EXAMINATION OF POWER QUALITY CONTROL WITHIN A
COST-BASED MICROGRID ARCHITECTURE

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EXAMINATION OF POWER QUALITY CONTROL WITHIN A COST-BASED MICROGRID ARCHITECTURE

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ABSTRACT

EXAMINATION OF POWER QUALITY CONTROL WITHIN A COST-BASED MICROGRID ARCHITECTURE

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Microgrids (MGs) are important because of their ability to provide a “greener” solution to obtain reliable, secure and sustainable electricity from renewable sources of energy. As a MG can be islanded (i.e. disconnected from the main grid), the power quality issues observed are very different when compared to the traditional centralized grid. These issues are of significant importance because the reliability of the grid is impacted by the MG operation. Currently, the typical power quality issues such as total harmonic content and transient stability have been studied only for an ideal voltage source of constant magnitude - assumed to be the distributed generator (DG) connected to a grid. However, under practical conditions, a MG might have more than one DG (Example: solar, wind, diesel generators, and CHP, among others) connected to it and some of these DGs would be subject to varying output throughout the day based on changes in intensity of solar radiation, wind speed, and other environmental factors. The current research takes this into account and examines the efficacy of an existing power quality control strategy for a MG consisting of a stochastically modeled renewable energy source i.e. a solar PV array.
A Robust Servomechanism Controller in conjunction with a Discrete Sliding Mode Controller is employed to achieve voltage and current regulation in the MG. Stochastic model of a solar PV array along with a supplemental DC voltage source model have been presented in this research. The solar PV array utilizes actual TMY3 irradiance data for Dayton, Ohio. The supplemental DC voltage source is connected in series with the solar PV output and helps to compensate for the intermittent nature of energy produced by the solar PV array. A cost-based approach to connecting and disconnecting the MG from the utility supply whilst ensuring the maximum use of incident solar energy is also presented in this research. The MG model developed in Matlab Simulink® follows the Consortium for Electric Reliability Technology Solutions (CERTS) architecture for modeling MGs. The examination of the efficacy of an existing control strategy in a MG topology capable of making real-time cost-based decisions is expected to help the practical implementation of MGs.
Dedicated to my அஞ்சுகள் and அதிகாரங்கள்
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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>DG</td>
<td>Distributed Generator</td>
</tr>
<tr>
<td>DSMC</td>
<td>Discrete Sliding Mode Controller</td>
</tr>
<tr>
<td>$\vec{I}<em>{inv</em>{abc}}$</td>
<td>Inverter Output Current Vector</td>
</tr>
<tr>
<td>$\vec{I}<em>{load</em>{abc}}$ (or $I_L$)</td>
<td>Load Current</td>
</tr>
<tr>
<td>$I_p$</td>
<td>Primary Line Current</td>
</tr>
<tr>
<td>$\vec{I}<em>{snd</em>{abc}}$ (or $I_s$)</td>
<td>Secondary Phase Current</td>
</tr>
<tr>
<td>MG</td>
<td>Micro Grid</td>
</tr>
<tr>
<td>PV</td>
<td>Photo-Voltaic</td>
</tr>
<tr>
<td>RSC</td>
<td>Robust Servomechanism Controller</td>
</tr>
<tr>
<td>RSP</td>
<td>Robust Servomechanism Problem</td>
</tr>
<tr>
<td>THD</td>
<td>Total Harmonic Distortion</td>
</tr>
<tr>
<td>TMY3</td>
<td>Typical Meteorological Year (1991-2005)</td>
</tr>
<tr>
<td>$\vec{V}<em>{inv</em>{abc}}$</td>
<td>Inverter Voltage</td>
</tr>
<tr>
<td>$\vec{V}<em>{load</em>{abc}}$ (or $V_L$)</td>
<td>Load Voltage</td>
</tr>
<tr>
<td>$V_p$</td>
<td>Primary Voltage</td>
</tr>
<tr>
<td>$\vec{V}<em>{pwm</em>{abc}}$</td>
<td>Inverter Output Voltage (line-to-line) i.e. $V_i$</td>
</tr>
<tr>
<td>$V_s$</td>
<td>Secondary Voltage</td>
</tr>
</tbody>
</table>
CHAPTER 1
INTRODUCTION

