Inverter-based Control to Enhance the Resiliency of a Distribution System

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Abstract

Due to the increase in the integration of renewable energy to the grid, there is a critical need for varying the existing methods and techniques for grid operation. With increased renewable energy, mainly wind and photovoltaics, there is a reduction in inertia as the percentage of inverter based resources is increasing. This can bring about an issue with the maintenance and operation of the grid with respect to frequency and voltage. Thus, the ability of inverters to regulate the voltage and frequency becomes significant. Under normal operation of the system, the ability of the inverters to support the grid frequency and voltage while following the grid is sufficient. However, the operation of the inverters during a resiliency mode, under which there is an extended outage of the utility system, will require the inverter functionality to go beyond support and actually maintain the voltage and frequency as done by synchronous machines, acting as the grid forming inverter. This project focuses on the operation of grid forming sources based on virtual synchronous generator to regulate the voltage and frequency in the absence of the grid voltage through decentralized control of the inverters in the distribution feeder. With the most recent interconnection standard for the distributed generation, IEEE-1547 2018, the inverter based generation can be used for this purpose. The simulations are performed in Simulink environment and the case studies are done on the IEEE 13 node test-feeder.
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General Audience Abstract

With the increase in the renewable energy sources in the present grid, the established methods for the operation of the grid needs to be updated due to the changes that the large amount of renewable energy sources bring to the system. Due to the While the conventional resources in the power system was mainly synchronous generators that had an inherent characteristic for frequency support and regulation due to the inertia this characteristic can be lacking in many of the renewable energy sources that are usually inverter-based. At present, the commonly adapted function for the inverters is to follow the grid which is suitable in case of normal operation of the power system. However, during emergency scenarios when the utility is disconnected and a part of the system has to operate independently the inverters need to be able to regulate both the voltage and frequency on their own. In this project the inverter-based control, termed as the virtual synchronous generator, has been studied such that it mimics the well-established controls for the conventional generators so that the inverter-based renewable resource appears similar to the conventional generator from the point of view of the grid in terms of the electrical quantities. The utilization of this type of control for operation of a part of the feeder with each inverter-based resource controlling its output in a decentralized manner is studied. The controls try to mimic the established controls for conventional synchronous machine and use it for maintain operation of the system with inverters.
Dedication

To my mother.
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1 Introduction

The power system has been evolving over the years from centralized power generation with conventional synchronous generators to distributed generation for the past few decades with a large number of renewable energy sources such as solar photovoltaics, wind energy and other sources. The addition of these distributed energy resources to the grid necessitates the revision and upgrade of the methods of operation, control, protection and every aspect of the system that has been a norm for many decades. Many of these resources operate with converters and inverters-based systems. With lower penetration, the conventional grid was able to handle the addition of these sources but as the level of penetration keeps increasing. As a result, the new facilities on the grid could cause serious problems to the operation of the system if it lacks the proper techniques to support the integration. For modeling and analysis purpose the renewable energy sources, mainly inverter based generation are considered as negative loads. However, with higher levels of distributed generation based on non-conventional sources both on transmission and distribution sides of the grid, the older techniques for modeling, simulation, control and analysis are no longer adequate. To make sure the grid operation is smooth and efficient, it is necessary to enhance these techniques.

1.1 Motivation and Prior Work

The high level penetration of inverter based generators requires the generators to be able to share power while maintaining the voltage and frequency. This trend of increasing distributed energy resources, renewable energy integration and converter based machines indicates that, in the near future, the paradigm of the power grid is going to change and inverter based resources are going to be significant sources. This is even more certain with the scenario of new installations being more and more inverter based renewable generation with storage, pertaining to the uncertain cost of carbon based fuel[1].

On the distribution side, the dynamic performance of distributed energy resources has not been of much concern until recently as the percentage of these sources starts to reach significant levels. With the rising need for the distributed energy resources to be able to operate in an islanded mode for resilient operation, the dynamic performance of these resources become a major concern. There has been a significant amount of work in the resiliency mode operation of distributed generation[2],[3]. Most of the work on resiliency operations of distributed generation focus on microgrids and centralized methods for restoration. The authors of [4] formulated transactive energy framework for critical load restoration using microgrids during resiliency mode which is modifying
focus from centralized control of microgrid to a decentralized control. The authors in [2] present a synchronous generator model for dynamic simulation in distribution systems and study the impact of synchronous based DGs for enhancing resiliency of distribution system; however, they do not consider the inverter-based resources. The dynamic performance of conventional synchronous based resources and the inverter interfaced renewable generation have significant differences and operating an inverter based system needs further detailed study. While operating in grid connected mode, the dynamics performance of the inverter based resources are not considered to be significant but during an islanded mode of operation the dynamics of the inverter based resources dictate the operation of the system when the penetration level of the inverter based renewable resources is high. Thus, there is a need for proper models that can be used for large scale studies to understand the performance of inverter based generations. The work in [5] develops grid-forming inverter models based on droop control with over-load mitigation controller to study transient stability of dynamic distribution systems. However, this model is based on voltage controlled voltage source inverter and does not have current control embedded in the system.

In the past the inverter based resources connected to the grid have been controlled as constant power sources, or unity power factor source without any involvement in the control of voltage and frequency in the grid. The updates on the standards for interconnection of distributed energy resources, the most recent IEEE-1547 2018, have allowed the DERs to regulate the voltage and frequency levels subject to the prior agreement between the Electric Power Supply (EPS) operator and the owners of the DERs[6]. Thus, there is a need for utilization of new control schemes for DERs to support the grid operation. The new standards have also opened horizons for the utilization of the smart inverter for operation a wide range of applications. Some of the work on advanced functions utilizing the inverters control; authors of [7] have studied inverter probing for topology identification of a distribution grid. A new class of function for inverters, termed as advanced inverter functions is a widely popular concept at present for addressing grid stability problems posed by high levels of variable distributed generation[8]. Conventionally, due to the low inertia nature of converter based resources and limited controls, they are disconnected when there is a fault on the grid side. However, with modified controls the inverter-interfaced renewable energy sources can be used for restoration and resiliency mode operation of the grid.

