phase. This allows the DVR to correct unbalanced voltage sag or swell. The measured instantaneous voltages for each phase at the source and the load side of the DVR are passed through an rms block in order to obtain their respective phase-to-neutral rms voltage values. The rms calculations are preformed to obtain steady voltage measurements that are easier to work with. To find the per unit value of the source and load voltages for each phase, the base phase voltage of the line must be calculated. Since the rated system voltage of the test circuit provided by SDG&E is 12.47 kV_{LL,rms}, this was chosen as the voltage base for the DVR design model. To calculate the voltage base in phase-to-neutral rms, the following equation was used:

$$\tilde{V}_{ph} = \frac{\tilde{V}_{LL}}{\sqrt{3}} = \frac{12.47 \text{ kV}}{\sqrt{3}} = 7.2 \text{ kV} \quad (3.9)$$

To calculate the rms phase voltages in per unit, the values must be divided by the line's phase-to-neutral rms voltage base calculated in Equation 3.9. Figure 3.14 shows how the phase-to-neutral per unit voltage values are obtained from the instantaneous voltage measurements made for each phase on both sides of the DVR. The real constants in

PSCAD represent kV values, so dividing the rms phase voltages by 7.2 represents a division of 7,200 in actuality.

Figure 3.14: PSCAD Calculation of Phase Voltages in Per Unit

A separate modulation index is calculated for each phase so that the DVR can correct the magnitude of each phase independently. The firing pulses for the SPWM inverter require a magnitude value (the modulation index) and a phase angle. As discussed previously, it is desired that the modulation index range from 0 to 1 so that the output of the inverter changes linearly with the modulation index. Per unitizing the phase voltages allows the calculation of the modulation index for each phase to yield a value between 0 and 1. The calculation of the modulation index for each phase involves summing the difference between the load and the source from a reference of 1 per unit.

The difference between the load voltage and the reference value of 1 per unit represents the magnitude of the voltage in per unit that must be added to restore the load bus voltage to 1 per unit. However, injecting this simple difference between the load voltage and the desired voltage of 1 per unit does not take into account the drop in source voltage. Since the DVR injects a voltage in series with the source, the difference in source voltage from 1 per unit must be added to the difference in the load voltage from 1 per unit. The sum of these differences represents the magnitude of the DVR injected voltage (in per unit) needed to restore the load bus voltage to 1 per unit when injected in series with the source. Figure 3.15 shows the calculation of the modulation index for each phase in PSCAD. The purpose of the comparator is to force the modulation index to zero for each phase until the simulation reaches steady state. In this model, steady state occurs when both the load and source voltages reach 1 per unit, which occurs just before 0.2 seconds. Thus, the DVR does not provide any voltage compensation until 0.1 seconds after the simulation reaches steady state (0.3 seconds into the simulation).

Figure 3.15: PSCAD Modulation Index Calculations

Another important point to note is that the sine wave firing pulses in Figure 3.7 were initially given the source phase so that the output of the inverter was in phase with the source. However, it was observed that the phase of the filtered output of the inverter was shifted +179 degrees from the source phase. To account for this phase shift, an additional value of -179 degrees was added to the source phase and then given to phase input of the sinusoidal generators.

In this control scheme, the modulation index for each phase equals the per unit voltage that needs to be injected in series with the source voltage for each respective phase. For example, if the modulation index for phase A is calculated to be 1 per unit, then the magnitude of the injected voltage for phase A must be 1 per unit. To make this occur, the turns ratio for each the three single-phase injection transformers must be set accordingly. To design the transformer and verify the functionality of the inverter, a test was performed where an inductive load was instantaneously added on the source side of the DVR, creating balanced voltage sag. During the voltage sag, the magnitude of the modulation index was found to be 0.2438. Figure 3.16 shows the unfiltered and filtered inverter output voltage V_{AB} . The plot clearly shows that the magnitude of the fundamental component of the output voltage is smaller than the dc input voltage. Additionally, from Figure 3.17 the peak value of the filtered output voltage V_{AB} was estimated to be 2.636 kV. Referring to Equation 3.9, the corresponding peak value of the phase voltage V_A is 1.5219 kV.