1.1. Background

A Micro Grid (MG) can be defined as an isolated electric grid which is generally connected to the central grid but can also function on its own in case of a fault in the central grid, improving overall supply reliability [1]. Additionally it may be convenient to employ islanded MGs to achieve peak shaving during regular grid operation for economic reasons. MGs are considered to be a “greener” solution to obtain reliable, secure and sustainable electricity from renewable sources of energy [2]. It is now well accepted that MGs and their integration into the Smart Grid will enhance the Smart Grid [3] in a variety of ways. The ability of a MG to use more distributed energy resources while generating electricity results in lower overall greenhouse gas (GHG) emissions and thus it constitutes a “greener” energy solution.

As MGs are located closer to their loads, the typical losses due to power transmission on the grid are greatly reduced. MGs are being increasingly used by hospitals, military installations, rural and/or remote communities, etc. because of their ability to provide uninterrupted power supply. Developing countries are utilizing MGs for rural electrification to bypass the development of the national electricity grid which is analogous to the use of cellphones to bypass
the landline infrastructure [3]. The MG concept is of particular significance, especially in the US and Europe, areas with well-established national grids, because of its capability to reinforce existing ageing transmission and distribution infrastructure, without a complete overhaul of electrical equipment.

The Microgrid Concept

Figure 1.1 shows the basic architecture of a MG. It is more commonly known as the Consortium for Electric Reliability Technology Solutions (CERTS) architecture. The microsource is a distributed generation (DG) unit(s), generally a renewable energy resource. There are two types of controllers that work in tandem with the energy manager; a microsource controller (MC) and a load controller (LC). The energy manager is a master program which monitors all the key MG parameters in real-time and initiates corrective measures when necessary to ensure effective operation. These controllers are located on each of the MG feeders permitting localized control. The Point of Common Coupling (PCC) is where the central grid connects to the MG. In case of a fault, the static switch adjacent to the PCC opens disconnecting a feeder from the grid and the MG is said to have been islanded.

![Figure 1.1: Basic architecture of a MG](image-url)
Figure 1.2 showcases the MG concept as a part of the distributed energy future. The ‘Home’, ‘Industrial’, and ‘Commercial’ setups could be visualized as individual MGs with self-generation capacity coupled with interconnection to each other via energy management software and controllers.

Figure 1.2: MGs as a part of the distributed energy future
(http://www.tclabz.com/2012/05/03/microgrids-and-the-distributed-energy-future/)

1.2. Literature Review

MGs have come into prominence only in the last decade or so. Several research questions have been posed and answered during this time. The following articles are among the well-cited articles in this field which introduce the reader to a wide variety of research questions:

Lasseter, et al. (2004) [4] introduced MGs as a conceptual solution to realize the emerging potential of distributed generators (DGs). Later in 2007, Lasseter [5] proposed control techniques for integration of DGs along with Combined Heat and Power (CHP) systems into a MG. The challenges of operating a DG solar PV unit at maximum efficiency were listed by Petrone, et al.
The concept of the DG interface to the CERTS MG was introduced by Nikkhajoei, et al. (2009) in [7]. A protection system for a low voltage (LV) DC MG was proposed by Salomonsson, et al. (2009) [8]. Zamora, et al. (2010) [9] review the advantages and disadvantages of exiting control techniques. They also deal with the control techniques used to extract maximum power from intermittent sources of energy. Lidula, et al. (2011) provide a summary of most of the practical MG test systems reported in literature [10]. Llaria, et al. (2011) have also proposed various control algorithms and techniques [11]: for islanding behavior of MGs; for various detection techniques for islanding; and for effective inverter control once a MG has been islanded.