To address the issue of increasing non-conventional inverter-based distributed resources and utilize their functionality, it is necessary to control the inverter such that it can stabilize both voltage and frequency. Inverters are categorized into three groups based on the functionality as grid-forming, grid-supporting and grid-following[9]. The
fundamental concepts of the categorization are also applicable for the new paradigm of inverter-dominated grid and the grid-forming inverters are expected to support the dynamic performance of distribution systems as their penetration increases in the system. For a resiliency mode of the distribution grid, there should be at least one grid-forming inverter for decentralized control of grid voltage and frequency even when they are the sole generation source. The grid forming inverters in literature have been widely discussed in the context of microgrids, which focus on droop control inverters and virtual machines and inertia emulation based grid forming controls or virtual synchronous generator(VSG) based control [10],[11],[12],[13] and more recently virtual oscillator based inverters[14],[15]. The droop control is a widely known scheme based on proper load sharing between multiple generators and utilizes the regulation of real and reactive power to regulate voltage and frequency. The virtual synchronous generator emulates the dynamic characteristics of synchronous generator. Virtual oscillator based control emulates the dynamics of an oscillator for the control of the inverters without communication so that they can synchronize (ensure the inverter terminal voltage oscillate in frequency unison) and share load in proportion to their ratings. However, the three control methods are different in terms of detailed implementation. They have some similarities in inherent characteristics and there are multiple studies comparing the droop control with VSG control some of which have also emphasized on their equivalence under certain conditions[16], [17]. It was concluded that the droop control and VSG based control schemes are equivalent for constant grid frequency and active power references, but not equivalent when the grid frequency and active power reference changes[16]. In addition, this work also concludes that the damping coefficient of the VSG is the reciprocal of the droop coefficient and the virtual inertia(J) is the ratio of the time constant of the active power frequency filter to the droop coefficient. Reference [17] has developed a generalized droop control for grid-supporting inverter that can function both as a traditional droop control and a VSG control. The work of [18] establishes that the sinusoidal state behavior of Virtual oscillator control can be engineered to correspond to droop laws although on circuit level it is fundamentally different compared to droop control. Thus, the grid forming inverters in one way or the other emulate the characteristics of synchronous machines and accomplish the regulation of voltage and frequency.

In addition to the controls, the modeling of distributed generation is also an important aspect for the study of distribution systems operation and stability. Models appropriate for dynamic simulations are needed. The models developed and studied extensively in the literature include three-phase electromagnetic models[19],[20],[21] and positive sequence electromechanical models[22]. While the electromagnetic models are suitable
for detailed analysis and controller design and stability analysis of a smaller system, it becomes increasingly complex for a large-scale distribution system. In contrast, the electromechanical positive sequence models are simpler but are focused on balanced system and not suitable for unbalanced systems with single- and double-phase laterals. Reference [23] discusses differential algebraic equations based models for dynamic analysis of PV inverter systems in a distribution system suitable for integration with a three phase distribution system analysis tool OpenDSS. In [5], there is a discussion of the dynamic model of a grid-forming inverter in GridLAB-D simulation environment. [24] provides a comprehensive summary of the modeling of inverter-based generation in dynamic studies and the challenges with the increasing inverter-based resources in the power system.

1.2 Objectives and Contributions

The main focus of this work is to analyze the operation of distributed resources in a 100% inverter based generation scenario to maintain voltage and frequency of a distribution system in a resiliency mode of operation. The operation of the distribution feeder in absence of the main substation feeder using distributed grid forming inverter resources’ decentralized control is studied.

The operation of the inverters during the resiliency scenario is expected to meet these objectives:

1. Voltage and frequency regulation of the nodes by the grid forming inverter
2. Load restoration using the available generation
3. Distributed control by individual generator without communication
4. Proper Power sharing between multiple grid-forming inverters

The grid forming inverter control based on the virtual synchronous generator concept is built and the ability of grid forming inverter at different parts of the grid to regulate voltage and frequency in the absence of the substation due to fault is studied. The grid-forming inverter is based on a swing equation based power-frequency and reactive power-voltage droop following the governor and the automatic voltage regulator of a synchronous generator with a cascaded voltage and current control source. Based on multiple case studies the ability of grid-forming inverters to enhance the operation of a resiliency mode is studied.

The main contribution of this work can be described as follows:

This work takes on the study of grid-forming inverters based on virtual synchronous generators and shows that the grid forming inverters can help sustain the operation of
part of the grid during emergency situations and enhance the resiliency of the grid in a scenario with a 100% inverter-based distributed energy resources in the distribution system.

Although the virtual synchronous generator has been discussed widely and its application and topology is being explored and updated continuously, the study of the virtual synchronous generator in context of grid forming inverters under resiliency mode in an unbalanced distribution feeder has not been explored to the best of the author’s knowledge. Thus, this work aims to utilize the swing equation-based virtual inertia of the virtual synchronous generator for improving the resiliency of an unbalanced distribution system which addresses the issue of low-inertia and grid-forming control necessary during such conditions. Based on the results, it is concluded that the virtual inertia based grid-forming inverters’ distributed control can be used for voltage and frequency regulation for a distribution system in the absence of utility source. Although the case-studies have been conducted in the 13 node test feeder, the models developed are suitable for a system-level large-scale simulation and can be extended to larger systems.

1.3 Thesis Outline

The rest of the thesis is structured as follows: Chapter 2 presents the preliminary concepts that this work relates to, the types of inverter-based resources and the prior work that has been done. Chapter 3 describes the model development for specific inverters used in this work. Chapter 4 presents the simulation-setup and case studies conducted. Finally, Chapter 5 discusses the conclusions from the modeling and simulation and future directions of the work.
2 Background

This chapter focuses on the literature review of the background and concepts that the thesis relates to including the basic concepts from conventional power generation and the application of those concepts to the inverter-based system and control.

2.1 Conventional droop control and its application in inverter control

Droop control is a fundamental concept in the conventional power system relating to synchronous machines. The droop control theory is based on the characteristic of synchronous generator in the context of power regulation. Basically, the frequency is coupled with the active power and voltage is coupled with the reactive power. These features can be extended and utilized for inverter based system by incorporating them into their control for voltage and frequency regulation.

The transfer of active and reactive power is dependent on voltage amplitude and phase angle at the sending and receiving end of transmission line which forms the base for parallel operation of synchronous generator.

![Diagram](image)

Where, \( X, \delta, \phi, \hat{I}, u_s, u_r, S_s, S_r \) are the line inductance, power angle, phase angle, current at sending side, voltage at sending side, voltage at receiving side, total power at sending side and total power at receiving side respectively.

The following equation describes the power flowing into the line at the sending end:

\[
S_s^* = P_s + jQ_s = u_s \hat{I}_s - u_s \left[ \frac{u_r \ e^{-j\delta}}{jX} \right]^* \tag{1}
\]
\[ P_s = \frac{u_s u_r}{X} \sin \delta \]  \hspace{1cm} (2)

\[ Q_s = \frac{u_s (u_s - u_r \cos \delta)}{X} \]  \hspace{1cm} (3)

Where, \( P_s \) and \( Q_s \) are sending end real and reactive power respectively.

Across a transmission line, generally the power angle difference between the two ends of the line is very small. Hence, \( \sin \delta \sim \delta \) and \( \cos \delta \sim 1 \).

Thus, the power transfer equations in (2) and (3) are simplified to:

\[ P_s = \frac{u_s u_r}{X} \delta \]  \hspace{1cm} (4)

\[ Q_s = \frac{u_s (u_s - u_r)}{X} \]  \hspace{1cm} (5)

From equations (4) and (5) it is concluded that the active power is coupled with power angle which directly relates to the frequency of the grid and the reactive power relates to the voltage at the sending side. Based on these relations, the droop equations can be written as:

\[ f - f_o = -m_p (P - P_o) \]  \hspace{1cm} (6)

\[ u - u_o = -n_q (Q - Q_o) \]  \hspace{1cm} (7)

Where \( f, u, f_o, u_o \) are grid frequency, grid voltage, nominal frequency and nominal grid voltage respectively. \( P, Q, P_o \) and \( Q_o \) are real power, reactive power output, active and reactive power setpoints of the inverter and \( m_p \) and \( n_q \) are frequency and voltage droop coefficients.