Figure 3.16: V_{ab} , Filtered and Unfiltered

Figure 3.17: V_{ab} , Filtered

In order to verify the plot in Figure 3.17, Equation 3.10 can be used to calculate the expected peak value of the fundamental component of the output voltage in line-to-line. With a dc input voltage of 12 kV and a modulation index of 0.2438, the theoretical peak value of the output voltage in line-to-line was calculated to be 2.534 kV. Using the “FFT” block in PSCAD, the peak value of the output voltage in line-to-line was measured to be 2.525 kV, validating the calculated theoretical value of 2.534 kV. A small gain across the filter (~ 1.044) accounts for the peak value of 2.636 kV measured in Figure 3.17.

$$\hat{V}_{ab} = \sqrt{3}m_a \frac{V_{dc}}{2} = \sqrt{3}(0.2438) \left(\frac{12 \text{ kV}}{2} \right) = 2.534 \text{ kV} \quad (3.10)$$

The final part of the DVR design involved setting the appropriate turns ratio for the three single-phase wye-connected transformers in the same test case above. Since the low voltage sides of the transformers are connected in wye, the voltage V_{AB} calculated in Equation 3.10 was converted from peak line-to-line to peak line-to-neutral. By Equation 3.9, the peak value of V_a was found to be 1.463 kV. The required injected voltage on the primary side of the transformers was calculated by multiplying the modulation index to the rated peak phase voltage of the line. Equation 3.11 shows how the rated peak phase voltage is calculated from the rated rms line-to-line voltage. The rated peak value of the phase voltage was calculated to be 10.1817 kV.

$$(\hat{V}_{ph})_{rated} = \frac{\sqrt{2} * \tilde{V}_{LL}}{\sqrt{3}} = \frac{\sqrt{2} * 12.47 \text{ kV}}{\sqrt{3}} = 10.1817 \text{ kV} \quad (3.11)$$

Multiplying the rated phase voltage of the line by an m_a of 0.2438, the desired injected value was calculated to be 2.4823 kV. Finally, the turns ratio was found by dividing the desired injected voltage (2.4823 kV) by the peak value of the measured secondary side voltage (1.5219 kV). In PSCAD, the winding voltage ratings must be inputted as a rated rms value, so 7.645 kV and 12.47 kV were inputted for windings 1 and 2, respectively. The winding voltage ratings are shown in Figure 3.18, representing a turns ratio of 1.631.

Figure 3.18: PSCAD Winding Voltage Ratings

The complete model of the DVR system can be seen in Figure 3.19. The DVR's ability to protect a sensitive load connected downstream from voltage sag or swell is investigated in the next section. Additionally, the DVR's capability to regulate the bus voltage at the rated value of 1 per unit will also be discussed. The main test circuit used in the DVR testing and analysis is a radial power system provided by San Diego Gas and Electric. The DVR was modulated so that it could be easily connected to a power system. The one line diagram of the test circuit is provided in Figure 3.20, and the external module of the DVR system is shown in Figure 3.21.

Figure 3.19: PSCAD DVR Model

Figure 3.20: Test Circuit One Line Diagram

Figure 3.21: DVR Module

4 Tests and Results

In order to test the DVR's ability to mitigate voltage fluctuations as well as regulate the bus voltage at the load terminal, several different test cases were developed in PSCAD. Specifically, the tests were designed to demonstrate the flexibility of the DVR in protecting a sensitive load from voltage sag and swell. Throughout the testing, the DVR was connected at the end of the test circuit in series with a sensitive 100 kW load. More specifically, the DVR and the sensitive load replace the PV load attached to bus 310 in Figure 3.20 of the previous section. The load was sized to 100 kW because of its similarity to the loads in the provided test circuit. Figure 4.1 shows the initial setup before any tests were performed.

Figure 4.1: DVR Module Protecting Sensitive Load

4.1 Load Side Voltage Sag Protection

Although the DVR is primarily designed to protect against a source side disturbance, it should also correct small voltage perturbations on the side nearest the sensitive load. To test this ability, a purely inductive load of 1 MVAR was added in parallel to the load in order to create a balanced voltage sag. Figure 4.2 shows the

inductive load attached in parallel with the sensitive load through a small transmission line impedance.