**Technology Gaps**

One of the major challenges in a MG is the issue of power quality within an isolated or islanded grid. The quality of power affects the reliability of the grid and supply reliability to all the nodes (households) connected to it. The effect of renewable energy integration into the grid on the overall power quality is reported by Gloystein in [12]. Gloystein describes how the increasing proportion of the renewable energy in the energy generation mix of the United Kingdom is leading to increasing instances of flickering of light bulbs in households and even outages. This effect on power quality is mainly attributed to the change in the frequency of the generated energy. Thus, there is a high impetus on the maintenance of a good overall power quality. Marwali et al. [13] have studied the maintenance of power quality for a single inverter topology with an ideal source.

Another issue in MGs is the generation of internal references when the MG is islanded. When the MG is connected to the main grid, the MG voltage and frequency references originate from the main grid. When it is islanded, these references are lost and a new references need to be internally generated. Additionally, knowing when and how to island a MG and managing a
reconnection back to the main grid presents both detection and control problems. The disconnection/islanding can be initiated subsequent to the detection of a fault or for other economic reasons.

The reduction of Total Harmonic Distortion (THD) and the control of transient coupling between real and reactive power are essential to maintain power quality and reliability. This has been studied only for islanded MGs comprising of a single DG unit [12]. Under practical conditions, many MGs would likely have more than one DG unit connected to it. Chen, et al. [15] have demonstrated the control of multiple DGs system using current sharing techniques between parallel inverters. However, the power control strategy described does not consider THD or transient coupling; which is crucial for maintaining the power quality in the system. Similarly, Green, et al. [16] have discussed the advantages and disadvantages of different inverter control techniques (single loop control, multi-loop control, etc.). They have demonstrated the use of multiple DGs (up to 3) in a MG in islanded mode. However, the effect on the MG when the system is islanded has not been studied for their proposed control system. Thus, verifying the validity of inverter control results for multiple DGs scenario while taking into account the transients created by islanding/reconnection will provide an important extension to the existing work.

The research presented by Marwali, et al. [12] details a control system structure that attempts to meet most of the gaps noted earlier. The authors describe a controller which incorporates both the Robust Servomechanism Control theory and the Discrete Sliding Mode Control Theory. The control system designed has good transient stability characteristics and yields a low THD output. However, the Simulink® model developed by them lacks a stochastic source model. Their model considers a DC source of constant magnitude to represent a renewable energy source (example: solar & wind among others). Since it is well known that renewable sources are not a constant source of energy; their output generally varies with the change in
environmental factors such as solar irradiance, wind speed, and temperature. Thus, the examination of the efficacy of the reported control system for a stochastically modeled energy source within a MG would further emphasize the effectiveness of their control system.

1.3. Current Research

The current research provides a power quality control schematic for a stochastically modeled MG. It primarily attempts to examine the efficacy of an existing power quality control strategy [17] for a MG consisting of a stochastically modeled renewable energy source i.e. a solar PV (Photo-Voltaic) array. A Robust Servomechanism Controller in conjunction with a Discrete Sliding Mode Controller is employed to achieve voltage and current regulation in the MG. A stochastic model of a solar PV array and a supplemental DC voltage source is developed and integrated into the MG. The solar PV array is modeled using actual TMY3 data for Dayton, OH. The supplemental DC voltage source is obtained from the utility by using a DC-DC converter where the isolated output is connected in series with the solar PV voltage output. The proposed structure compensates for the intermittent nature of energy produced by the solar PV array. A cost-based approach to connecting and disconnecting the MG from the utility supply is also presented in this research. The MG model developed in Matlab Simulink® follows the Consortium for Electric Reliability Technology Solutions (CERTS) architecture for modeling MGs. It is expected that the presented examination of an existing control strategy in a stochastically modeled MG environment would deliver results that can be used to model practical MGs.
1.4. Organization of the Thesis

Chapter 1 introduces the concept of MGs, reviews literature in that field and defines a research goal. Chapter 2 presents the power system control technique used in this research. Chapter 3 presents the stochastic modeling of energy sources and the structure of the simulation test-bed. Chapter 4 showcases the simulation results obtained for the improved MG model. Chapter 5 summarizes the research results.
CHAPTER 2
CONTROL SYSTEM DEVELOPMENT

The control system examined in this thesis has been obtained from [13]. An overall understanding of the control system, its parameters associated, assumptions, model structure, etc. was acquired from the research monograph ‘Integration of Green and Renewable Energy in Electric Power Systems’ [17] written by the same research group as [13]. This chapter provides a re-statement of Keyhani et al.’s [17] primary approach in modeling their power converter system and its associated control system for a single inverter. This work is outlined below. The essential model development and control solution is credited to [17].