It should be noted that decoupling of active and reactive power is possible in case of low R/X ratio. However, for low voltage grids, the coupling can become weak depending on the nature of line parameters[26].

\textbf{2.1.1 Droop Control of inverters}

Droop control for power converters is a widely studied topic in the context of microgrids. The basic idea follows the droop control of synchronous machines and is applicable for inverters. However, there are a few distinctions with respect to the inverters which will be discussed in the following section.
Typically, the three-phase voltage source control strategy aims to fix voltage and frequency to constant values which would limit the operation of the inverters in parallel as large current circulation can result due to small variation between voltage and phase. However, droop control aims to adjust frequency and voltage of the grid to allow grid-forming inverters for proper power sharing while maintaining voltage and frequency stability[25].

The droop control implementation in inverters are dependent on the output impedance of the inverter and may cause improper power sharing in case of LV grids with high R/X ratio. Thus, there will not be completely decoupled relations but both P and Q will be dependent on voltage amplitude and angle. To address the issue, different techniques have been implemented such as designing a virtual impedance for accurate power sharing and a generalized droop control strategy[27]. However, designing the impedance of the inverter between the range of 0.05 and 0.15 p.u. still ensures proper decoupling of P and Q. Hence, the conventional droop control can still be considered valid. This decoupling reduces the complexity of the controller design[28].

2.2 Inertia Emulation in Power converters

When the conventional synchronous machine based resources are replaced by inverter based resources, the grid becomes a low inertia grid as most of the inverter-based distributed generation sources have very little or no rotating mass and damping property that is important for the stability of the system. Thus the dynamic performance of the system is significantly affected. For dealing with this issue one of the solutions is replicating some features of synchronous machines in the controllers of the converter controls so that the inverter-based resource can behave in a similar manner to that of the synchronous machine so that the established controls on the higher level can be implemented.

For the balance of generation and load, multiple control actions over varied time-frames are implemented. When a frequency event occurs, the governor response takes place within a number of seconds (10~30s) to reduce the frequency deviation. Following the governor action, the automatic generation control executes within minutes to bring back the frequency to its nominal value. The tertiary control action is utilization of the reserve to manage the resources to handle present or future disturbances. The inertia response of a generator based on the kinetic energy stored in the rotors is counteracts the imbalance between the generation and consumption until the primary response is activated. The system with increased penetration of inverter-based generation with low inertia faces increased rate-of-change-of-frequency(ROCOF) and a low frequency nadir
rapidly. Since the primary response usually takes more than 10s to counteract the frequency change, lower inertia systems may cause tripping of under frequency relays and even lead to cascaded outages in extreme cases [13]. To deal with this issue there is a need for addition of virtual inertia to the system so that they can operate in a very short interval.

![Graph showing frequency response in a power system after a disturbance](image)

Virtual inertia is the emulation of inertia characteristics in the inverter control and is a widely discussed idea. It has also been discussed that the virtual inertia emulation due to converters may be even faster than synchronous generator and if deployed appropriately can enhance system stability[13]. The two main ways for emulating the virtual inertia is:

- Operating the renewable energy source (RES) below the maximum power point so that it can provide frequency restoration during transients.
- Utilizing the inertia due to energy storage coupled with the inverter interfaced resources.

Virtual Inertia emulation discussion in literature can be divided into first generation and second generation. In the first generation the focus is on developing topologies and control to emulate virtual inertia following SG. The second generation ideas focus on optimizing these systems for dynamic performance and energy usage. In this work we focus on the first generation virtual inertia implementation.
Chapter 2. Background

The frequency variation in a power system can be approximated by swing equation[13]:

\[
P_{\text{gen}} - P_{\text{load}} = \frac{d(E_{K,E})}{dt} = \frac{d\left(\frac{1}{2}J\omega^2\right)}{dt}\]

\[
P_{\text{gen}} - P_{\text{load}} = J\omega \frac{d\omega}{dt}\]

Where, \(P_{\text{gen}}\) is the generated power and \(P_{\text{load}}\) is the power demand including losses, \(J\) is the total system inertia and \(\omega\) is the system frequency. \(H\) is machine inertia constant which determines the time period during which the machine is able to supply the nominal load using energy storage (in rotating mass) and is given as kinetic energy normalized apparent power \(S_g\) of the connected generators.

\[
\frac{2H df}{f dt} = \frac{P_{\text{gen}} - P_{\text{load}}}{S_g}
\]

Where, \(\frac{df}{dt}\) is the ROCOF of the system and with reduced inertia the ROCOF of the system increases which causes larger changes in frequency in the same time-frame. Thus there is a need for additional inertia as inverter-based generation increases on the system. As a result, virtual inertia is necessary.

Virtual inertia is a combination of the distributed generation, storage and power electronics that emulates the inertia of a conventional power system. The concept of virtual inertia was first developed by Beck and Hesse[29]. The following section discusses some topologies that implement the virtual inertia concept.

2.3 Virtual synchronous machines and generators

From the previous sections it has been clarified that the inverter based system can be designed to emulate the inertia and damping/droop control that is a common property of the synchronous machine. The converters that emulate these characteristics are termed as virtual synchronous generators (VSG). The virtual synchronous machines
operate by generating gating signals based on the current/voltage feedback from the inverter output.

Based on the extent of the synchronous machine characteristics that these generators mimic, they can be made to resemble the synchronous generator dynamics from the perspective of the grid and assist in enhancing system stability. However, the extent of emulation of synchronous machine dynamics in the control of the inverter depends on the application and desired level of sophistication. Some models try to replicate the exact synchronous generator by a detailed mathematical model based on the synchronous machine dynamics. Some try a simpler approach based on the swing equation to mimic the synchronous machines while others try to make the DGs responsive to the frequency deviations in the system.

Some of the most active groups and their work on synchronous generator based models are Synchronverters, Virtual synchronous machines (VISMA) project, Institute of Electrical Power Engineering (IEPE) Topology, Kawasaki Heavy Industries (KHI) Lab’s topology. Swing equation based models that are most popular are ISE Lab’s topology and Synchronous Power Converter[30]. Frequency-power response based models comprise of VSYNC’s topology and virtual synchronous generators. Other approaches include droop based approaches, virtual oscillator control and Inducverters [13].

This section will provide a summary of two of these technologies that have been referred to for the modeling of controls.

### 2.3.1 ISE Lab VSG Topology

The VSG model developed by ISE’s lab[31] at Osaka University is based on the swing equation as shown in Figure (3).