Figure 4.2: Load Side Voltage Sag Setup

The DVR does not perform any voltage magnitude correction until the simulation run time reaches 0.3 seconds so that its response can be seen after steady state has occurred. In this test, the inductive load is added at start up, so the steady state voltage sag is evident just before 0.2 seconds run time. Figure 4.3 shows the three-phase rms voltages of the load and the source as the DVR begins to correct the voltage sag at 0.3 seconds. The source voltage remains fairly steady at around 0.93 per unit, but the load voltage is corrected from 0.89 per unit to 0.975 per unit and held there by the DVR. The DVR successfully protects the load without repairing the magnitude of the source voltage. Figure 4.4 shows the phase voltages for the source, the load, and the DVR during the voltage sag. It should be noted that the DVR injects a voltage in phase with the source voltage to restore the magnitude of the load voltage to within 5% of rated value. The load angle is not conserved, as it is forced to be in phase with the source during the DVR compensation. Additionally, the source, load and DVR phase A voltages are overlaid in Figure 4.5, showing the in-phase compensation even more clearly.

Figure 4.3: Load and Source Voltages During Load Side Voltage Sag (RMS, pu)

Figure 4.4: Source, Load, and DVR Phase Voltages During Load Side Sag

Figure 4.5: Phase A Load, Source, and DVR Voltages During Load Side Sag

This same test was performed for a few more loads in order to gain more knowledge of the DVR's response to load side voltage sag. The acceptable range for the steady state load bus voltage is between 0.95 and 1.05 per unit. The data in Table 4.1 shows that the DVR could regulate the load bus voltage to within 5% (0.05 per unit) of rated value up to an inductive load of 2 MVar. Figure 4.6 further demonstrates the DVR's ability to protect a sensitive load from load side sag.

Table 4.1: DVR Load Side Voltage Sag Correction with Added Load

Added Load (MVar)	Load Voltage w/out DVR (pu)	Load Voltage w/ DVR (pu)
0.5	0.94363	0.98670
1	0.89336	0.97547
1.5	0.84748	0.96192
2	0.80683	0.95015

Figure 4.6: Load Bus Voltage for Various Load Side Sag

4.2 Load Side Voltage Swell Protection

A similar test to the one performed to simulate voltage sag was done to emulate voltage swell on the load side of the DVR. However, instead of adding an inductive load in parallel with the sensitive load, a purely capacitive load of -1 MVar was added.

Figure 4.7 shows the added load in parallel with the protected load.

Figure 4.7: Load Side Voltage Swell Setup

Once again, the comparator in the modulation index calculation is designed to prevent the DVR from injecting a voltage until 0.3 seconds into the simulation. Figure 4.8 shows the load and source voltages in per unit as the DVR begins to inject a compensation voltage to counteract the voltage swell. Before correction, the capacitive load increases the load and source voltages, with the load voltage leveling out at 1.132 per unit. Once the DVR turns on, and the voltage magnitude of the load is quickly brought down to 1.025 per unit. This value is well within the acceptable 5% range from the rated value, and the DVR shows the ability to regulate the load bus voltage. Figure 4.9 shows the phase voltages for the source, the load and the DVR during the voltage swell. In this case, the DVR injects a voltage that is 180 degrees out of phase with the source voltage in order to restore the magnitude of the load voltage to within 5% of rated value. Figure 4.10 shows the phase A voltages of the source, load, and DVR. The DVR injected voltage is 180 degrees out of phase with the source so that the magnitude of the load voltage is reduced to the rated value.

Figure 4.8: Load Voltage During Load Side Voltage Swell (RMS, pu)

Figure 4.9: Source, Load, and DVR Phase Voltages During Load Side Swell

Figure 4.10: Phase A Load, Source, and DVR Voltages During Load Side Swell

Much like the test done for voltage sag, the size of the capacitive load was varied to observe the DVR's ability to correct for different sized voltage swells. Table 4.2 shows the load bus voltage in per unit with and without the DVR for various capacitive loads. The DVR demonstrates the ability to keep the bus voltage at the load to within 0.05 per unit (5%) of rated for loads up to -1.4 MVar. Figure 4.11 clearly shows the effectiveness of the DVR in protecting the sensitive load from load side swell.