2.1. Power Converter System

The overall isolated grid shown in Figure 2.1 has a DC source which is connected to a 3-phase PWM based inverter. The output of the inverter is filtered by an L-C output filter. This is followed by a delta-wye transformer which is connected to a 3-phase load. The DC voltage source shown here is intended to represent renewable generation sources such as PV solar technology or even battery storage.
Figure 2.1: Overall Islanded System - 3-phase load connected to a single PWM-based inverter interfacing a single distributed generator [12]

Figure 2.2: Delta-Wye Transformer Model™ [16]

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Keyhani et al. [17] modeled the Delta-Wye transformer using controlled voltage sources, controlled current sources, and equivalent impedances. The details of the transformer model are as follows:

Power Rating = 600 kVA

Turn Ratio \((N_p/N_s) = 245:208\)

\(V_p/V_s = 980V/832V\)

Inverter Output Voltage (line-to-line) = \(\vec{V}_{pwm_{abc}} = V_i = [V_{iAB} V_{iBC} V_{iCA}]^T\)

Inverter Output Current Vector = \(\vec{I}_{inv_{abc}} = I_i = [i_{iAB} i_{iBC} i_{iCA}]^T = [i_A - i_B \ i_B - i_C \ i_C - i_A]^T\)

Primary Voltage = \(\vec{V}_{inv_{abc}} = V_p = [V_{pAB} V_{pBC} V_{pCA}]^T\)

Primary Line Current Vector = \(I_p = [I_{pA} I_{pB} I_{pC}]^T\)

Secondary Voltage = \(V_s = [V_{sa} V_{sb} V_{sc}]^T\)

Secondary Phase Current = \(\vec{I}sd_{abc} = I_s = [I_{sa} I_{sb} I_{sc}]^T\)

Load Voltage = \(\vec{V}_{load_{abc}} = V_L = [V_{La} V_{Lb} V_{Lc}]^T\)

Load Current = \(\vec{I}_{load_{abc}} = I_L = [I_{La} I_{lb} I_{lc}]^T\)

Using basic transformer relationships, we can express the transformer voltages and currents as:

\[V_{sa} = \frac{N_s}{N_p} V_{pAB}, \quad V_{sb} = \frac{N_s}{N_p} V_{pBC}, \quad V_{sc} = \frac{N_s}{N_p} V_{pCA}\]

\[i_{AB} = \frac{N_s}{N_p} i_{sa}, \quad i_{BC} = \frac{N_s}{N_p} i_{sb}, \quad i_{CA} = \frac{N_s}{N_p} i_{sc}\]

Also, \(i_{pA} = i_{AB} - i_{CA}, \quad i_{pB} = i_{BC} - i_{AB}, \quad i_{pC} = i_{CA} - i_{BC}\)
The L-C filter is modeled using the following current equations on the primary side of the transformer:

\[ \begin{align*}
    \frac{d}{dt} i_A + C_f \frac{dV_{pCA}}{dt} &= C_f \frac{dV_{pAB}}{dt} + i_A \\
    \frac{d}{dt} i_B + C_f \frac{dV_{pAB}}{dt} &= C_f \frac{dV_{pBC}}{dt} + i_B \\
    \frac{d}{dt} i_C + C_f \frac{dV_{pBC}}{dt} &= C_f \frac{dV_{pCA}}{dt} + i_C
\end{align*} \]