The ISE lab’s model solves the power-frequency swing equation every control cycle to emulate the inertia. The controller senses the inverter output current and voltage and computes the grid frequency and power output.
In this model the swing equation is represented as:

\[ P_{in} - P_{out} = J \omega_m \frac{d\omega_m}{dt} + D\Delta\omega_m \]  

(11)

\[ \Delta\omega_m = \omega_m - \omega_g \]  

(12)

Where,

\( P_{in} \) = is the input power (similar to prime mover input power in SG)
\[ P_{\text{out}} = \text{measured output real power} \]

\[ J = \text{virtual moment of inertia} \]

\[ D = \text{virtual damping factor} \]

\[ \omega_m = \text{virtual angular frequency} \]

\[ \omega_g = \text{grid/reference angular frequency} \]

A governor model as seen in Figure 44 is utilized to compute the input power \( P_{\text{in}} \) based on frequency deviation from a reference frequency \( \omega^* \). The governor is a first-order lag element with gain \( K \) and time constant \( T_d \). The voltage reference \( V^* \) can be generated by the Q-v droop. This topology can be used for operating DG as a grid forming unit, however, there should be proper tuning of \( J \) and \( D \) parameters.

### 2.3.2 KHI’s VSG Topology

VSG can be controlled as voltage controlled inverters when the output of the power loops is used to derive the references, however, the distributed resources are mainly current controlled meaning that they are connected to the grid and synchronized by a PLL. That is, it cannot operate in an isolated mode. In an isolated mode, the default control is constant voltage constant frequency control (CVCF) such that the output frequency and output voltage are constant and such a mode of inverter cannot work in grid-connected mode. Thus, in this work, the inverter with a current-control based VSG without a PLL is modeled with the governor and automatic voltage regulator giving it the capability to work in both grid-connected and islanded operation. This type of model is an appropriate example of the grid-supporting inverters.
Figure 5: Control diagram of grid-connected inverter with VSG of algebraic type[32]

The VSG with algebraic stator is based on impedance model by algebraic approximation of Park’s equation[32]. The following Figure 6 shows the impedance model of the virtual synchronous generator. The synchronous impedance of the generator is denoted by $r + jx$. The emf of the windings is denoted by $\hat{E}_f$ and the terminal voltage is represented by $\hat{V}_g$.

Figure 6: VSG impedances model[32]

The load angle denoted by $\delta$ is the phase difference between the rotor and the grid. The d-axis is chosen as parallel with $E_d$ and the q-axis is perpendicular to it. The grid
voltage projections are denoted by \( V_d \) and \( V_q \). The generator currents and its projections to d-q axes are denoted by \( I \), \( I_d^* \) and \( I_q^* \).

Using the reactive power command and voltage feedback through droop controller the AVR produces \( E_f \) and the governor model utilizes the droop controller to get the load angle \( \delta \).

The current references to the inverter can be calculated based on the phasor diagram in Figure 7:

\[
\begin{bmatrix}
I_d^* \\
I_q^*
\end{bmatrix} = \frac{1}{r^2 + x^2} \begin{bmatrix} r & x \\ -x & r \end{bmatrix} \begin{bmatrix} E_d - V_d \\ E_q - V_q \end{bmatrix}
\] (13)

The current references drive the PWM controller to generate the pulses.

\[ E_d \] and \( E_q \) can be generated as \( E_f \sin \delta \) and \( E_f \cos \delta \) respectively.

2.4 Types of inverter-based resources

With increase in renewables and non-conventional sources the number of electrically-interfaced converter/inverter based resources is becoming more prevalent throughout the grid. Energy sources including Solar Photovoltaics and Wind that are inherently interfaced through inverters/ power converters. Conventional sources are also moving towards electronic interface in the grid. The inverters in an ac system can be classified into three categories namely, grid forming, grid feeding and grid supporting. This
categorization was done based on ac micro-grids[27], however, this is equally applicable in case of inverter-based distributed generation in the distribution system.

2.4.1 Grid forming inverters
Grid-forming converters are represented as an ideal voltage source with a low-output impedance in series and set the voltage amplitude and frequency of the local grid as shown in Figure 8 [33]. These inverters control the voltage and frequency and are basically equivalent to controllable voltage sources behind a coupling reactance (similar to synchronous generators). During contingencies, these inverters increase or decrease their output current to balance loads and maintain voltage and frequency[34]. In a system with multiple converters grid forming inverters can be the reference for other grid following inverters. Grid forming inverters have a faster response and can provide robust frequency control. Thus, these type of sources can independently operate even during autonomous modes of operation.

The grid forming inverters in most cases are modeled as voltage-controlled voltage source converter(VC-VSC) such the VSC controls the voltage and frequency at the point of common coupling of the distributed generation unit. However, controlling in this manner does not provide inherent current-limiting capability during faults. Thus there is a need for additional current limiting strategy when VC-VSC based grid forming converters are used. The authors of [35] have implemented a current limiting strategy for the VC-VSC based topology.
2.4.2 Grid following/feeding inverters

The grid following inverters/grid feeding inverters control the output current magnitude and phase angle with respect to the grid voltage. These inverters can be considered as a current source connected with high impedance in parallel to control the power exchange between the distributed generator and the main grid. They can control real and reactive power as well as fault currents but not voltage and frequency and behave like a negative load as opposed to a traditional source with inertia.

These types of converters follow the already established voltage and frequency reference of the grid and need to be perfectly synchronized with the ac voltage at point of common coupling to regulate the active and reactive power exchanged with the grid. In other words, they cannot operate independently and require some other grid forming source for operation.
Chapter 2. Background

Figure 9: General control structure of grid-feeding inverter[27]

However, recent grid following inverters also have capabilities for grid support such as frequency watt (FW) that adjusts the output power in response to system’s change in frequency (droop-like frequency watt curve). Figure 9 shows a typical control diagram for a grid-feeding inverter.

2.4.3 Grid supporting inverters

Grid supporting converters can be represented either as an ideal ac-controlled current source in parallel with a shunt impedance or an ideal ac voltage source in series with a link impedance. This type of inverters that support the control of grid parameters. The main function of this type of converters is to regulate the voltage/current to keep the value of grid frequency and voltage amplitude close to their rated values. This type of power converters can operate independently when modeled as a voltage source as shown in Figure 11 and requires a grid forming source to set the voltage and frequency when operating as a current source as shown in Figure 10.
Figure 10: General control structure of grid supporting inverter operating as a current source [27]

Figure 11: General control structure of grid supporting inverter as a voltage source [27]
3 Inverter-based Resources Modeling and Control

For study of the transient performance of inverter based resources in resiliency mode of operation, a couple of concepts need to be understood. This section discusses some background on the modeling and control for grid forming and grid following inverters. They will be used in the subsequent chapter for simulation of these inverters on the distribution feeder.

3.1 Modeling of Inverter-based resources

The modeling of inverters/ power converters depends on the application of the model. Based on the depth of the detail and complexity the converter models can be categorized as follows:

3.1.1 Detailed models

This type of model includes the details of the switches that constitute the inverter. The component of the switches, the transistor behavior, the diode and their nature of operation is included in these models. This model is important for in-depth study of the power converter and the design of new technology in the power converter. The models are suited for electromagnetic study of the converters/inverters itself.

3.1.2 Switching models

The next level of converter models comprises of switching models which model the switches not in details of its components but as a function of switching based on whether it is on or off. The converter is defined by the switching action every cycle. These models identify the characteristics of the converter as seen from the converter terminals. The switching model can accurately describe the steady-state and dynamic behavior of the converter. The instantaneous values of the current and voltages can be calculated using switching models. These computed values contain both high-frequency components due to switching and slower transients.