Table 4.2: DVR Load Side Voltage Swell Correction with Added Load

Added Load (MVar)	Load Voltage w/out DVR (pu)	Load Voltage w/ DVR (pu)
-0.5	1.06023	1.01387
-1	1.13183	1.02519
-1.2	1.16307	1.03552
-1.4	1.20229	1.05000

Figure 4.11: Load Bus Voltage for Various Load Side Swell

4.3 Source Side Voltage Sag Protection

The primary function of the DVR is to protect the sensitive load from voltage sags occurring on the source side, everything upstream from the DVR, since this is most common sort of disturbance in the real world. Similar to the load side test, the voltage sag in this test is created by adding a large inductive load on the source side of the DVR. More specifically, a 3 MVar load is connected to bus 310 inside the test circuit as shown in Figure 4.12.

Figure 4.12: Source Side Voltage Sag Setup

The DVR injects a three-phase series compensation voltage to correct the three-phase voltage sag after the steady-state sag condition has occurred. Figure 4.13 shows the source and load per unit rms voltages as the DVR begins to compensate for the voltage sag. During the sag, the load and source voltages are 0.83801 per unit. Once the DVR turns on, the load voltage is quickly restored to exactly 1 per unit. Figure 4.14 shows the load, source, and DVR injected voltages during sag mitigation. The DVR injects the compensation voltage in phase with the source in order to correct the magnitude of the load bus voltage. A closer look at this relationship between the source, load and DVR voltages for phase A can be seen in Figure 4.15.

Figure 4.13: Load and Source Voltages During Source Side Voltage Sag (RMS, pu)

Figure 4.14: Source, Load, and DVR Phase Voltages During Source Side Sag

Figure 4.15: Phase A Load, Source, and DVR Voltages During Source Side Sag

The size of the reactive load added to bus 310 was varied to observe the DVR's ability to correct for different sized voltage sags. Table 4.3 shows the load bus voltage in per unit with and without the DVR for various inductive loads. The DVR demonstrates the ability to regulate the bus voltage to the rated value of 1 per unit regardless of the load size. Figure 4.16 shows the effectiveness of the DVR in protecting the sensitive load from source side sag.

Table 4.3: DVR Source Side Voltage Sag Correction with Added Load

Added Load (MVar)	Load Voltage w/out DVR (pu)	Load Voltage w/ DVR (pu)
0.5	0.96841	1.00046
1	0.93905	1.00054
1.5	0.91053	0.99970
2	0.88474	1.00059
2.5	0.86034	1.00008
3	0.83801	1.00000
5	0.75612	0.99993
10	0.60846	1.00066

Figure 4.16: Load Bus Voltage for Various Source Side Sag

4.4 Source Side Voltage Swell Protection

In addition to compensating for voltage sag, the DVR should provide dynamic response and voltage regulation during a source side voltage swell. To demonstrate the DVR system's ability to correct a source side swell, a purely capacitive load of -2 MVAR was added to bus 310 in the test circuit. The setup for testing source side swell with the added load is shown in Figure 4.17.

Figure 4.17: Source Side Voltage Swell Setup

Similar to the tests in previous sections, the DVR is prevented from performing voltage correction until the system has reached steady state. In this case, the load and source rms voltages reached a steady state swell value of 1.1448 per unit. Figure 4.18 shows the DVR turning on at 0.3 seconds and then quickly restoring the load voltage to the rated voltage of 1 per unit. Like the test for source side voltage sag, the DVR corrected the load voltage to exactly the rated value, so the discussion of reaching the

permissible 5% deviation from rated voltage is not required. Figure 4.19 shows the source, load, and DVR injected voltages during the voltage swell mitigation.

Additionally, Figure 4.20 shows the DVR injected voltage 180 degrees out of phase with the source voltage so that the load bus voltage magnitude can be decreased to its rated value.