We can now write,

\[ \begin{align*}
    (i_A - i_B) + C_f \frac{dV_{pCA}}{dt} - C_f \frac{dV_{pAB}}{dt} &= C_f \frac{dV_{pAB}}{dt} - C_f \frac{dV_{pBC}}{dt} + (i_A - i_B) \\
    i_{AB} + \left( C_f \frac{dV_{pCA}}{dt} + C_f \frac{dV_{pBC}}{dt} \right) &= 2C_f \frac{dV_{pAB}}{dt} + (i_{AB} - i_{CA} - (i_{BC} - i_{AB})) \\
    i_{iAB} - C_f \frac{dV_{pAB}}{dt} &= 2C_f \frac{dV_{pAB}}{dt} + (2i_{AB} - i_{CA} - i_{BC}) \\
    i_{iAB} &= 3C_f \frac{dV_{pAB}}{dt} + \left( \frac{N_s}{N_p} \right)(2i_{sa} - i_{sb} - i_{sc})
\end{align*} \]

\[ \begin{align*}
    \therefore \frac{dV_{pAB}}{dt} &= \left( \frac{1}{3C_f} \right) i_{iAB} - \left( \frac{1}{3C_f} \right) \left( \frac{N_s}{N_p} \right)(2i_{sa} - i_{sb} - i_{sc}) \\
    \therefore \frac{dV_{pBC}}{dt} &= \left( \frac{1}{3C_f} \right) i_{iBC} - \left( \frac{1}{3C_f} \right) \left( \frac{N_s}{N_p} \right)(-i_{sa} + 2i_{sb} - i_{sc}) \\
    \therefore \frac{dV_{pCA}}{dt} &= \left( \frac{1}{3C_f} \right) i_{iCA} - \left( \frac{1}{3C_f} \right) \left( \frac{N_s}{N_p} \right)(-i_{sa} - i_{sb} + 2i_{sc})
\end{align*} \]

In matrix form:

\[ \frac{dV_p}{dt} = \left( \frac{1}{3C_f} \right) i_t - \left( \frac{1}{3C_f} \right) \left( \frac{N_s}{N_p} \right) T_i V_s, \quad (2.1) \]

where, \( T_i = \left( \frac{N_s}{N_p} \right) \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \) and, \( V_s = \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} = \left( \frac{N_s}{N_p} \right) \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} V_{pAB} \\ V_{pBC} \\ V_{pCA} \end{bmatrix} = T_s V_p \)
The L-C filter voltages can now be written as follows,

\[
\begin{align*}
L_f \frac{di_A}{dt} - L_f \frac{di_B}{dt} &= V_{lAB} - V_{pAB} \\
L_f \frac{di_B}{dt} - L_f \frac{di_C}{dt} &= V_{lBC} - V_{pBC} \\
L_f \frac{di_C}{dt} - L_f \frac{di_A}{dt} &= V_{lCA} - V_{pCA}
\end{align*}
\]

In matrix form, the above equation can be written as,

\[
\frac{dl_i}{dt} = \left( \frac{1}{L_f} \right) V_i - \left( \frac{1}{L_f} \right) V_p
\]  
\[(2.2)\]

We now write the load current equation as,

\[
\frac{dV_l}{dt} = \left( \frac{1}{C_L} \right) I_s - \left( \frac{1}{C_L} \right) I_L,
\]  
\[(2.3)\]

and the voltage on the secondary side of the transformer is expressed as,

\[
\frac{dl_s}{dt} = -\left( \frac{R_T}{L_T} \right) I_s - \left( \frac{1}{L_T} \right) T_s V_p - \left( \frac{1}{L_T} \right) V_L
\]  
\[(2.4)\]