3.1.3 Average models

Despite the advantages of switching models having reduced complexity but also representing high frequency and lower frequency transients, they are not always suitable for large scale dynamic analysis and control design purposes as the details of high frequency variables are not needed. Indeed, the closed loop control system usually exhibits low-pass characteristics and do not react to high-frequency components[36].
Switching models also do not adequately inform about the relation between modulating signal and the current and voltage variables while the average model describes the dynamics of the converter as the function of modulating signal. For the development of average models, the output of the converter is averaged over each switching cycle and the output only includes the average value of the inverter quantities.

When the average of the variable is a function of time and changes from one switching cycle to the next, the averaging operator is defined as:

$$\bar{x} = \frac{1}{T_s} \int_{t-T_s}^{t} x(\tau) d\tau$$

(14)

Where \(x(t)\) is the variable and the bar \(\bar{x}(t)\) is the average value.

For the average model of inverter of the inverter model above, the ac-side current dynamics in d-q frame can be described as:

$$L \frac{d i_n}{dt} + R i_n = v_{tn} - v_{sn}$$

(15)

$$v_{tn} = \frac{V_{dc}}{2} m$$

(16)

Figure 12: Three phase inverter with RL filter

For the averaged model of inverter of the inverter model above, the ac-side current dynamics in d-q frame can be described as:
Chapter 3. Inverter-based Modeling and Control

Where, \( v_{tn} \) is control input, \( v_{sn} \) is the disturbance input and \( i_n \) is the state variable for phases a, b and c.

In the d-q frame equation (15) and equation (16) corresponds to:

\[
L \frac{di_d}{dt} = L \omega i_q - Ri_d + v_{td} - v_{sd}
\]

\[
L \frac{di_q}{dt} = -L \omega i_d - R i_q + v_{tq} - v_{sq}
\]

\[
v_{td} = \frac{V_{dc}}{2} m_d
\]

\[
v_{tq} = \frac{V_{dc}}{2} m_q
\]

Where, \( m_d \) and \( m_q \) are modulating signals in dq-frame.

Throughout this thesis averaged models of inverters have been developed and validated using the detailed inverter model in Simulink to make sure their performance is accurate. The complete averaged model is developed for the current control and voltage control loops parameter identification and later the models are used for phasor mode simulation in Simulink environment.

3.2 Control of Inverter-based resources

For the inverter-based resources the electrical part is the main component of the source and therefore the inverter is characterized by the type of control it constitutes. The steady state and dynamic characteristics of inverter are the result of the control parameters and filter interface to the load or the grid. Thus, control of inverter is the most important aspect of the inverter-based resource.
3.2.1 Control of the converters using dq and αβ frames

The design of the controller for three phase converters is a complex task as it intends to track sinusoidal voltage and current commands. While tracking a DC command can be done using a Proportional Integral (PI) compensator, the sinusoidal command tracking may require higher order and higher bandwidth design making the controller design complicated.[36]

To simplify the analysis and control design process the two dimensional frames, stationary reference (αβ) frame and rotating or synchronous reference (dq) frame are commonly used. Both αβ-frame and dq-frame transform the problem of controlling a three phase converter into control of two equivalent subsystems. In addition, if control is implemented in the dq-frame a sinusoidal command tracking problem can be transformed to an equivalent DC command tracking problem. Thus, PI compensators can be used for the control of the converter. For the rest of the thesis the controls are built in the d-q frame.

3.3 Modeling of grid forming inverters

As the paradigm of energy resources on the grid shifts to being heavily inverter-based, grid forming inverters are necessary for the proper operation of the system. The main objective of grid forming inverter is to be able to maintain the voltage and frequency on its own without the need to follow another generating source. This is different for grid following inverters that follow the grid voltage and frequency for its operation. A grid following inverter cannot operate on its own while a grid-forming inverter can operate by itself and in synchronism with the system with a slight change in the control topology.

For this work, the grid forming inverter is based on the virtual synchronous machine (VSM) concept. The studied grid forming inverter provides real power with virtual inertia control that provides frequency and phase angle references to the internal loops for the voltage source converter operation. The reactive power controller provides the voltage reference for the inner controllers, i.e., the cascaded voltage and current controllers. From the previous section discussing inertia emulation and virtual synchronous generator, this grid forming inverter model refers to the inertia emulation based on the ISE Lab’s model and the cascaded voltage and current controller is added to as inner controllers as seen in Figure 13.
This section aims to describe each component of the grid forming inverter based on VSM control.

### 3.3.1 Control of the grid forming inverter

#### 3.3.1.1 Virtual synchronous machine inertia emulation and active power droop control

The grid forming inverter is based on the VSM implementation based on conventional swing equation representing the inertia and damping of the traditional synchronous machines.

Referring to the swing equation of the synchronous generators, the emulation of the swing equation can be written as[11]:

$$P_{in} - P_{meas} = J\omega_m \frac{d\omega_m}{dt} + D \frac{\omega_m - \omega_g}{\omega_o}$$  \hspace{1cm} (21)

Where,

- $P_{in}$ = virtual shaft power determined by governor
\( P_{meas} = \) measured output real power

\( J = \) virtual inertia/mechanical time constant corresponding to 2H in a traditional synchronous machine

\( D = \) virtual damping factor

\( \omega_m = \) rotor angular frequency

\( \omega_g = \) angular frequency at the point of measurement of voltage

\( \omega_o = \) nominal angular frequency

The governor model for the virtual synchronous generator (VSG) is based on the conventional SG and can be represented as:

\[
P_{in} = P_{nom} - k_p \frac{\omega_m - \omega_o}{\omega_o}
\] (22)

Where,

\( P_{nom} = \) normal active power value

\( k_p = \) droop coefficient for \( P - \omega \) control

\[ P_{ref} \rightarrow P_{meas} \rightarrow m_f \rightarrow \frac{1}{sT_d + 1} \rightarrow \omega_0 \rightarrow \omega_g \rightarrow \delta \]

\[ Figure \ 14: \ P-\omega \ droop \ control \]

The \( P - \omega \) control loop corresponds to the governor model. In this model, the difference between the active power output measured and the reference power and droop characteristics is denoted by the gain \( m_f \).

From the equations (21) and (22), on simplifying with the assumptions that one can substitute \( \omega_g \) by \( \omega_o \) and damping factor representing the droop coefficient we obtain the following equation (23):
Chapter 3. Inverter-based Modeling and Control

\[ \omega_m = \omega_0 + \int_0^t \left( \frac{1}{J} (P_{nom} - P_{meas}) + k_p (\omega_o - \omega_m) \right) dt \]  \hspace{1cm} (23)

The per unit mechanical speed of the virtual inertia is given by the integral of the power balance and the phase angle of the virtual synchronous machine is given by the integral of the speed.