Figure 4.18: Load and Source Voltages During Source Side Voltage Swell (RMS, pu)

Figure 4.19: Source, Load, and DVR Phase Voltages During Source Side Swell

Figure 4.20: Phase A Load, Source, and DVR Voltages During Source Side Swell

The size of the capacitive load added to bus 310 was varied to observe the DVR's ability to correct for different sized voltage swells. Table 4.4 shows the load bus voltage in per unit with and without the DVR for various capacitive loads. The DVR demonstrates the ability to regulate the bus voltage to the rated value of 1 per unit regardless of the load size. Figure 4.21 shows the effectiveness of the DVR in protecting the sensitive load from source side swell.

Table 4.4: DVR Source Side Voltage Swell Correction with Added Load

Added Load (MVar)	Load Voltage w/out DVR (pu)	Load Voltage w/ DVR (pu)
-0.5	1.03229	1.00077
-1	1.06730	1.00050
-1.5	1.10260	1.00079
-2	1.14480	1.00180
-2.5	1.18880	1.00016

Figure 4.21: Load Bus Voltage for Various Source Side Swell

4.5 Three-Phase Fault Protection

Evaluating the DVR system's ability to protect the sensitive load from a source side disturbance cannot be done without performing a fault test case. As shown by Figure 4.22, a three-phase to ground fault was applied upstream in the test circuit at bus 209. Providing protection for a three-phase to ground fault is a harsh test for the DVR system.

Figure 4.22: Three-Phase to Ground Fault Setup

The three phase fault was applied at 0.5 seconds for 0.5 seconds by using the “timed logic fault” block in PSCAD. Figure 4.23 shows the load and source per unit voltages before, during, and after the fault. The DVR responds by restoring the load voltage to rated value within a few cycles. At 1 second in the simulation, the load voltage rises for a brief moment but is then restored back to 1 per unit in a couple of cycles as the DVR reacts to the fault clearing itself. Figure 4.24 shows the load, source and DVR voltages just as the fault occurs. The DVR quickly reacts to the fault by increasing the magnitude of its injected voltage. Also, Figure 4.25 shows a single phase (phase A) being corrected as the DVR begins to react to the fault. The DVR demonstrates a dynamic response to a three phase fault as well as an ability to regulate the load bus voltage after the initial correction.

Figure 4.23: Load and Source Voltages During Three Phase Fault (RMS, pu)

Figure 4.24: Source, Load, and DVR Phase Voltages During Three Phase Fault

Figure 4.25: Phase A Load, Source, and DVR Voltages During Three Phase Fault

5 Conclusion

The rising demand for clean, reliable and renewable energy resources has led to an increase of the annual government investment into the research and development of these technologies. The increased government funding and incentives has led to an increase in the number of grid-tied renewable energy sources as their economic benefits become more renowned. However, this large influx of grid-tied renewable energy resources has adversely affected power quality and total system operation. The outputs of these renewable resources are often highly variable, resulting in undesirable voltage disruptions that are harmful to some sensitive electronic devices. Mitigating these voltage fluctuations and maintaining power quality is becoming increasingly important as the number of renewable sources continues to grow.

Recent advances in power electronics have opened up new solutions to the voltage support problem in power systems. One such device is the Dynamic Voltage Regulator (DVR), which is a series compensating device used to protect a sensitive load that is connected downstream from voltage sag or swell. This thesis presents the modeling and analysis of a DVR system using PSCAD software. The results from simulation demonstrate the DVR's ability to protect a sensitive load from voltage sag and swell as well as regulate the load bus voltage to its rated value. Using a robust in-phase compensation strategy for series voltage injection, the DVR dynamically corrects large voltage sags and swells in only a few cycles. The DVR module developed in this thesis provides a useful engineering tool for future analysis and placement of DVR systems.

Voltage disruptions and power quality problems will continue to rise as the number of grid-tied renewable energy sources increases, so the use of an effective DVR model is essential for protecting loads that are sensitive to these issues.

