IMPLEMENTATION OF VIRTUAL SYNCHRONOUS GENERATOR TO STABILIZE SYNCHRONOUS GENERATOR AND GRID CONNECTED OPERATIONS

A Project Report

submitted by

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To My Parents

THESIS CERTIFICATE

This is to certify that the thesis entitled **"IMPLEMENTATION OF VIRTUAL SYNCHRONOUS GENERATOR TO STABILIZE SYNCHRONOUS GENERATOR AND GRID CONNECTED OPERATIONS"** submitted by **AMARJYOTI BORO** to the Indian Institute of Technology, Madras for the award of the degree of Master of Technology is a bona fide record of the research work done by him under my supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

KEYWORDS: Virtual Synchronous Generator; Voltage Source Converter; Distributed Generator; Virtual Inertia; Synchronous Machine.

The ongoing evolution of the power system towards a "Smart Grid" implies a dominant role of power electronic converters, but poses strict requirements on their control strategies to preserve stability and controllability. In this perspective, the definition of decentralized control schemes for power converters that can provide grid support and allow for seamless transition between grid-connected or islanded operation is critical. Since these features can already be provided by synchronous generators, the concept of Virtual Synchronous Generators (VSGs) can be a suitable approach for controlling power electronics converters. The concept of Virtual Synchronous Generators (VSGs) is emerging as an alternative approach for control of power electronic converters operating in the power system. One main motivation for applying VSG-based control is to achieve a simple approach for emulating the inertia effect of traditional synchronous machines. This paper starts with a discussion of the general features offered by the VSG concept in the context of stability of the power system. A specific VSG implementation is then presented in detail together with some of its specific configuration.

The virtual synchronous generator (VSG) is a control scheme applied to the inverter of a distributed generating unit to support power system stability by imitating the behavior of a synchronous machine. The VSG design incorporates the swing equation of a synchronous machine to express a virtual inertia property. Unlike a real synchronous machine, the parameters of the swing equation of the VSG can be controlled in real time to enhance the fast response of the virtual machine in tracking the steady-state frequency. Based on this concept, the VSG with alternating moment of inertia is elaborated in this paper. In addition, the performance of the proposed inertia control in stability of nearby machines in power system is addressed. The idea is supported by simulation and experimental results, which indicates remarkable performance in the fast damping of oscillations.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

AC	Alternating Current
DC	Direct Current
DER	Distributed Energy Resource
DG	Distributed Generator
HVDC	High Voltage Direct Current
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistor
PCC	Point of Common Coupling
PQ	Power Quality
PLL	Phase Locked Loop
PWM	Pulse width modulation
SG	Synchronous Generator
SM	Synchronous Machine
SRF	Synchronous Reference Frame
VSC	Voltage Source Converter
VSG	Virtual Synchronous Generator

NOTATIONS

C_{DC}	DC storage capacitance
D	Damping Factor
δ	Load angle
$\Delta\omega$	Difference of angular velocity of virtual rotor and grid
f_{grid}	Grid frequency
f_{base}	Base frequency
H	Inertia constant of the machine
I_{grid}	Grid current
J	Moment of Inertia of the Virtual Rotor
J_{big}	Bigger value of Moment of Inertia
J_{small}	Smaller value of Moment of Inertia
ω_m	Virtual angular velocity of Virtual Rotor
ω_0	Initial virtual angular velocity of Virtual Rotor
ω_{grid}	Grid frequency or reference frequency
P_{in}	Input Power to VSG
P_{out}	Output Power of VSG
P_{ref}	Reference power
R_L	Grid resistance
S	Apparent power
S_{base}	Base apparent power
S_{rated}	Rated apparent power
θ_m	Virtual rotor angle
V_{DC}	DC-link voltage
V_{grid}	Grid voltage
V_{ref}	Voltage reference
X_F	Filter Inductance
X_L	Grid inductance

CHAPTER 1

INTRODUCTION

This chapter introduces the reader to the subject of the report and covers the motivation for the thesis, the objectives, the scope of work, the limitation and finally describes the structure of the report.

1.1 MOTIVATION

In classical power systems, the Synchronous Machine (SM) with speed governor and excitation control offers favorable features to support the system operation within a distributed control scheme. Indeed, SMs contribute to the system damping through their inertia, participate in the primary frequency regulation through the droop response of the speed controller, and provide local control of voltage or reactive power flow. These capabilities, and especially the inertial and damping response common to all SMs, are not inherently offered by the power electronics interfaces commonly adopted for the integration of renewable energy sources. A distributed model for production and local control is also opening the possibility of islanded operation, which is inherently feasible with one or more controllable SMs in the islanded area. Such islanding operation is usually more complex to achieve with power converter interfaces designed for integration with a large-scale power system.

Power from many traditional large-scale generation facilities is currently being replaced by distributed generation capacity from windpower and photovoltaics. The traditional control structures implemented in the power converters for these applications rely on the synchronization to a stable grid frequency supported by large rotating inertias and are not inherently suitable in a Smart Grid context. Thus, from an implementation perspective, significant research efforts are still devoted towards development of control schemes for power electronic converters explicitly conceived to address the conditions emerging in future Smart Grids. Given the inherent benefits of the SMs outlined above, a captivating approach is the control of power electronic converters to replicate the most essential properties of the SM and by that gain equivalent features from a functional point of view. Thus, several alternatives for providing auxiliary services like reactive power control, damping of oscillations and emulation of rotating inertia with power electronic converters have been proposed. Some of these control strategies are explicitly designed to mimic the dynamic response of the traditional SM, and can therefore be classified in broad terms as Virtual Synchronous Generators (VSG).

Conventional enormous synchronous generators (SGs) comprise rotating inertia due to their rotating parts. These generators are capable of injecting the kinetic potential energy preserved in their rotating parts to the power grid in the case of disturbances or sudden changes. Therefore, the system is robust against instability. On the other hand, penetration of distributed generating (DG) units in power systems is increasing rapidly. The most challenging issue with the inverter-based units is to synchronize the inverter with the grid and then to keep it in step with the grid even when disturbances or changes happen [2]. A power system with a big portion of inverter based DGs is prone to instability due to the lack of adequate balancing energy injection within the proper time interval. The solution can be found in the control scheme of inverter based DGs. By controlling the switching pattern of an inverter, it can emulate the behavior of a real synchronous machine. In the VSG concept, the power electronics interface of the DG unit is controlled in a way to exhibit a reaction similar to that of a synchronous machine to a change or disturbance. The VSG control generates amplitude, frequency, and phase angle for its terminal voltage based on its power command. Therefore, as a corollary, it can contribute to the regulation of grid voltage and frequency.

The VSG concept and application were investigated in [3]. The same concept under the title of synchroconverter is described in [4]. The VSG systems addressed in [5] is designed to connect an energy storage unit to the main grid. Hesse et al. [6] implement a linear and ideal model of a synchronous machine to produce current reference signals for the hysteresis controller of an inverter. Xiang-Zhen et al. The work carried out in [7] introduces a mechanism for voltage, frequency, and active and reactive power flow control of the VSG. The effect of the VSG on the transient response of a microgrid is addressed in a more recent publication [8]. Various research groups has introduced a new VSG design, enhanced the voltage sag ride-through capability of the VSG [9], evaluated it in various voltage sag conditions, and finally added reactive power control to have a constant voltage at VSG terminals.

1.2 OBJECTIVES

The aim of this thesis is to explore the characteristics of a Virtual Synchronous Generator and its performances in various fields and how it can be an alternative to conventional Synchronous Machine. Also the operation of the VSG with fixed inertia compared to its operation with alternating inertia will be discussed in detail. The following objectives are to be carried out:

1. Design a relevant system to study
2. Build a simulink model of the system
3. Explore the system behavior and identify relevant test cases
4. Simulate said test cases
5. Present and discuss the results

1.3 SCOPE OF WORK

As stated in the task description, the focus of this thesis is on the applicability of VSG when connected to the power grid. The VSG may be in parallel with other machines or it may be also used as an interface between Synchronous Generator and the Grid. The aim will be to study how the controllers of the different components will interact with each other and what effect they have on load flow and other parameters such as grid frequency. The stability of the grid and its enhancement due to the introduction of alternating inertia will be studied in the events of fault at load point or in the case of voltage sag.

1.4 LIMITATIONS

The thesis will cover the control strategies of the various components of the system to a greater extent than the physical components themselves. The model that is built in this thesis introduces a set of limitations. Several simplifications have been done when modeling in order to better fit the scope, and to make the modeling easier. The modeling is covered in detail in Chapter 3, so this section will cover what limitations the model has, and why it has them. As mentioned in the scope of work, the modeling of the physical components themselves has not been a priority. The power electronic converters in the model for example, is based on average models. The average model of a converter cannot represent harmonics, so harmonics cannot be studied. The average model also assumes the converter to be ideal, which implies that there are no losses in the electronics. The power system studied in this thesis is not very complex and has been simplified to a great extent in order to make analysis and simulations easier. This low complexity imposes limitations on how advanced the test cases can be. It also limits the relevancy of the findings to real life cases by making them more theoretical and related to only a small part of an actual system. This is of course all related to the scope of work and a design and analysis of much more complex system would not have been feasible with the time and resources at hand. The system do not contain any infrastructure for reconnecting the VSG to the grid if it initially was running in island operation. The system would need to have a synchronization controller such as the one described in [10] in order to make reconnection possible. The lack of this technology in the system means that scenarios such as synchronization of the VSG with an already operational synchronous generator cannot be studied. Furthermore, no application specific constraints of the DC side of the VSC are considered and thus the modeling and control of the energy source or storage on the DC side of the converter is not further discussed.