Since the swing equation is a model of the conventional synchronous generator, the inertia characteristic \( J \) is given as:

\[ J = \frac{2HS_o}{\omega_o^2} \]  \hspace{1cm} (24)

Where,

\( H \)=machine inertia constant which determines the time period during which the machine is able to supply the nominal load using energy storage (in rotating mass)

\( S_o \)= nominal apparent power

\( \omega_o \)=system frequency

The machine inertia constant depends on the machine size and power and is typically 2 to 10 s[37].
3.3.1.2 Reactive power-droop control

The reactive power droop control used here is similar to the droop-based reactive power controller commonly implemented in microgrid control. The voltage reference ($E_{\text{ref}}$) is the external voltage reference for the inner cascaded voltage and current controllers. The difference of reactive power reference ($Q_{\text{ref}}$) and the measured reactive power output multiplied by the reactive power droop coefficient ($n_q$) gives the voltage deviation which is subtracted from the nominal voltage to get a new voltage set-point. This voltage set-point is compared to the voltage magnitude at the inverter output and an integrator is used to obtain the correct voltage reference. This reactive-power voltage droop follows the automatic voltage regulator control for conventional synchronous machines.

\[ Q_{\text{ref}} \rightarrow n_q \rightarrow \frac{1}{sT_a + 1} \rightarrow V_{\text{nom}} \rightarrow k/s \rightarrow E_{\text{ref}} \]

\[ Q_{\text{meas}} \]

\[ V_{\text{mag}} \]

Figure 16: $Q-V$ droop control

3.3.1.3 Inner voltage controller

The voltage reference obtained from the reactive-power vs voltage droop, $E_{\text{ref}}$, and the angle $\delta$, obtained from the real-power frequency droop controller are used to obtain the voltage references for the voltage controller of the cascaded voltage-current controller.
In the d-q frame, $E_d = E_{ref} \cos \delta$ and $E_q = E_{ref} \sin \delta$, are used as direct references for the voltage control loop. The voltage control loop contains the current reference is produced from this loop and can be expressed as:

$$i_{Ld\_ref} = (E_d - V_{gd}) + k_{iv} \frac{d(E_d - V_{gd})}{dt} + C\omega V_{gq}$$  \hspace{1cm} (25)$$

$$i_{Lq\_ref} = (E_q - V_{gq}) + k_{iv} \frac{d(E_q - V_{gq})}{dt} + C\omega V_{gd}$$  \hspace{1cm} (26)$$

Where,

$k_{iv} = \text{integral gain for voltage PI controller}$

$k_{pv} = \text{proportional gain for voltage PI controller}$
\( V_{gd}, V_{gq} = d\) - and q- axis grid side/ capacitance voltage.

\( C \) = capacitance of the LC filter

\( \omega \) = reference frequency

Here, the term \( C\omega V_{gq} \) and \( C\omega V_{gd} \) are the decoupling terms for the voltage controller.

### 3.3.1.4 Inner current controller

The inner current controller is the second part of cascaded voltage and current control. The current references are obtained from the voltage controller described in the previous section. The current controller provides the output voltage references, \( V_{d, conv} \) and \( V_{q, conv} \) as described in the following equations:

\[
V_{d, conv} = k_{pc}(i_{Ld, ref} - i_{Ld}) + k_{ic}\frac{d(i_{Ld, ref} - i_{Ld})}{dt} + L\omega i_{Lq} \tag{27}
\]

\[
V_{q, conv} = k_{pc}(i_{Lq, ref} - i_{Lq}) + k_{ic}\frac{d(i_{Lq, ref} - i_{Lq})}{dt} + L\omega i_{Ld} \tag{28}
\]

Where,

\( i_{Ld}, i_{Lq} \) = inductor currents in the d-q frame,

\( k_{pc}, k_{ic} \) = proportional and integral gains for the current controller
For the implementation of voltage source converter control system based on the averaged model as discussed earlier, the output voltage references for the converter $V_{d\_conv}$ and $V_{q\_conv}$ are divided by the DC-link voltage $V_{dc}$ to get the modulation indices $m_d$ and $m_q$ respectively.

$$m_d = \frac{V_{d\_conv}}{V_{dc}}$$  \hspace{1cm} \text{(29)}

$$m_q = \frac{V_{q\_conv}}{V_{dc}}$$  \hspace{1cm} \text{(30)}
As discussed in the averaged modeling of inverters section, when the switching operation of the converter and the delay due to PWM implementation are neglected, the average value of the output voltage is given by the product of modulation index and the dc voltage. In this way the AC side operation of converter is decoupled from any DC side dynamics and the DC side dynamics are not discussed further. It is assumed that the power required by the AC side is available at the DC link of the converter.

3.3.2 Electrical Part/Power Circuit of the grid forming inverter

The electrical part of the converter/inverter consists of the set of LC filter’s inductor and capacitor and the terminal voltage that is considered the point of common coupling of the inverter. The complex AC grid or the feeder topology is not included in the control as the objective is to control the local output.

Based on the averaged model of the inverter, the state space equations of the electrical part of the inverter in synchronous reference frame/d-q frame can be established as follows:

\[ L \frac{d i_{Ld}}{dt} = -Ri_{Ld} + L\omega i_{Lq} + m_d V_{dc} - V_{gd} \]
\[ L \frac{d i_{Lq}}{dt} = -Ri_{Lq} - L\omega i_{Ld} + m_q V_{dc} - V_{gq} \]
\[ C \frac{d V_{cd}}{dt} = i_{Ld} - i_{od} - C\omega V_{gd} \]
\[ C \frac{d V_{cq}}{dt} = i_{Lq} - i_{oq} + C\omega V_{ga} \]

Where, \( i_{Ld} \) and \( i_{Lq} \) are filter inductor currents in the dq-frame, \( V_{gd} \) and \( V_{gq} \) are the output voltages of the converter, \( i_{od} \) and \( i_{oq} \) are the output currents of the converter. \( L \) is the filter inductor and \( C \) is the filter capacitor while \( R \) is the equivalent series resistance of the filter inductor. \( m_d \) and \( m_q \) are the modulating signals in dq-frame.

3.3.3 Parameter selection

3.3.3.1 LC filter design

For the purpose of the LC filter design, the procedure described in [38] was followed.

The filter inductance is chosen as:
Chapter 3. Inverter-based Modeling and Control

\[ L = \frac{V_{dc}}{6f_s \Delta I_{max}} \]  

(35)

Where,

\( L \) = filter inductor

\( V_{dc} \) = dc voltage

\( f_s \) = switching frequency of the inverter

\( \Delta I_{max} \) = maximum ripple in line current which is chosen as 30% of the maximum current

\( I_{max} \) is determined as:

\[ I_{max} = \frac{\sqrt{2}P_{max}}{\sqrt{3}V_{L-L}} \]  

(36)

The base value for the capacitor can be calculated as:

\[ C_b = \frac{P_{max}}{\omega_g V_{L-L}^2} \]  

(37)

And the filter capacitor can be chosen as

\[ C = x C_b \]  

(38)

Where,

\( x \) = operation factor based on the compensation for voltage drop of inductor at the full load condition. It is chosen as 0.05 for this case.