Further Work

Battery Energy Storage System with Grid-Tied Charging System

A major advancement to this study would include the development of an accurate battery energy storage system model with a grid-tied charging system. The current model uses an ideal voltage source to supply the necessary active power during lengthy sag or swell. The ideal voltage source does not emulate the discharging or voltage collapse of a typical energy storage system such as a battery. In fact, the ideal voltage source will supply an infinite amount of power if it is required by the system. An effective battery model with a charging system would provide a better base for testing the DVR's ability to provide voltage regulation for long durations.

Pre-Sag Voltage Injection Compensation

An alternative voltage compensation method that could improve the design presented in this thesis is known as pre-sag voltage injection. In pre-sag compensation, the DVR injects a voltage of the required magnitude and phase to restore the load to its original condition regardless of the type of disturbance. The magnitude of the DVR injected voltage depends on the phase jump and voltage drop during the disturbance. Pre-sag compensation can eliminate balanced or unbalanced voltage sags. Figure 5.1 shows a phasor diagram of pre-sag voltage compensation [31].

Figure 5.1: Phasor Diagram of Pre-Sag Compensation

This thesis presents a DVR using an in-phase compensation technique to restore the magnitude of the load voltage. The phase angle of the load is not restored during a disturbance, as the DVR injects a voltage in phase with the source in order to fix the magnitude of load bus voltage. Although the current in-phase compensation strategy allows the DVR to provide a dynamic response to voltage fluctuations and protect a sensitive load for long periods of time, implementing a pre-sag compensation strategy would be a major improvement.

BIBLIOGRAPHY

- [1] C.-C. Fung, W. Thanadechteemapat and D. Harries, "Acquiring knowledge and information on alternative energy from the world wide web," in *Power & Energy Society General Meeting*, 2009.
- [2] D. E. Martinot, "REN21 Renewables Global Futures Report (GFR)," REN21, Paris, 2013.
- [3] W. Zghal, G. Kantchev and H. Kchaou, "Determination of the exploitable solar energy for electricity generation using the photovoltaic systems," in *Renewable Energies and Vehicular Technology (REVET), First International Conference on*, 2012.
- [4] L. Sherwood, "U.S. Solar Market Trends 2011," Interstate Renewable Energy Council (IREC), 2012.
- [5] G. Barbose and R. Wiser, "Berkeley Lab Report Shows Significant Decline in the Installed Cost of Solar Photovoltaic Systems in the U.S.," Lawrence Berkeley National Laboratory, 2011. [Online]. Available: <http://eetd.lbl.gov/newsletter/nl37/eetd-nl37-7-trackingthesun.html>. [Accessed 12 March 2013].
- [6] L. Boyd and G. Wilson, "Photovoltaics Research," NREL, 29 October 2012. [Online]. Available: <http://www.nrel.gov/pv/>. [Accessed 13 March 2013].
- [7] C. Benachaiba and B. Ferdi, "Voltage Quality Improvement Using DVR," *Electrical Power Quality and Utilisation*, vol. 14, no. 1, pp. 39-45, 2008.
- [8] G. C. Lazaroiu, "Power Quality Assessment in Small Scale Renewable Energy Sources Supplying Distribution Systems," *Energies 2013*, vol. 6, no. 1, pp. 634-645, 2013.
- [9] "Voltage Sags," Platts, a Division of The McGraw Hill Companies, Inc., Moncks Corner, SC, 2004.
- [10] "What is the Smart Grid?," U.S. Department of Energy, 2013. [Online]. Available: www.smartgrid.gov. [Accessed 13 March 2013].
- [11] S. J. Bossart and J. E. Bean, "Metrics and Benefits Analysis and Challenges for Smart Grid Field Projects," in *Energytech, 2011 IEEE*, Cleveland, OH, 2011.
- [12] S. Pal and S. Nath, "An Intelligent on Line Voltage Regulation in Power Distribution System," in *Power, Control and Embedded Systems (ICPCES), 2010 International Conference on*, Allahabad, 2010.