1.5 STRUCTURE OF THE REPORT

The thesis work in five chapters is described as given below.

Chapter 1 gives an introduction to Virtual Synchronous Generators. It also gives a comparison between the conventional SM and the VSG. It discusses about the driving force behind doing this project and along with it the various objectives that needs to be carried out. It also throws some light on the scope of its work and at the same time restricts itself with the unavoidable limitations.

Chapter 2 covers the background for the technologies and concepts of the subject matter studied in the thesis. A detailed information about the VSGs and its characteristic behavior in different aspects has been discussed. The role of virtual inertia in the working of VSG has been broadly discussed. Lastly, it mentions about the VSG control unit and how it generates the necessary control signals.

Chapter 3 gives an overview of the system description and also the modeling of the system has been covered. Here the possible configuration of the VSG with the rest of the system such as the Grid and other machines has been discussed.

Chapter 4 discusses all the results of the simulations of the relevant test cases while presenting graphical plots for the same. Various comparisons are done for the enhancement of performance of the VSG and the same will be proved with the help of the results.

Chapter 5 presents the important conclusions of the work and also suggests some of the possible future scope of the work.

CHAPTER 2

BACKGROUND

This chapter covers all the technical aspects of the various concepts studied in this thesis and also all the state of the different technologies are discussed.

2.1 TRADITIONAL POWER SYSTEMS

In traditional power systems, generation is provided by a rather small number of large power plants, which are connected to the transmission system. In a traditional power generation unit, a prime mover (usually a turbine or a combustion engine) converts the primary source of energy into mechanical energy. The prime mover drives a synchronous machine (SM), which transforms the mechanical energy into electrical energy. A governor (speed controller/governor) controls the power output or the speed, based on a given active power-frequency droop characteristic. An exciter provides the field (excitation) current, necessary to create the magnetic field inside the SM. An automatic voltage regulator (AVR) controls the field current and, in consequence, the SM terminal voltage [14].

The stability of a traditional power system is strongly affected by its controls, which are highly distributed in a hierarchical configuration. Controllers operate directly on individual elements like boilers, prime movers, excitation systems, power (electronic) converters and transformer tap changers. The controllers of closely linked elements are coordinated by plant controllers. System controllers supervise the plant controllers at system control centers, and pool-level controllers coordinate the system controllers at pool control centers.

Within the distributed control structure, traditional power generation units support traditional power system operation in different ways. They participate in the system damping via their inertia, contribute in the primary frequency regulation by means of their governor droop characteristics, and take part in the local control of voltage or reactive power flow through their excitation controls. Such features are not intrinsic to the conventional control of the renewable energy sources (RES) power electronics interfaces, which depend on the synchronization to a stable grid frequency [14].

2.2 POWER SYSTEM STABILITY

Power system stability refers to the capacity of an electric power system to recover operating equilibrium after undergoing a disturbance, with most of the system remaining intact. The initial operating conditions and the nature of the disturbance influence this ability [14].

Power systems undergo a great diversity of disturbances. Load variations take place constantly, acting as small disturbances, and power systems have to operate satisfactorily while adapting to such changing conditions. The components must also come through large disturbances, such as the loss of a large generator or a short circuit in a transmission line. Such disturbances can result in structural changes caused by the isolation of faulted elements or deliberate disconnections to maintain the major part of the system in operation. Interconnected power systems can also be deliberately divided into independent systems called "islands" [14].

Simplifying assumptions are made to concentrate on the aspects determining the specific kinds of stability problems. Stability in traditional power systems has been consequently classified into various categories. This facilitates the identification of essential aspects that contribute to instability and the development of methods for enhancing stability.

2.2.1 ROTOR ANGLE STABILITY

For SMs to be interconnected, the frequency of their stator voltages and currents has to be the same, and, since their rotors mechanical angular speed is synchronized to that angular frequency, the rotors of all interconnected SMs need to be in synchronism. The stability category concerned with the capacity of the interconnected SMs of a power system to stay in synchronism after undergoing a disturbance is called rotor angle stability. Such ability is determined by the capacity of each SM to sustain or regain equilibrium even after small disturbances. That operating equilibrium is disrupted when the power system undergoes a disturbance, which causes the acceleration or deceleration of the rotors [14].

2.2.2 VOLTAGE STABILITY

The stability category concerned with the capacity of a power system to keep voltage levels within their limits at all buses after undergoing a disturbance is called voltage stability. Such ability is determined by the capacity to sustain or regain equilibrium between power (load) supply and demand. Corresponding instability arises as a gradual voltage drop or increase in some buses. Voltage instability occurs often together with rotor angle stability. One can result in the other, and it can be difficult to differentiate them. The distinction has been made nevertheless in the traditional classification of power system stability with the purpose of comprehending the factors causing the problems, so that suitable design and operating methods can be elaborated [14].

2.3 THE VOLTAGE SOURCE CONVERTER

In this thesis, voltage source converters will be used as an application to be the interface of the grid with a battery storage unit. It will be controlled as a virtual synchronous machine and the combination of the VSC and battery may sometimes be referred to as simply "the VSG". A voltage source converter is a power electronic device used to convert DC to AC (inverter mode) or AC to DC (rectifier mode). The VSC use transistors, usually the insulated-gate bipolar transistor (IGBT) in parallel with diodes to achieve self-commutation. The IGBT is controlled by a signal which enables the closing or opening of the IGBT switch [15].

The operation of the VSC is done through the concept of pulse-width-modulation(PWM). This involves comparing a control signal with a saw-tooth signal to provide "on or off" orders to the IGBT/diode blocks of the VSC. However, this thesis will not focus on the switching operation of the VSC, but rather on the controller of the VSC.

The control signals to the VSC are sent by the VSG control unit after being modulated by the PWM. The VSG control unit generates signals with the help of the references provided by the Frequency detector and the Power meter which are basically the voltages and currents measurements of the Grid [15].

2.4 DISTRIBUTED ENERGY RESOURCES

Environmental, technological and economic incentives are shifting paradigms in power systems. Traditional generation units exploiting centralized energy resources are giving way to smaller, more distributed energy resources (DER). DER include distributed storage (DS), demand response (DR) loads and distributed generation (DG), and encompass a wide range of emerging technologies, most of which have power electronics interfaces to the electrical power system. As opposed to traditional generation units, most DER are connected to distribution networks [14].

One of the major differences from traditional generation is that DG interfaced with power electronics cannot inherently supply the instantaneous power needs because of the absence of large rotors. Since most DG are inertia-less and respond slowly to control signals, load tracking problems occur when operating without the presence of traditional generation. Thus, a system with groups of such DG designed to operate in that condition needs some sort of (distributed) energy storage to guarantee initial energy balance.

The technical challenges associated with the centralized control of a significant number of units is a fundamental problem for DER. In such a complex control system, the malfunction of a control, communication or software component could potentially cause a system collapse [14].

2.5 THE VIRTUAL SYNCHRONOUS GENERATOR

The concept of a Virtual Synchronous Generator was first presented in [11]. The paper uses the abbreviation "VISMA", while this thesis will use "VSG". The original application for the VSG was for use in distributed energy sources. As discussed in [12], the traditional power system has a vertical structure with power production in one end and consumption in the other. The large, centralized power plants of the traditional power system use synchronous machines for electric power generation. The synchronous machine possess several important parameters such as inertia and damping that are crucial

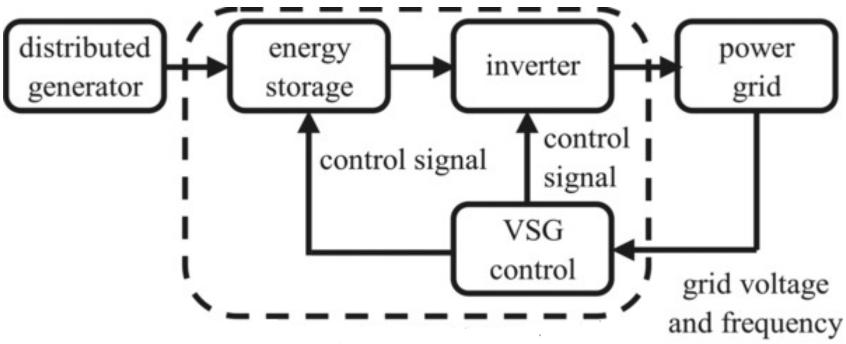

Fig. 2.1 Simplified block diagram of a VSG unit [15]

for the operation of a power system. However, the power system is moving toward more distributed energy sources, such as photovoltaics (PV) and local energy storage. The connection of these sources to the grid is achieved through the use of power electronics such as VSC. A distributed power source that is connected to the grid with a VSC does not introduce properties such as inertia and damping of which the power system relies on. The idea of the VSG is therefore to control the VSC in such a way that it mimics the behavior of a synchronous machine, and in that way provide the properties of damping and inertia that the power system is wanting as shown in Fig 2.1. The underlying idea behind the VSG concept is to emulate the essential behavior of a real SM by controlling a power electronic converter. Thus, any VSG implementation contains more or less explicitly a mathematical model of a SM. The specific model of the SM and its parameters is largely an arbitrary design choice as proved by the many different solutions discussed in literature. However, the emulation of the inertial characteristic and damping of the electromechanical oscillations are common features for every VSG implementation. Additional aspects as the transient and sub-transient dynamics can be included or neglected, depending on the desired degree of complexity and accuracy in reproducing the SM dynamics. Furthermore, the parameters selected for VSG implementations are not constrained by the physical design of any real SM. Thus, the VSG parameters can be selected to replicate the behavior of a particular SM design or can be specified during the control system design to achieve a desired behavior.