Collectively, the four state-space equations can be re-written as follows,

\[
\begin{align*}
\frac{d\bar{V}_{inv}^{abc}}{dt} &= \frac{1}{\left(3, C_{\text{inv}}\right)} \bar{I}_{inv}^{abc} - \frac{1}{\left(3, C_{\text{inv}}\right)} Tr_i. \bar{I}_{snd}^{abc} \\
\frac{d\bar{I}_{inv}^{abc}}{dt} &= \frac{1}{L_{\text{inv}}} \bar{V}_{PWM}^{abc} - \frac{1}{L_{\text{inv}}} \bar{V}_{inv}^{abc} \\
\frac{d\bar{V}_{load}^{abc}}{dt} &= \frac{1}{C_{\text{load}}} \bar{I}_{snd}^{abc} - \frac{1}{C_{\text{load}}} \bar{I}_{load}^{abc} \\
\frac{d\bar{I}_{snd}^{abc}}{dt} &= -\frac{R_{\text{trans}}}{L_{\text{trans}}} \bar{I}_{snd}^{abc} + \frac{1}{L_{\text{trans}}} Tr_v. \bar{V}_{inv}^{abc} - \frac{1}{L_{\text{trans}}} \bar{V}_{load}^{abc}
\end{align*}
\]  
\[(2.5)\]
And we can define the state variables and respective vectors as follows:

$$\text{States} = \begin{bmatrix} \vec{V}_{inv_{abc}} \\ \vec{I}_{inv_{abc}} \\ \vec{V}_{load_{abc}} \\ \vec{I}_{snd_{abc}} \end{bmatrix} = \begin{bmatrix} V_p \\ I_i \\ V_L \\ I_S \end{bmatrix} ;$$

Control Input = $\vec{V}_{pwm_{abc}} = V_i$;

Disturbance = $\vec{I}_{load_{abc}} = I_L$

Tri and Trv denote the current and voltage transformations of a delta-wye transformer

$$Tri = t_r \cdot \begin{bmatrix} 1 & -2 & 1 \\ 1 & 1 & -2 \\ -2 & 1 & 1 \end{bmatrix} ; \ Trv = t_r \cdot \begin{bmatrix} 0 & 0 & -1 \\ -1 & 0 & 0 \\ 0 & -1 & 0 \end{bmatrix}$$

t_r \rightarrow \text{turns ratio of the transformer}

If we now transform the familiar ABC frame of reference to DQ frame of reference using the transformation presented by Krause et al.$^1$,

$$\vec{f}_{qdo} = K_s \cdot \vec{f}_{abc}$$

$$K_s = \begin{bmatrix} 1 & -0.5 & -0.5 \\ 0 & \frac{-\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \\ 0.5 & 0.5 & 0.5 \end{bmatrix}$$

the power converter system modeled in DQ frame of reference is given by

\[
\begin{align*}
\frac{d\vec{V}_\text{inv} \quad qd}{dt} &= \frac{1}{(3. C_\text{inv})} \vec{I}_\text{inv} \quad qd - \frac{1}{(3. C_\text{inv})} \vec{T}_\text{rd} \quad \vec{I}_\text{snd} \quad qd \\
\frac{d\vec{I}_\text{inv} \quad qd}{dt} &= \frac{1}{L_\text{inv}} \vec{V}_\text{pwm} \quad qd - \frac{1}{L_\text{inv}} \vec{V}_\text{inv} \quad qd \\
\frac{d\vec{V}_\text{load} \quad qd}{dt} &= \frac{1}{C_\text{load}} \vec{I}_\text{snd} \quad qd - \frac{1}{C_\text{load}} \vec{I}_\text{load} \quad qd \\
\frac{d\vec{I}_\text{snd} \quad qd}{dt} &= \frac{-R_\text{trans}}{L_\text{trans}} \vec{I}_\text{snd} \quad qd + \frac{1}{L_\text{trans}} \vec{T}_\text{rd} \quad \vec{I}_\text{vd} \quad qd - \frac{1}{L_\text{trans}} \vec{V}_\text{load} \quad qd
\end{align*}
\]

(2.6)

where, \(\vec{T}_\text{rd} \quad qd = [K_s \cdot \vec{T}_s \cdot K_s^{-1}] = t_r \cdot \frac{3}{2} \begin{bmatrix} \frac{1}{\sqrt{3}} & 0 \\ \frac{\sqrt{3}}{2} & 1 \\ 0 & 0 \end{bmatrix}\)