- [13] A. Domijan, A. Montenegro, A. J. F. Keri and K. E. Mattern, "Custom Power Devices: An Interaction Study," *Power Systems, IEEE Transactions on*, vol. 20, no. 2, pp. 1111-1118, 2005.
- [14] A. Domijan, A. Montenegro, A. J. F. Keri and K. E. Mattern, "Custom Power Devices: An Interaction Study," *Power Systems, IEEE Transactions on*, vol. 20, no. 2, pp. 1111-1118, 2005.
- [15] Taufik and D. Dolan, *Advanced Power Electronics*, 6 ed., San Luis Obispo, CA, 2013.
- [16] L. Gyugyi, "Power Electronics in Electric Utilities: Static VAR Compensators," in *Proceedings of the IEEE*, Pittsburgh, PA, 1988.
- [17] M. Noroozian, "Benefits of SVC and STATCOM for Electric Utility Application," in *Transmission and Distribution Conference and Exposition, 2003 IEEE PES*, 2003.
- [18] J. Z. C. Z. W.-J. L. Kejun Li, "Dynamic Simulator for Thyristor-Controlled Series Capacitor," *IEEE Transactions on Industry Applications*, vol. 46, no. 3, pp. 1096-1102, May/June 2010.
- [19] G. F. Mazilah Binti A Rahman, "Overview of Thyristor Controlled Series Capacitor (TCSC) in Power Transmission System," [Online]. Available: <http://www.scribd.com/doc/83310456/e03421>. [Accessed 11 March 2013].
- [20] E. H. W. M. A. Carlos A. C. Cavaliere, "Analysis and Operation of STATCOM in Unbalanced Systems," [Online]. Available: <http://www.ipst.org/TechPapers/2001/IPST01Paper207.pdf>. [Accessed 11 March 2013].
- [21] Y. Suresh and A. K. Panda, "Dynamic Performance of STATCOM Under Line to Ground Faults in Power System," in *5th IET International Conference on Power Electronics, Machines and Drives (PEMD 2010)*, Brighton, UK, 2010.
- [22] A. Ghosh and G. Ledwich, "Structures and Control of a Dynamic Voltage Regulator," in *IEEE Power Engineering Society Winter Meeting, 2001*, Columbus, Ohio, 2001.
- [23] A. M. Gole, "Sinusoidal Pulse Width Modulation," 2000.
- [24] Taufik and D. Dolan, *Introduction to Power Electronics*, San Luis Obispo, CA, 2012.
- [25] Maxim Integrated Products, "Class D Amplifiers: Fundamentals of Operation and Recent Developments," 31 January 2007. [Online]. Available: <http://pdfserv.maximintegrated.com/>. [Accessed 15 March 2013].

- [26] H. Tiwari and S. Kumar Gupta, "DC Energy Storage Schemes for DVR Voltage Sag Mitigation System," *International Journal of Computer Theory and Engineering*, vol. 2, no. 3, June 2010.
- [27] S. C. Rao, "Enhancement Of Fast Loop Controlling Mechanism For Capacitor- Supported Dynamic Voltage Restorer (DVR) Using Modulation Technique," *International Journal of Engineering Research and Applications*, vol. 3, no. 2, pp. 1474-1491, April 2013.
- [28] J. Kim, J. Choi and H. Hong, "Output LC Filter Design of Voltage Source Inverter Considering the Performance of Controller," in *International Conference on Power System Technology*, Perth, WA, 2000.
- [29] K. Hatua, A. Jaon, D. Banerjee and V. Ranganathan, "Active Damping of Output LC Filter Resonance for Vector-Controlled VSI-Fed AC Motor Drives," *IEEE Transactions on Industrial Electronics*, vol. 59, no. 1, pp. 334 - 342, 2012.
- [30] C. Zhan, M. Barnes, V. Ramachandaramurthy and N. Jenkins, "Dynamic Voltage Restorer with Battery Energy Storage for Voltage Dip Mitigation," in *International Conference on Power Electronics and Variable Speed Drives*, London, 2000.
- [31] A. Sadigh and K. Smedley, "Review of Voltage Compensation in Dynamic Voltage Restorer (DVR)," in *2012 IEEE Power and Energy Society General Meeting*, San Diego, 2012.