If the purpose of VSG is to accurately replicate the dynamic behavior of a SM, a full order model of the SM has to be included in the converter control system. This includes a 5th order electrical model with dq-representation of stator windings, damper windings and the field winding, together with a 2nd order mechanical model resulting in a 7th order model [13].

2.5.1 GENERAL CHARACTERISTICS OF VSG

The VSG concept can offer a basis for realizing flexible decentralized converter control schemes that can operate both in grid connected and islanded conditions, and that can almost seamlessly switch between the corresponding operating modes. Furthermore the inherent inertial characteristic of the VSG can provide services as frequency support and transient power sharing as primary control actions. These are indeed based only on local measurement and do not depend on external communications as in typical alternative schemes. Still, there is no conflict between this local controllability and the ability to operate in a hierarchical structure while following external references and set-points provided by a centralized controller for optimizing the system operation. Moreover, a further advantage of the VSG approach lies in its conceptual simplicity, due to the immediate and intuitive physical interpretation of its behavior with analogy to the corresponding behavior of a physical machine.

The dominant behavior of SMs in terms of inertia response and damping can be modeled by the traditional swing equation [1]. Considering these general characteristics, several control strategies have been developed for allowing power electronic converters to provide synthetic or virtual inertia to the power system, and have been proposed for a variety of applications like for instance wind turbines, energy storage systems and HVDC transmission schemes. Some of these control methods provide a synthetic inertial response to variations in the grid frequency and only a few aims to explicitly replicate the features of the traditional SMs. However, emulation of the inertia and damping effects requires an energy buffer with sufficient capacity to represent the energy storage effect of the emulated rotating inertia available. Thus, the amount of virtual inertia that can be added to the system by a single VSG unit will be limited by the DC-side configuration and by the current rating of the converter.

2.5.2 SWING EQUATION FOR VSG INERTIA EMULATION

While a full order model faithfully represents the behavior of a real SM, it adds unnecessary complexity if the goal of the VSM is to emulate the inertia and damping properties of the SM. Indeed, these two main aspects can be already captured by the swing equation (2.1) well known from the literature on power system stability and dynamics [1].

$$P_{in} - P_{out} = J\omega_m(\frac{d\omega_m}{dt}) + D\Delta\omega \quad (2.1)$$

where P_{in} , P_{out} , J , ω_m and D are the input power (as same as the prime mover power in a SG), the output power of the VSG, the moment of inertia of the virtual rotor, the virtual angular velocity of the virtual rotor, and the damping factor, respectively. $\Delta\omega$ is given by $\Delta\omega$ = ω_m - ω_{grid}, ω_{grid} being the grid frequency or the reference frequency when the grid is not available. Having the essential parameters, (2.1) can be solved by numerical integration.

2.5.3 DEPENDENCE OF VSG ON INERTIA

The quantities of the VSG, such as its output frequency and power oscillate after a change or disturbance similar to those of a synchronous machine. However, the transient condition tolerance of an inverter-based generating unit is much less than a real synchronous machine. Therefore, a VSG system may stop working redundantly due to oscillations with high amplitude after a change or disturbance. On the other hand, VSG control has an advantage in that its swing equation parameters can be adopted in real time to obtain a faster and more stable operation. This property of the VSG system is used to introduce the VSG with adoptive virtual inertia [1]. This scheme removes the oscillations and thereby, increases the reliability of the VSG unit against changes or disturbances. In this concept, the value of the virtual moment of inertia is changed based on the relative virtual angular velocity (the difference between virtual mechanical velocity generated by the VSG and grid angular frequency) and its rate of change.

Consider the power-angle curve of Fig. 2.2. After a change in system, for example, a change in prime mover power from P_{in0} to P_{in1}, the operating point moves along the power curve, from point a to c and then from c to a. The machine condition during each phase of an oscillation cycle is summarized in Fig 2.3. One cycle of the oscillation consists of four segments. During each segment, the sign of the $d\omega_m/dt$ together with the sign of the relative angular velocity $\Delta\omega$ defines the acceleration or deceleration. For example, in segment 3 of Fig. 2.2, during transition from points c to b, both $d\omega_m/dt$ and $\Delta\omega$ are negative and act in the same direction; therefore, it is an acceleration period, whereas when they have opposite signs like segment 4, it is a deceleration period.

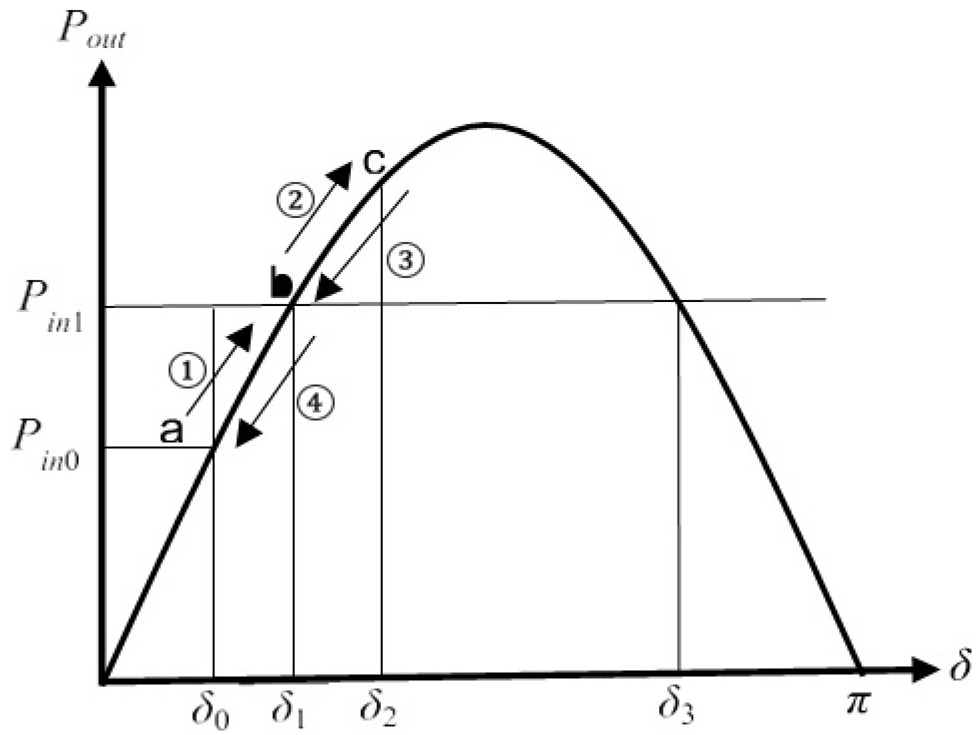

Fig. 2.2 Power angle curve of a typical Synchronous Machine [1]

Segment	$\Delta\omega$	$d\omega_m/dt$	Mode	Alternating J
a→b	$\Delta\omega > 0$	$d\omega_m/dt > 0$	Accelerating	Big value of J
b→c	$\Delta\omega > 0$	$d\omega_m/dt < 0$	Decelerating	Small value of J
c→b	$\Delta\omega < 0$	$d\omega_m/dt < 0$	Accelerating	Big value of J
b→a	$\Delta\omega < 0$	$d\omega_m/dt > 0$	Decelerating	Small value of J

Fig. 2.3 Machine modes during oscillation [1]

The objective is to damp frequency and power oscillation quickly by controlling the acceleration and deceleration term. The derivative of angular velocity, $d\omega_m/dt$ indicates the rate of acceleration or deceleration. Considering equation (2.1), it is observed that this rate has a reverse relation to the moment of inertia, J . Based on this fact, one can select a large value of J during acceleration phases (a to b and c to b) to reduce the acceleration and a small value of J during deceleration phases (b to c and b to a) to boost the deceleration. The big moment of inertia J_{big} and the small one J_{small} can be chosen within a wide range depending on the rated power so that the difference between J_{big} and J_{small} determines the damped power in each half-cycle of oscillation by alternating inertia. The value of J_{big} can be equal to the normal value of J . However, applying a very larger value than the normal J will result in a smaller frequency excursion at the first quarter-cycle but a sluggish response. The value of J_{small} determines the transient of the second quarter-cycle of oscillation. A very small value of J_{small} $(< 0.1 kgm^2)$ will result in a satisfactory response.

During each cycle of oscillations, the value of J is switched four times. Each switching happens at the points that the sign of either $\Delta\omega$ or $d\omega_m/dt$ varies. Before the disturbance, the VSG is operating with the normal value of J. When the disturbance happens, the transition from a to b starts with $\Delta\omega > 0$ and $d\omega_m/dt > 0$. In this condition, the J_{big} is adopted. At the end of the first quarter-cycle, that is point b, the sign of $d\omega_m/dt$ changes. It means that the small value for J is adopted at this point. At point c, the sign of $\Delta\omega$ changes and J retrieves it big value. It will be the end of the first half-cycle. During the second half-cycle, the value of J is switched to the J_{small} at point b, and again at the end of one cycle at point a, J_{big} is adopted. This procedure is repeated for each cycle of oscillation until the transients are suppressed and $\Delta\omega$ equals zero at the new equilibrium point, that is, point b. A threshold for $\Delta\omega$ can be applied to avoid the chattering of J during normal operation. However, this threshold is set to zero in this paper.