Once the filter parameters are determined, the resonant frequency should be checked to verify this condition,

\[ 10f_l < f_{res} < f_s \]  

(39)

Where,
\( f_l = \text{line frequency (60Hz)} \)

\( f_{res} = \text{resonant frequency} \)

\( f_s = \text{switching frequency (20kHz)} \)

The resonant frequency is calculated as:

\[
 f_{res} = \frac{1}{2\pi \sqrt{LC}} \tag{40}
\]

### 3.3.3.2 Current control loop parameters design

For the design of the current control loop parameter, the closed loop gains for the controller seen in Figure 19: is as follows:

\[
l(s) = \frac{k_{pc}}{L_f} \left( s + \frac{k_{ic}}{k_{pc}} \right) \left( s + \frac{k_{ic}}{L_f} \right) \tag{41}
\]

Where,
$k_p =$ proportional gain of PI controller

$k_i =$ integral gain of PI controller

$L_f =$ filter inductor

$R_f =$ filter resistance

To improve the open loop response, the pole $-\frac{R_f}{L_f}$ can be cancelled by zero of the PI compensator. So one can choose, $\frac{k_{ic}}{k_{pc}} = R \frac{L_f}{L_f}$ and $\frac{k_{ic}}{L_f} = \frac{1}{\tau_i}$, where $\tau_i$ is the desired time constant of closed-loop system. The closed loop system can then be represented as:

$$G_i(s) = \frac{i(s)}{i_{ref}(s)} = \frac{1}{\tau_i s + 1} \quad (42)$$

The time constant of the current control loop should be small for a fast current control response but the bandwidth of the closed loop system should be almost 10 times smaller than the switching frequency of the converter. Considering this, the time constant is usually in the range of 0.5-5ms[36].

3.3.3.3 Closed loop voltage control design

The voltage controller parameters $k_{pv}$ and $k_{iv}$ have been designed following the symmetrical optimum method discussed in [36].
4 Case Study and Simulation Results

The grid-forming inverter modeled in the previous section is built in the Simulink environment for various capacities. Initially, the inverter is modeled in the discrete simulation mode of Simulink and the results of the averaged model based inverter is compared with the inbuilt Simulink inverter using the same control and the same parameters.

Modeling the inverter-based resources in the 13 node test feeder

The IEEE- node test feeder is used for simulation of the resiliency conditions. The inverter-based resources are added to the original feeder at different location and the transient performance of the system as the loads are restored is observed and studied. The load demand on the 13 node test feeder in Simulink is as follows:

<table>
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<th>Node</th>
<th>Phases</th>
<th>Pa</th>
<th>Qa</th>
<th>Pb</th>
<th>Qb</th>
<th>Pc</th>
<th>Qc</th>
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</thead>
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<tr>
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<td>5.00</td>
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<td>19.00</td>
<td>58.50</td>
<td>34.00</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>634</td>
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<td>675</td>
<td>ABC</td>
<td>485.00</td>
<td>190.00</td>
<td>68.00</td>
<td>60.00</td>
<td>290.00</td>
<td>212.00</td>
</tr>
<tr>
<td>652</td>
<td>A</td>
<td>128.00</td>
<td>86.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>680</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

All values are in kW and kVAR. The total load on the 13 node test feeder is around 3.8MVA. Different case studies are performed as described below.
The case studies conducted were on 13 node test feeder with the original nodes and loads. The inverters were added to the 13 node feeder at different locations and the simulation was run for restoration of the feeder by the inverter-based distributed resources. The inverters controls are decentralized. Each inverter is used to regulate the voltage and frequency at its terminals.

4.1 Case 1: 2.5 MVA inverter supplying a varying load

To verify the control and performance of the virtual synchronous generator described above, a single inverter with a varying load level was modeled in Simulink to simulate an islanded scenario.

The following Table 2 summarizes the parameters for the simulation.
Table 2: 2.5 MVA virtual synchronous generator parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>4.16 KV(L-L)</td>
</tr>
<tr>
<td>Total Power (S)</td>
<td>2.5 MVA</td>
</tr>
<tr>
<td>Frequency</td>
<td>60 Hz</td>
</tr>
<tr>
<td><strong>Filter parameters</strong></td>
<td></td>
</tr>
<tr>
<td>L_filter(Lf)</td>
<td>0.039mH</td>
</tr>
<tr>
<td>R_filter(Rf)</td>
<td>1.8e-3 ohms</td>
</tr>
<tr>
<td>P-ω droop coefficient (mf)</td>
<td>1% droop</td>
</tr>
<tr>
<td>Q-V droop coefficient(nq)</td>
<td>5% droop</td>
</tr>
<tr>
<td><strong>Current loop parameters</strong></td>
<td>Time constant is chosen as 0.0001s</td>
</tr>
<tr>
<td>$K_p_c = \frac{L_f}{\text{time constant}}$</td>
<td>3.6</td>
</tr>
<tr>
<td>$K_i_c = \frac{R_f}{\text{time constant}}$</td>
<td>0.7925</td>
</tr>
<tr>
<td><strong>Voltage control loop parameters</strong></td>
<td></td>
</tr>
<tr>
<td>$K_p_v$</td>
<td>0.1</td>
</tr>
<tr>
<td>$K_i_v$</td>
<td>4.9</td>
</tr>
<tr>
<td><strong>Inertia constant</strong></td>
<td>$J = 35.18 \text{kgm}^2$</td>
</tr>
</tbody>
</table>

Figure 21: 2.5 MVA Virtual synchronous generator Simulink implementation

The elements of the block diagram are designed following the above described elements of the VSG.

The simulation was conducted as follows:

At 0s the load was 0.625 MW and 0.625 MVAR. At 1s simulation time, the load was increased by 1.75MW. The following figure shows the frequency deviation, the power
output, the voltage level and the current levels for the virtual synchronous generator output.

Figure 22: Output plots for frequency, voltage, real and reactive power and current for a single VSG
The results indicate the ability of the inverter to handle large fluctuations in loads with only primary control.

The frequency can be brought back to the nominal with secondary control. To simulate the secondary control a simple step change of the active power reference is used.

![Figure 23: Frequency plot with secondary control](image)

This simulation is the first step towards studying the performance of virtual inertia based grid-forming inverter. This same control is utilized for the case study in 13 node feeder but the models are developed in phasor model.
### 4.2 Case 1: 1 grid forming inverter in the 13 node test feeder

Table 3: Parameters for 4MVA virtual synchronous generator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>4.16 KV(L-L)</td>
</tr>
<tr>
<td>Total Power (S)</td>
<td>4 MVA</td>
</tr>
<tr>
<td>Frequency</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Filter parameters</td>
<td></td>
</tr>
<tr>
<td>L_filter(Lf)</td>
<td>0.07mH</td>
</tr>
<tr>
<td>R_filter(Rf)</td>
<td>1.8e-3 ohms</td>
</tr>
<tr>
<td>P-\omega droop coefficient (mf)</td>
<td>1% droop</td>
</tr>
<tr>
<td>Q-V droop coefficient(nq)</td>
<td>5% droop</td>
</tr>
<tr>
<td>Current loop parameters</td>
<td></td>
</tr>
<tr>
<td>Kp_c= Lf/time constant</td>
<td>Time constant is chosen as 0.0005s</td>
</tr>
<tr>
<td>Ki_c=Rf/time constant</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>0.4953</td>
</tr>
<tr>
<td>Voltage control loop parameters</td>
<td>Kp_v=0.02</td>
</tr>
<tr>
<td></td>
<td>Ki_v=4.9</td>
</tr>
<tr>
<td>Inertia constant</td>
<td>J=56.3kgm$^2$</td>
</tr>
</tbody>
</table>
4.2.1 Case 1.1: VSG at node 632

In this case study, the VSG is placed at node 632. The inverter is rated 4MVA. The substation feeder is disconnected due to fault, breaker 1 is open.