CHAPTER 3

MODELING

In this chapter a detailed analysis of the considered system has been carried out, as well as a description on how it has been modeled has been discussed.

3.1 SYSTEM DESCRIPTION

The studied system, seen in Fig. 3.1, is representing the block diagram of a simplified VSG unit connected to the grid [1]. It consists of:

1. A Distributed Generator
2. An Energy Storage device
3. A VSG control unit
4. A Frequency detector
5. A Power measurement device
6. A VSC unit

Fig. 3.1 shows the structure of a DG using the basic VSG control. The primary source of the DG could be photovoltaic panels, fuel cells, a gas engine or other distributed energy resources (DERs). The energy storage is designed for emulating the kinetic energy stored in rotating mass of a SG, in order to supply or absorb insufficient/surplus power generated by the primary source in transient state [9]. As this paper focuses on the control scheme of the inverter, the design and control of the primary source and energy storage are beyond the scope of this paper. In this scheme, a distributed resource is connected to the main power system via an inverter controlled with the VSG concept. The well-known swing equation of SGs is used as the heart of the VSG model. A governor

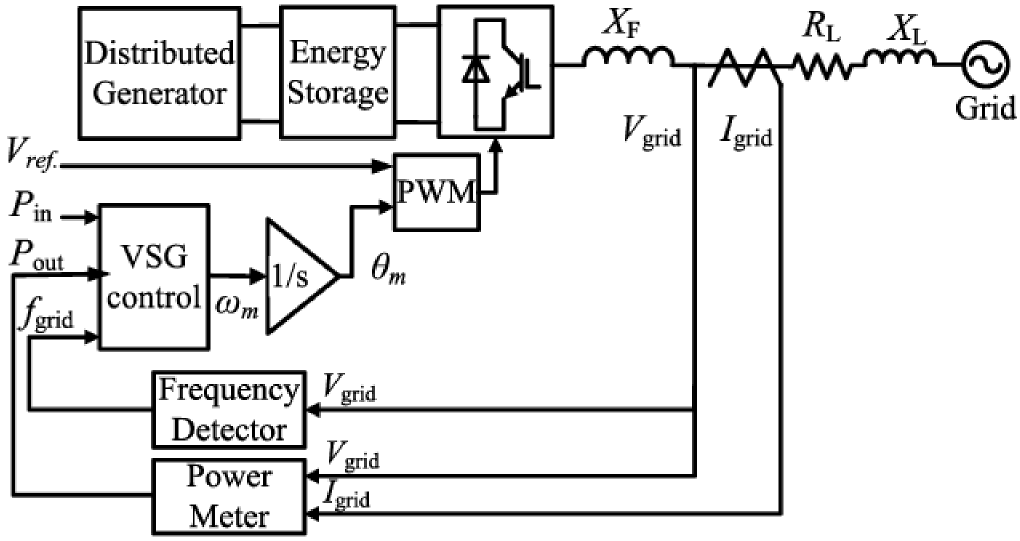

Fig. 3.1 Block diagram of a VSG unit [1]

model shown in Fig. 3.2 is implemented to tune the input power command based on the frequency deviation [1]. Having the essential parameters, the Swing Equation can be solved by numerical integration. By solving this equation in each control cycle, the momentary ω_m is calculated and by passing through an integrator, the virtual mechanical phase angle θ_m is produced. V_{ref} in Fig. 3.1 is the voltage reference that determines the voltage magnitude at the inverter terminal. Implementing a controller for V_{ref} results in a regulated voltage and reactive power at the VSG terminal. However, V_{ref} is set constant in the simulations and experiments because voltage control does not affect the idea of this paper. The phase angle and the voltage magnitude reference are used as the VSG output voltage angle and magnitude commands for generating pulsewidth modulation pulses for the inverter. The value of J together with D determines the time constant of the VSG unit. Selecting the proper value of them is a challenging issue without a routine. Mimicking a synchronous machine, J is given by $J = 2HS_{base}/\omega_0^2$ where H is the machine inertia constant, S_{base} is the base power of the machine, and ω is the system frequency. The parameter H tells that for which period of time the machine is able to supply the nominal load based solely on the energy stored in the rotating mass. The higher H, the bigger the time constant, resulting in a slower response but smaller frequency deviation after a change or disturbance. Although it depends on the machine size and power, for typical synchronous machines H varies between 2 and 10 secs.

Voltage source converter is used as an interface of the grid with a battery storage unit. It will be controlled as a virtual synchronous machine and the combination of the VSC and battery may sometimes be referred to as simply "the VSG". A voltage source converter

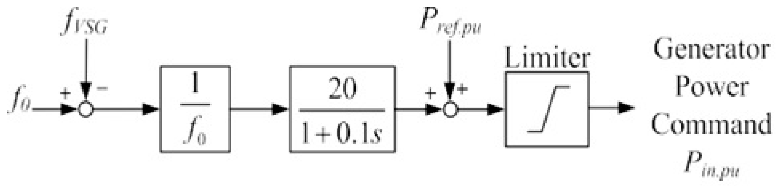

Fig. 3.2 Governor diagram [1]

is a power electronic device used to convert DC to AC (inverter mode) or AC to DC (rectifier mode). The VSC use transistors, usually the insulated-gate bipolar transistor (IGBT) in parallel with diodes to achieve self-commutation. The IGBT is controlled by a signal which enables the closing or opening of the IGBT switch.

The operation of the VSC is done through the concept of pulse-width-modulation(PWM). This involves comparing a control signal with a saw-tooth signal to provide "on or off" orders to the IGBT/diode blocks of the VSC. However, this thesis will not focus on the switching operation of the VSC, but rather on the controller of the VSC.

The control signals to the VSC are sent by the VSG control unit after being modulated by the PWM. The VSG control unit generates signals with the help of the references provided by the Frequency detector and the Power meter which are basically the voltages and currents measurements of the grid.

3.2 VSG IN PARALLEL WITH OTHER MACHINES

Parallel operation of a synchronous generator (SG) and an inverter-interfaced distributed generator (DG) is required in some islanded microgrids. However, dynamic performance of a small SG is usually poor, i.e. the rotor speed usually deviates largely during a loading transition, due to small inertia and slow governor response. Moreover, unbalanced SG current should be prevented to protect the SG, which makes this issue more challenging. An inverter-interfaced DG based on virtual synchronous generator (VSG) concept is proposed, to improve the overall performance of parallel operation of SG and DG.

The VSG is effective not only for increasing the stability of the power system but also for the operation of an inverter connected DG in parallel with other generators. In an isolated system composed only of inverter connected virtual generators, one inverter generally operates as the master that determines the frequency and voltage of the sys-

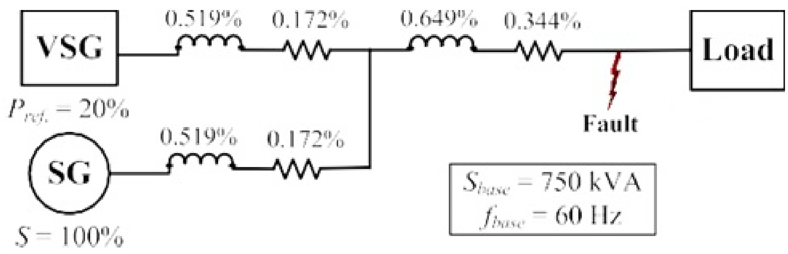

Fig. 3.3 VSG unit in parallel with the SG in microgrid [1]

tem, while the remaining inverters track this frequency and are operated as slaves that are current controlled so as to output constant power. When a synchronous generator is present in the isolated system, the synchronous generator becomes the master and the inverter connected DGs are all operated as slaves. Under current control, the slave generators cannot absorb disturbances in the system, and consequently the disturbances are absorbed by the master generator alone. If a disturbance is large and cannot be absorbed by the master generator, the system becomes unstable. However, if a VSG is used, the generators are synchronized by the mutual synchronization capability and operate autonomously. As a result, even if there is a relatively large disturbance the generators can absorb it, and stable operation is possible. Further, in an inverter connected distributed power source, all of the DGs are operated under current control when connected to the system. Consequently, if the distributed power source is separated from the system, control must be switched. However, when VSGs are used, the distributed power sources have the same characteristics as the synchronous generator, and thus operation is possible using the same control method in the grid connected state and in isolated operation. Consequently, during separation from the system, a transition to isolated operation can be made without interruption and without switching of control.

In microgrid applications, an inverter-based DG works in parallel with other DGs that may include synchronous machines. Consider the islanded microgrid of Fig. 3.3 [1]. The VSG block has the control scheme shown in Fig. 3.1 with the output filter inductance of 9.7%. The objective of this part is to assess the effect of the VSG on the stability of the system when connected in parallel with a SG. To clarify the effectiveness of the idea, the capacity of the VSG unit was assumed to be 20% of the SG that is insignificant. The performance of this system in the event of a symmetrical fault occuring at the load point has been discussed in Chapter 4 as results. A symmetrical fault happened at the load point at t = 0.2 secs and lasted for 0.3 secs. In this condition, the system comprising the VSG with the fixed value of moment of inertia $J = 8.445kgm^2$ was not able to recover from the fault. The same scenario was applied to the system with alternating inertia of $J_{big} = 8.445kgm^2$ and $J_{small} = 0.0844kgm^2$. The waveforms of power, SG rotor angle, and angular frequency are shown in Chapter 4 as results. It will come to notice that the alternating inertia scheme improved the stability of the adjacent machine by the extra damping effect imposed on the transient energy directly. The results will show that the VSG is easily able to maintain stability with the adjacent machine even in the event of a fault provided the machine is running on the scheme of alternating inertia.

3.3 VSG AS AN INTERFACE BETWEEN THE SG AND GRID

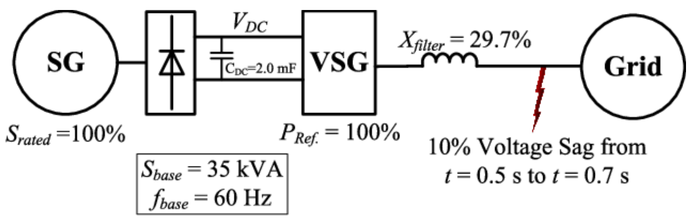

Fig. 3.4 SG connected to the grid via VSG unit [1]

Another configuration is shown in Fig. 3.4 [1]. A SG is connected to the grid/microgrid through a VSG unit. The prime mover of the SG can be a gas or diesel engine, and an inverter interface is required to correct the generated power to be injected to the grid. If the VSG unit is not robust enough, the disturbances from grid/microgrid will affect the stable operation of the SG. The system behavior has been studied for stability by introducing a three-phase voltage sag with 10% remained voltage magnitude and the duration of 0.2 secs was applied from grid side, and the performance of the system was monitored, the simulation results of which has been discussed in Chapter 4. The reference power and damping factor of the VSG were 1 and 17 pu, respectively, and a fixed inertia factor equal to 5 kgm^2 was applied. The results will show that the SG rotor angle and dc-link voltage were affected by the grid voltage sag considerably. The high-peak transient of dc-link voltage is mainly because of the oscillation of the VSG output power. The same scenario was applied to the system with the alternating inertia control with J_{big} = 5 and J_{small} = 0.05. To discriminate the stabilizing effect of alternating inertia as the only stabilizing effect in the system, the damping factor D was set to zero. It should be mentioned that the system with fixed inertia and a zero damping factor was unable to recover from much milder faults. And it will be observed in the results that the oscillation were suppressed by the alternating inertia scheme, and the severe transient of dc-link voltage was also eliminated.

3.4 SUMMARY

The system as shown in Fig. 3.1 has been modelled in Matlab Simulink to study the performance of the VSG. Also two more configurations of the system are considered i.e VSG in parallel with an SG and VSG as an interface between SG and Grid. In all the cases the performance characteristic of the VSG has been studied. The performance of the VSG with fixed moment of inertia and with alternating inertia has been focused. And it has been confirmed in Chapter 4 that the VSG with alternating inertia has the capacity to maintain stability in the mentioned cases.

CHAPTER 4

RESULTS OF SIMULATION STUDIES

This chapter will present the results of various simulations performed in Matlab Simulink. The simulated events will attempt to represent realistic scenarios related to the operation of the system described in Chapter 3. The goal is to demonstrate and explore the various properties and capabilities of the VSG, as well as its practical suitability. This is done by studying the system behavior during several scenarios.

4.1 DYNAMIC RESPONSE TO CHANGE IN LOADING

This section contains results from simulation scenarios carried out on the system as shown in Fig. 3.1 whose primary objective is to demonstrate how the active load is distributed between the various components in the system during different events. It is important for the practical suitability of the VSG to see how it performs while operating alone.

Figs. 4.1 to 4.4 show simulation results of this concept. Simulations were performed on the system model of Fig. 3.1 with the parameters values given in Table 4.1. The system was subjected to increase in the VSG power reference in two steps of 70% and 30% at t = 2 secs and t = 8 secs, respectively. Figs. 4.1 and 4.2 shows the output power and frequency of the VSG with the fixed value of J = 6 kgm^2. To show the effectiveness

Table 4.1 System Parameters for Simulation Studies

System quantities	Values
System voltage and frequency	440 V rms phase to phase, 60 Hz
Base Power	50 kW
Base Frequency	60 Hz
Feeder impedance parameters	R_L = 12.5 %, X_L = 33.0 %
Filter Inductance	X_F = 42.4 %
Fixed value of Inertia	$J = 6\ kgm^2$
Alternating values of Inertia	$J_{big} = 6\ kgm^2$, $J_{small} = 1\ kgm^2$
Damping Factor	$D = 17 pu$

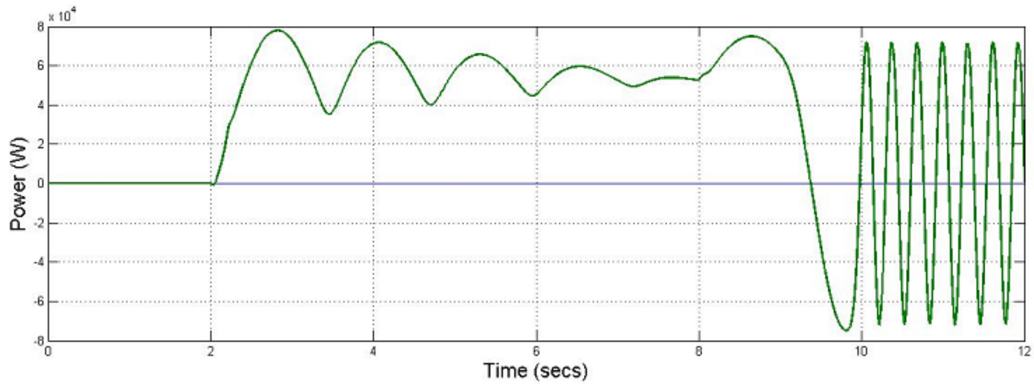

Fig. 4.1 Output power of VSG with fixed J = 6 kgm^2 and D = 17 pu

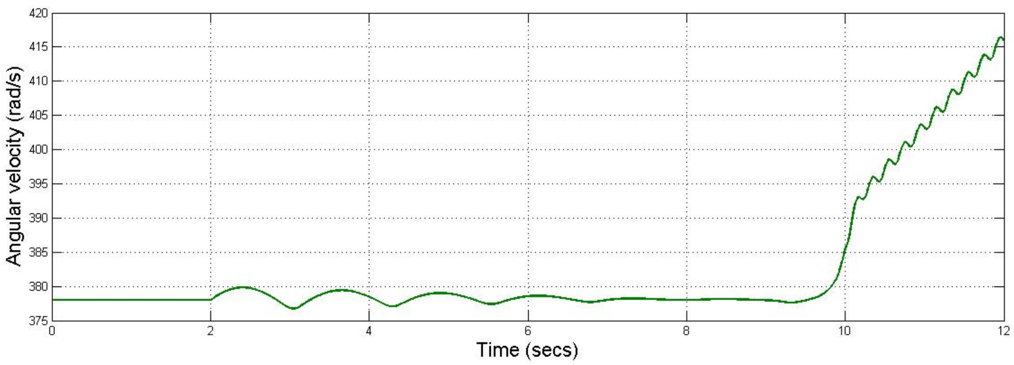

Fig. 4.2 Virtual angular velocity of VSG with fixed J = 6 kgm^2 and D = 17 pu

of the proposed idea, simulations were carried out on a weak system with fixed J that could not stabilize the system at the second step of power increase. Then, the control scheme of the VSG was changed to alternating inertia control, and the same scenario was applied. As it is observed in Figs. 4.3 and 4.4, alternating inertia selects the values of J out of J_{big} = 6 kgm^2 and J_{small} = 1 kgm^2 . This process does not only stabilize the system, but also suppresses the frequency and power oscillations effectively.

This case is equivalent to a sudden increase in the input power or torque on the shaft of a SM connected to an infinite bus. The power reference and the resulting electrical power from the VSG are plotted in above figures, where it is shown that the VSG with the selected parameters exhibits a smooth transient response and reaches steady state conditions in less than 2 secs without any overshoot. The step change in the reference triggers also a dynamic response in the rotating speed of the virtual inertia. Indeed, the excess mechanical power input is accumulated in the virtual inertia of the VSG, resulting in an increasing speed during the first part of the transient. When the electrical power reaches the input power and the steady-state power balance of the system is restored, the rotational speed of the virtual inertia returns to the synchronous speed of

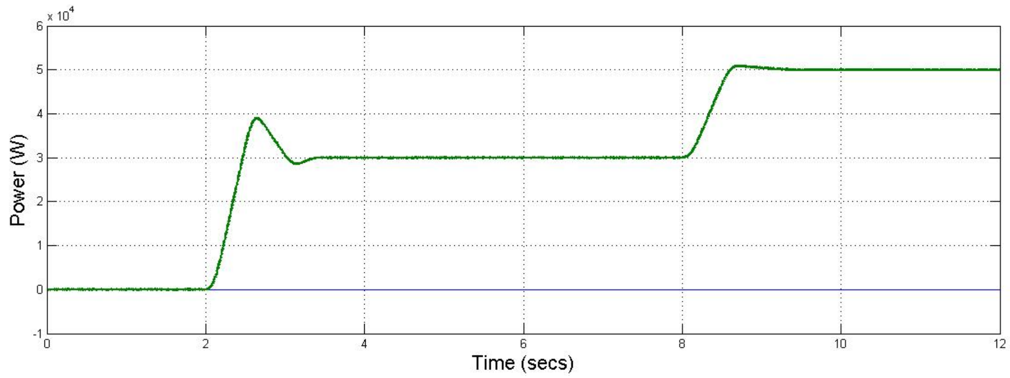

Fig. 4.3 Output power of VSG with alternating J : 1 and 6 kgm^2 and D = 17 pu

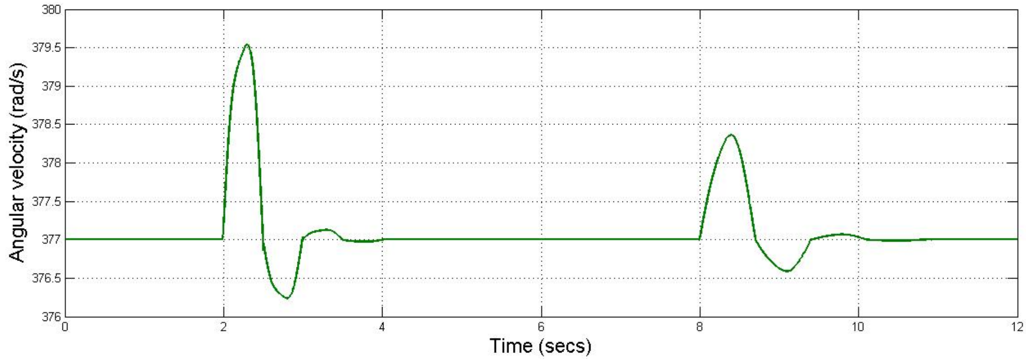

Fig. 4.4 Virtual angular velocity of VSG with alternating J : 1 and 6 kgm^2, D = 17 pu

the grid source, just as for a traditional SM.