Objective of simulation: Restore all the loads and maintain the voltage and frequency of the nodes.

**Restoration Sequence of events:**

- At 0s, the breakers 2 and 3 are open [Assumption: When the utility is lost indicated by opening of breaker 1, the breaker 2 and 3 also open so that the inverter connected to the feeder is supplying minimum amount of load that is the critical load at the start of the islanded operation of distribution grid]
- At 2s, the breaker 2 closes
- At 4s, breaker 3 is closed and all loads are restored.

The following plots summarize the voltages, frequency, currents and power at node 632 without any secondary control.
Chapter 4. Case Study and Simulation Results

Figure 25: Output plots for frequency, voltage, real and reactive power and current for a single VSG at node 632

The voltage and frequency are within the desired range that satisfies the DER emergency limits specified by the IEEE 1547-2018.
4.2.2 Case 1.2: Grid forming VSG at node 675
In this simulation case the same inverter is placed at node 675 and the simulation sequence as follows is observed.

**Restoration sequence**

- At 0s the breakers 2 and 3 are open
- At 1s, breaker 3 is closed
- At 3s, breaker 2 is closed and all the loads are restored

The following plots summarize the voltages, frequency, currents and power at node 675 without any secondary control.
Figure 27: Output plots for frequency, voltage, real and reactive power and current for a single VSG at node 632
The voltage and frequency are within the desired range that satisfies the DER emergency limits specified by the IEEE 1547-2018.

4.3 Case 2: Two grid forming inverters working to restore the loads

*Table 4*: Parameters for simulation of 3MVA virtual synchronous generator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>4.16 KV(L-L)</td>
</tr>
<tr>
<td>Total Power (S)</td>
<td>3 MVA</td>
</tr>
<tr>
<td>Frequency</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Filter parameters</td>
<td></td>
</tr>
<tr>
<td>L_filter (Lf)</td>
<td>0.33mH</td>
</tr>
<tr>
<td>R_filter (Rf)</td>
<td>1.8e-3 ohms</td>
</tr>
<tr>
<td>P-ω droop coefficient (mf)</td>
<td>1% droop</td>
</tr>
<tr>
<td>Q-V droop coefficient(nq)</td>
<td>5% droop</td>
</tr>
<tr>
<td>Current loop parameters</td>
<td>Time constant is chosen as 0.5ms</td>
</tr>
<tr>
<td>Kp_c = Lf/time constant</td>
<td>3.6</td>
</tr>
<tr>
<td>Ki_c = Rf/time constant</td>
<td>0.6605</td>
</tr>
<tr>
<td>Voltage control loop parameters (Designed following Symmetrical optimum method)</td>
<td>Kp_v=0.0154</td>
</tr>
<tr>
<td></td>
<td>Ki_v=3.4450</td>
</tr>
<tr>
<td>Inertia constant</td>
<td>J=42.2172kgm²</td>
</tr>
</tbody>
</table>

4.3.1 Case 2.1: Two VSGs at node 632 and node 675

In this case two grid-forming inverters are placed at nodes 632 and 675 respectively. The rating of each inverter is 3 MVA.
The sequence of events is:

- At 0s breaker 1 (substation is absent due to some fault) and Breaker 2 is open and breaker 3 is closed.
- At 2s breaker 2 closes and the two inverters start sharing power proportionately as seen.

The first set of plots in Figure 29 summarizes the simulation without any secondary control.
Figure 29: Output plots for frequency, real and reactive power, voltage, and current for two VSG at node 675 and node 632.

The voltage and frequency fluctuates during the load fluctuations however they are maintained back within acceptable limits in reasonable amount of time.
4.3.2 Case 2.2: Two inverters at 680 and 675

The inverters are placed at node 675 and node 680. These two inverters are trying to restore the loads beyond the breaker 2.

Sequence of events:

- At 0s breaker 1 (substation is absent due to some fault) and Breaker 2 is open and breaker 3 is closed.
- At 2s breaker 2 closes and the two inverters start picking up the additional loads beyond breaker 2.

The following set of plots in Figure 31 below summarizes the simulation results using the swing equation based virtual synchronous generator control for both the inverters at node 675 and node 680 on the 13 node feeder. The voltage and frequency fluctuates during the load fluctuations however they are maintained back within acceptable limits in reasonable amount of time. The power is shared proportionately accounting for the unbalanced nature of the distribution system and the position of the inverters.
Figure 31: Output plots for frequency, voltage, real and reactive power and current for two VSG at node 675 and node 680 picking up the loads beyond breaker 2.
5 Conclusions and Future Work

5.1 Conclusions

Based on the simulation and case studies discussed in the previous chapter it can be seen that the addition of grid forming inverter controls to the distributed resources facilitates the operation of the feeder during emergency scenarios under the islanded scenario. The virtual synchronous generator based grid forming inverters enhance the frequency control of the system and make sure that the frequency and voltage are maintained during sudden changes and disturbances in the system. The simulations have been performed with distributed local control by each inverter. Thus, it can be seen that the presence of multiple grid-forming inverters and their control in a distributed manner enhances the resiliency of the distribution feeder in islanded mode of operation. The controls for the swing equation-based virtual synchronous generator have been able to maintain the voltage and frequency in an unbalanced feeder and can be applicable for the operation in the future grid with more distributed generation and inverter-interfaced generation in resiliency mode of operation.

5.2 Future Work

The simulation performed in this model is based on local control and for the simulation with secondary control a simplistic representation of secondary control by using step references for the real power references. Also the controls are focused on regulating the voltage and frequency at the terminal of the inverter itself. For multiple inverters of different capacities, the additional secondary control along with feedback control can help improve the performance of the inverters.

This work has not considered the protection issues that arise during the simulation as the main focus is on the controls for the inverter. Future work would need to focus on the breaker response based on the response of the inverter during different conditions. The synchronization between multiple inverters has not been explicitly dealt with and assumes that the synchronization conditions such are satisfied. For a comprehensive study of the system future studies should consider the synchronization details. Future analysis would extend to modify the controls based on the network design. The dc side dynamics have not been included in the controls and considered as fixed, which is idealistic and extension of this work would consider the dc side dynamics in the control of the inverter. One other extension to this work could consider modification necessary
for the protection design of the protection system based on the inverter response and the requirement for load-shedding in the system in case of large load fluctuations.

In this work, the PI controller parameters have been designed based on the conventional methods and are not optimal design methods. An optimal controller design would enhance the performance of the virtual synchronous generators used in the distribution system. Besides, the aspect of storage for the virtual synchronous generator is not explicitly modeled and is something that can be extended upon this work.
Bibliography