The transient behavior shown in the presented curves exhibits the same general characteristics as for a conventional SM, but with a more damped response. Indeed, the VSG replicates the behavior of a classical SM, but its parameters do not have to comply with any physical design constraint. Thus, the parameters of the VSG can be selected with more freedom, without considering any efficiency aspects. In particular, power losses due to the damping effects of the VSG appear only in the control system and not in any physical circuit.

4.2 VSG IN PARALLEL WITH OTHER MACHINES

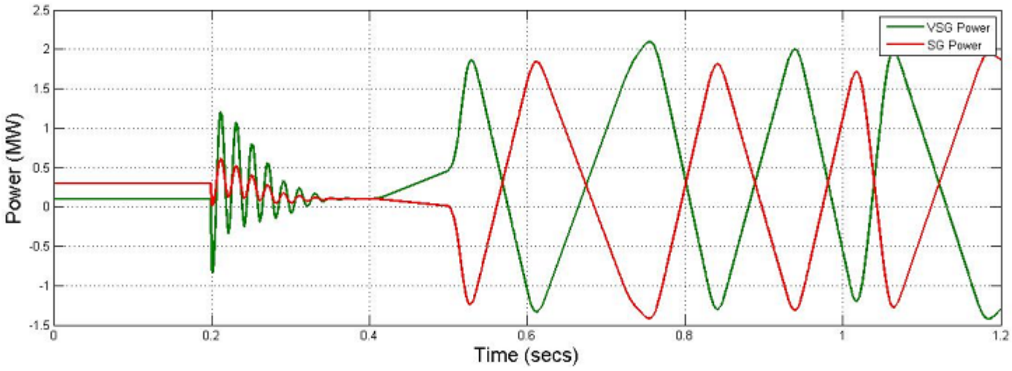

Fig. 4.5 VSG and SG powers with fixed J and D = 17 pu

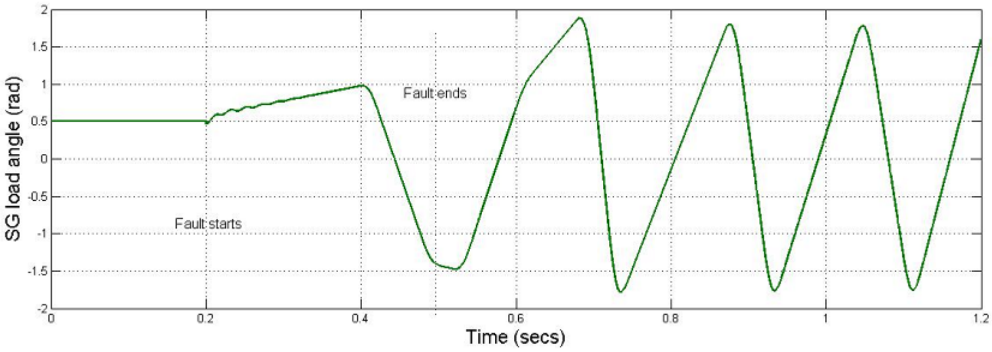

Fig. 4.6 SG rotor angle with fixed J and D = 17 pu

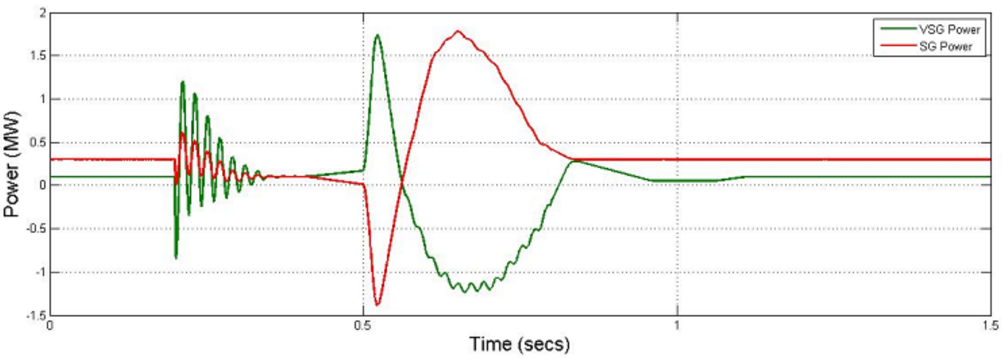

Fig. 4.7 VSG and SG powers with alternating inertia and D = 0 pu

These simulations has been carried out on the system as shown in Fig. 3.3 whose objective is to assess the effect of the alternating inertia scheme of the VSG on the stability of the parallel SG. To clarify the effectiveness of the idea, the capacity of the VSG unit was assumed to be 20% of the SG that is insignificant. A symmetrical fault happened at the load point at t = 0.2 secs and lasted for 0.3 secs. In this condition, the system comprising the VSG with the fixed value of moment of inertia $J = 8.445 kgm^2$

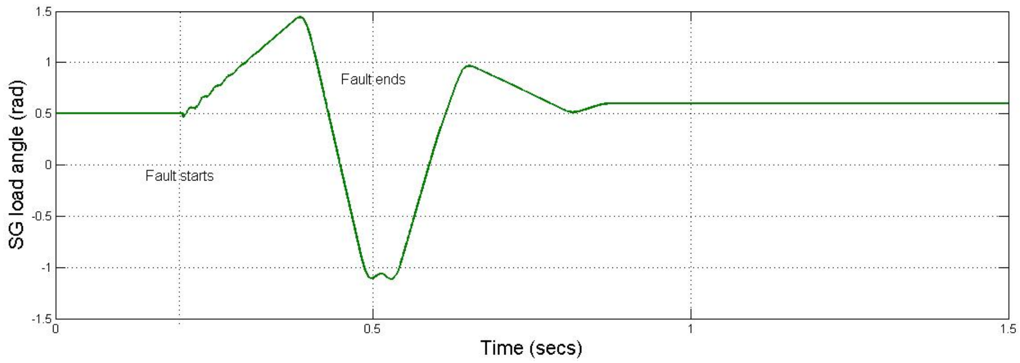

Fig. 4.8 SG rotor angle with alternating inertia fixed and $D = 0$ pu

Table 4.2 System Parameters for VSG in parallel with SG

System quantities	Values
Base Apparent Power	750 kKA
Base Frequency	60 Hz
Capacity of VSG unit	$P_{ref} = 20$ %
Capacity of SG unit	$S = 100$ %
Line Impedance connected to Load	$R_L = 0.344$ %, $X_L = 0.649$ %
Line Impedance connected to VSG	$R_L = 0.172$ %, $X_L = 0.519$ %
Line Impedance connected to SG	$R_L = 0.172$ %, $X_L = 0.519$ %
Fixed value of Inertia	$J = 8.445\ kgm^2$
Alternating values of Inertia	$J_{big} = 8.445\ kgm^2$, $J_{small} = 0.0844\ kgm^2$
Damping Factor	$D = 17pu$

was not able to recover from the fault as shown in Figs. 4.5 and 4.6. The same scenario was applied to the system with alternating inertia of $J_{big} = 8.445kgm^2$ and $J_{small} = 0.0844kgm^2$. The waveforms of power and SG rotor angle are shown in Figs. 4.7 and 4.8. As it is observed, the alternating inertia scheme improved the stability of the adjacent machine by the extra damping effect imposed on the transient energy directly.

4.3 VSG AS AN INTERFACE BETWEEN THE SG AND GRID

Simulations has been carried out on the system as shown in Fig. 3.4 where a symmetrical three-phase voltage sag with 10% remained voltage magnitude and the duration of 0.2 secs was applied from grid side, and the performance of the system was monitored. The reference power and damping factor of the VSG were 1 and 17 pu, respectively, and a fixed inertia factor equal to 5 kgm^2 was applied. Figs. 4.9 and 4.10 shows the SG rotor angle and dc-link voltage were affected by the grid voltage sag considerably. The high-peak transient of dc-link voltage is mainly because of the oscillation of the VSG output power. The same scenario was applied to the system with the alternating inertia control with J_{big} = 5 and J_{small} = 0.05. To discriminate the stabilizing effect of alternating inertia as the only stabilizing effect in the system, the damping factor D was set to zero. It should be mentioned that the system with fixed inertia and a zero damping factor was unable to recover from much milder faults. As it is observed in Figs. 4.11 and 4.12, the oscillation was suppressed by the alternating inertia scheme, and the severe transient of dc-link voltage was also eliminated.

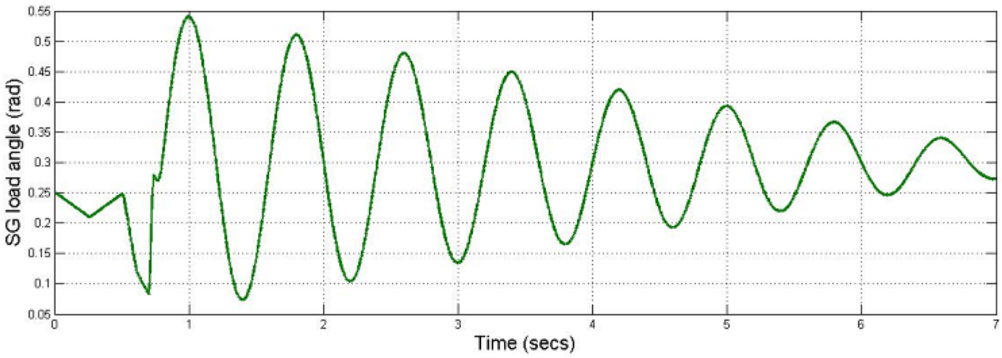

Fig. 4.9 SG Load angle with fixed inertia

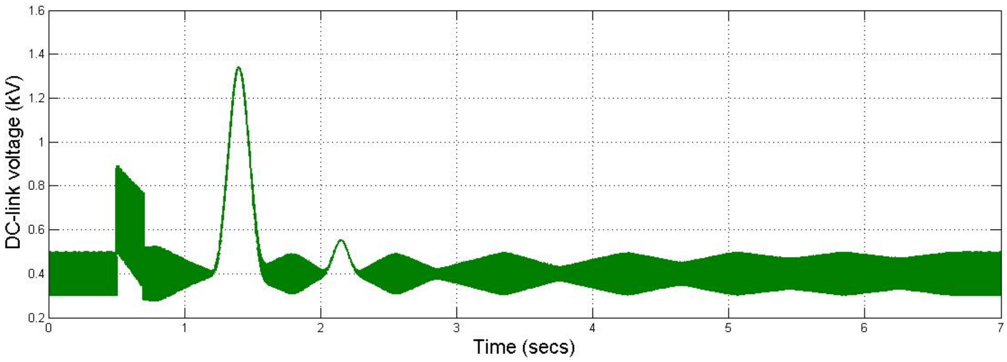

Fig. 4.10 DC-link voltage with fixed inertia

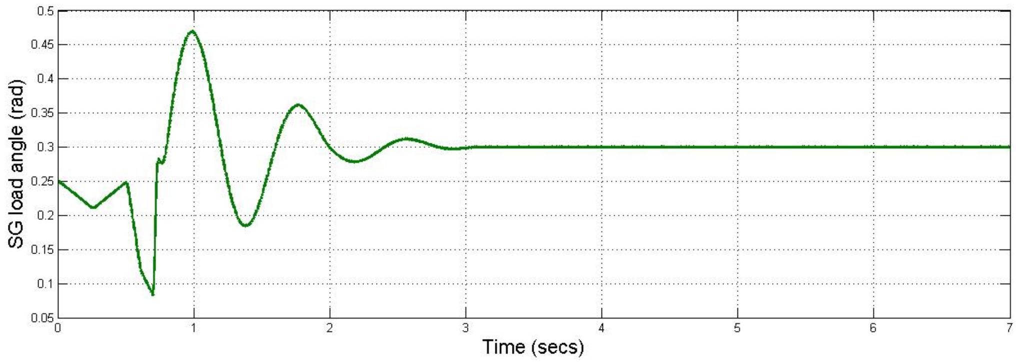

Fig. 4.11 SG Load angle with alternating inertia

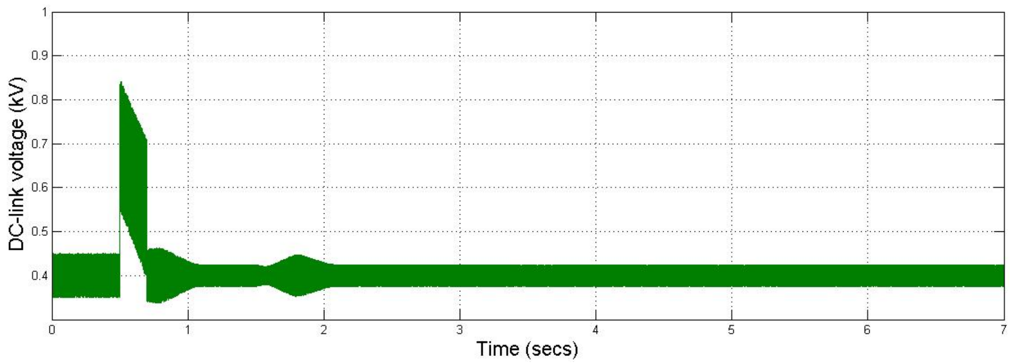

Fig. 4.12 DC-link voltage with alternating inertia

CHAPTER 5

CONCLUSION

The concept of a Virtual Synchronous Generator (VSG) as an approach for controlling power electronics converters to replicate the behavioral characteristics of Synchronous Machines (SMs) has been introduced during the last decade. This paper has highlighted the inherent advantages of the VSG as a possible alternative for releasing the potential advantages of distributed autonomous control actions of power electronics converter. An electrical system was designed for this thesis and its purpose was to represent the grid. The designed system was a considerable simplification of a system that in reality would be a lot more complex. However, the system served its purpose and fitted the scope of this thesis. The low complexity made it easier to study the components that were relevant and to observe how they affected the system.

Said system consists of distributed generator, a battery bank operated as a virtual synchronous machine in combination with a VSC and a VSG control unit. All these components were connected to a point of common coupling with a grid impedance in between. The modeling of the various components has been covered and a model of the system has been implemented into the Matlab Simulink environment with the use of Simscape Power Systems. Several simplifications were made when modeling the various components. This was done in order to make the simulations easier, and to make the modeling less complex.

This model was explored and experimented with during the work of implementation and the components of the system has been continuously tested with simulations. This was necessary in order to confirm the correct functioning of the various part of the system, but it also helped to recognize the behavior of the various components.

After completing the implementation of the model began the work of identifying relevant test cases. This work comprised of further exploration of the system in order to recognize scenarios of interest. The effort of identifying test cases also brought about a better understanding of the functionality of the components, as well as the system as a whole.

The first test cases presented in Chapter 4 examines the management of load in the power system. This was achieved by studying the response in power and speed at the power sources during events such as a sudden increase in input power. Further test cases involved the working of VSG in parallel with other machines and also with the VSG as an interface between the SG and Grid. This system was subjected to variations in the values of moment of inertia in order to examine the functioning of VSG accordingly.

Also in this paper, the alternating inertia structure was elaborated. The alternating inertia scheme adopts the suitable value of the moment of inertia of the VSG considering its virtual angular velocity and acceleration/deceleration in each phase of oscillation. By selecting a big value for the moment of inertia during acceleration, the haste was mitigated, and on the other hand, during deceleration, a small value for inertia factor was adopted to increase the deceleration effect. The system transient energy analysis was used to assess the stabilizing effect of alternating inertia control. It was clarified by the energy analysis that the system transient energy is reduced promptly by the reduction in the value of the moment of inertia. Actually, in the case of a real synchronous machine, this transient energy is dissipated by damping terms during oscillations, whereas the alternating inertia control eliminates the transient energy directly and prevents its flow from dc storage and dissipation. Compared to normal damping factor, the damping exerted by alternating inertia is considerably more effective and has identical results in any conditions. In addition, the transient energy can be reduced to zero at the end of the first quarter-cycle by alternating inertia control. Therefore, any transients can be eliminated before appearing. The idea does not only stabilize the VSG unit, but also enhances the stability of other machines in the system.

These test cases indicates that this VSG implementation has good practical suitability for the interfacing between a SG and Grid. It performs well in parallel with a traditional synchronous generator, and also has the ability to operate in a power electronic dominated environment where it defines the grid speed with its own swing equation. The VSG responds to changes in power inputs and also other abnormalities while maintaining stability of the system.

5.1 SCOPE FOR FURTHER WORK

The introduction of this thesis presented several limitations for the work that has been conducted. The main limiting factor is the simplifications of the studied system and the modeling of said system. A more complex system would indeed enable a more detailed analysis and the study of more test cases. A technology to synchronize and connect the VSG to a stiff grid or an operational synchronous generator would for example allow for a whole new range of highly relevant scenarios to be studied.

The model of the system could also be expanded to include more detailed implementations of gas turbines, wind turbines, cables, loads battery banks and converters. This would make it possible to further study the impacts of contingencies on such a system and explore the VSG response to these events.

APPENDIX A

SCREENSHOT OF THE SIMULINK MODELS

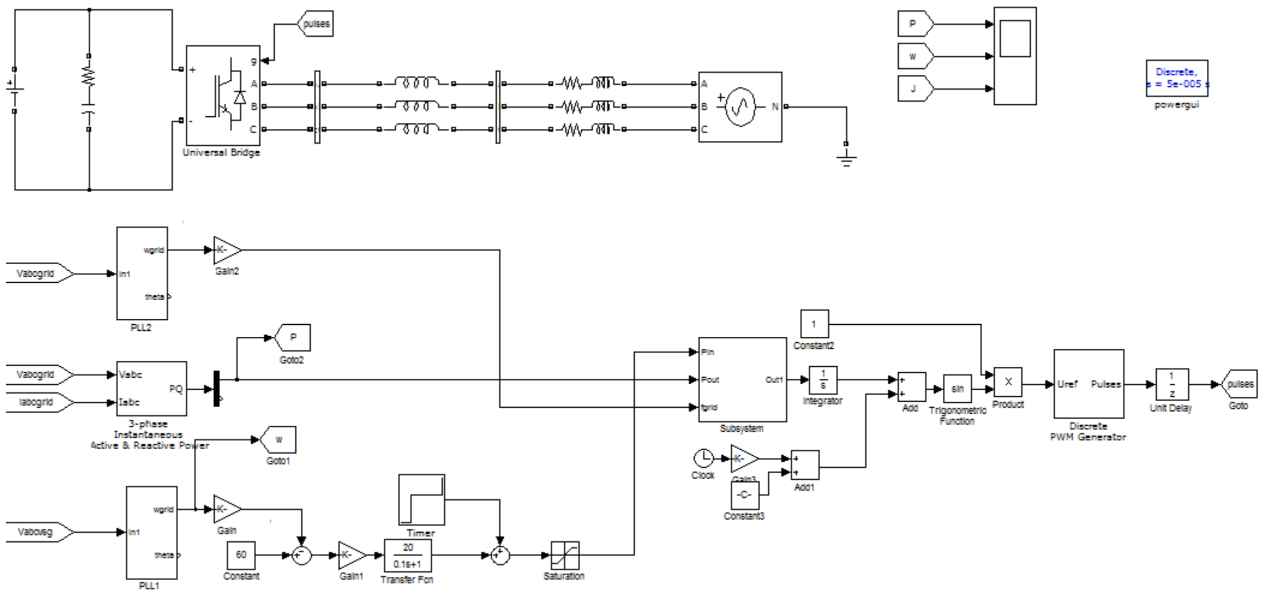

Fig. A.1 Screenshot of the VSG model connected to grid

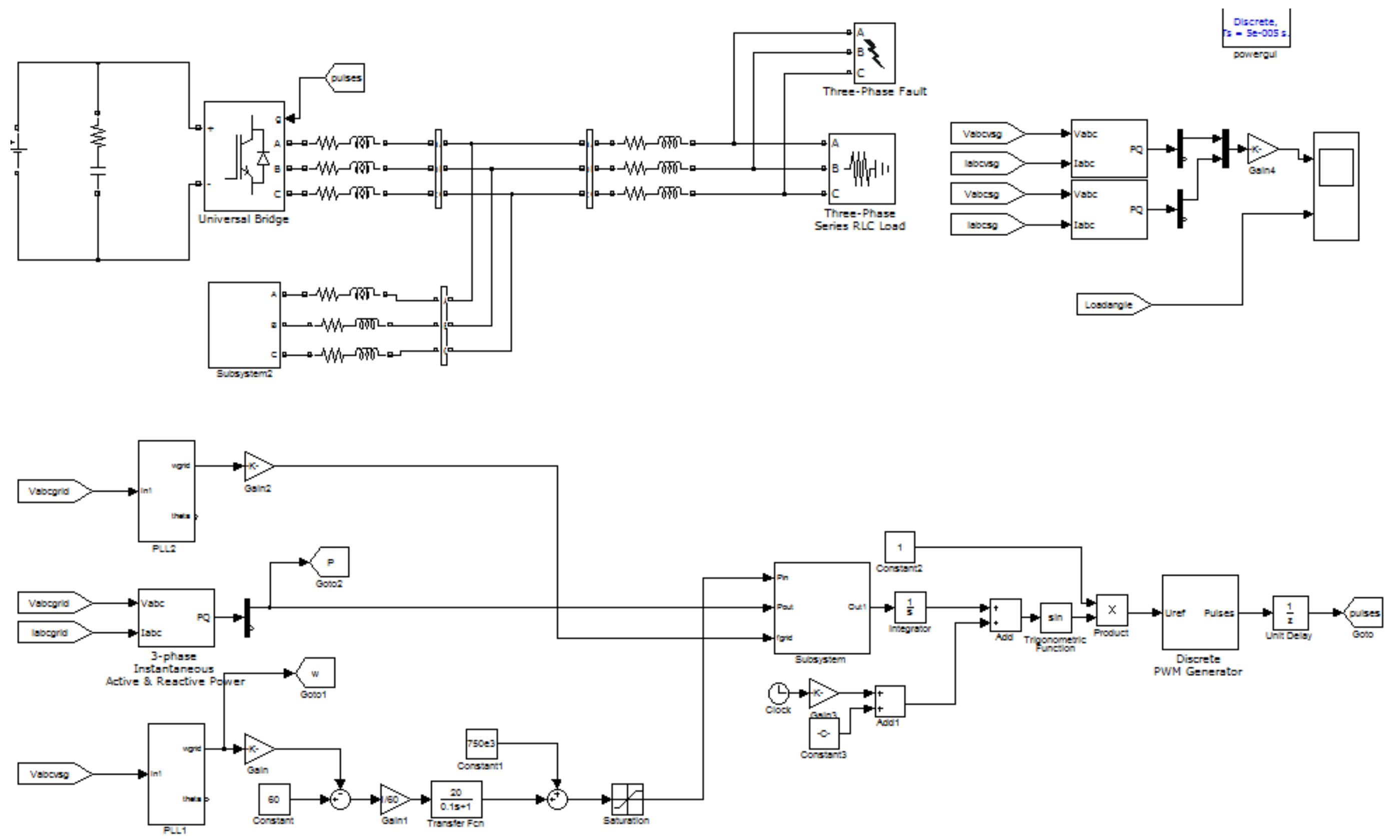

Fig. A.2 Screenshot of VSG in parallel with SG

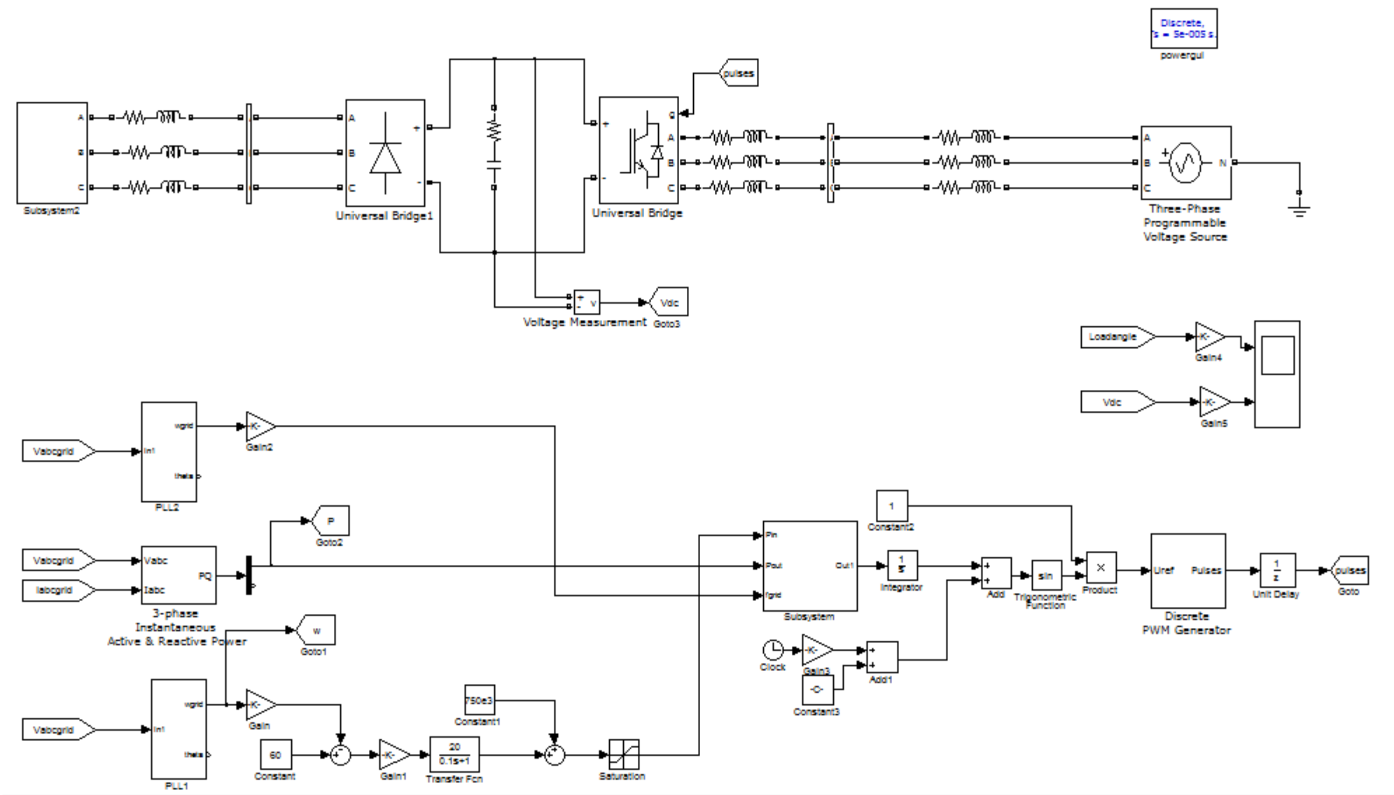

Fig. A.3 Screenshot of VSG as interface between SG and Grid

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