\(\vec{T}_\text{rd} \quad qd = [K_s \cdot \vec{T}_s \cdot K_s^{-1}] = t_r \cdot \frac{3}{2} \begin{bmatrix} \frac{1}{\sqrt{3}} & 0 \\ \frac{\sqrt{3}}{2} & 1 \\ 0 & 0 \end{bmatrix}\)
2.2. Control Strategy

The control system designed in [17] utilizes a two-loop control strategy to achieve effective and fast limiting of current as shown in Figure 2.3. The two loops are:

- Inner inverter current loop
- Outer load voltage loop

The outer loop employs a controller based on a solution to the Robust Servomechanism Problem (RSP) [18] to regulate the load voltage ($\vec{V}_{load_{qd}}$) to a balanced three-phase reference voltage ($\vec{V}_{ref_{qd}}$) and generates an inverter current control command $lcmd_{qd}$.

The inner control loops employ a Discrete Sliding Mode Controller (DSMC) to generate a PWM voltage (gating signal) to regulate the inverter current ($linv_{qd}$) to $lcmd_{qd}$. Keyhani et al. in [17] have used a standard voltage-space-vector algorithm to realize the PWM gating signals. Additionally, the zero-sequence components of load voltages have not been designed to be controlled by this control design in [16] because they are found to be uncontrollable.

![Figure 2.3: Overview of Control System [17]](image)
2.2.1. Discrete Sliding Mode Controller (DSMC)

2.2.1.1. Why DSMC?

Keyhani, et al. [17], cite the following advantages of DSMC for the MG application:

- The DSMC provides a fast, critically damped response
- DSMC provides a fast current controller limiting the inverter currents under overload condition.
- DSMC use for current control as an inner loop is compatible with the perfect Robust Servomechanism (RS) control of the output voltages in the outer loop.
- The perfect RS voltage control case here has been designed to account for the extra dynamics introduced by the DSMC; and,
- The combined control approach guarantees the stability of the entire control system.

2.2.1.2. DSMC-based Current Control

The power converter system can be represented as a continuous Linear Time Invariant (LTI) system as follows:

\[
\dot{x}(t) = Ax(t) + Bu(t) + Ed(t)
\]

\[
y(t) = Cx(t)
\]

\[
e(t) = y(t) - y_{ref}(t)
\]

Where

States: \(x(t) = \begin{bmatrix} V_{inv_qd} \\ I_{inv_qd} \end{bmatrix}\)

\[
A = \begin{bmatrix}
0_{2\times2} & (3. C_{inv})^{-1} T_{ri_qd0} \\
-(L_{inv})^{-1} I_{2\times2} & 0_{2\times2}
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
0_{2\times2} \\
(L_{inv})^{-1} I_{2\times2}
\end{bmatrix}
\]
\[ E = \begin{bmatrix} -(3, C_{inv})^{-1}T \delta_{q0} \\ 0_{2 \times 3} \end{bmatrix} \]

Input = \( u(t) = \bar{V}pwm_{qd} \), and disturbance = \( d(t) = \bar{I}sn_{qd} \)

When discretized with sampling time \( T_s \),

\[
x(k + 1) = A^*x(k) + B^*u(k) + E^*d(k)
\]

\[
y(k) = Cx(k)
\]

\[
e(k) = y(k) - y_{ref}(k)
\]

Where

\[
A^* = e^{A^T_s}B^* = \int_0^{T_s} e^{A^T_s}Bd\tau, E^* = \int_0^{T_s} e^{A^T_s}Ed\tau
\]

To pursue the DSMC control design we define the following:

Sliding Manifold:

\[
s(k) = C_1x(k) - y_{ref}(k) = C_1x(k) - lcmd_{qd},
\]

where \( C_1x(k) = linv_{qd}(k) \) such that \( s(k) = 0 \) or \( linv_{qd}(k) = lcmd_{qd} \) when sliding mode occurs. Writing,

\[
s(k + 1) = C_1A^*x(k) + C_1B^*u(k) + C_1E^*d(k)
\]

the equivalent control input for the DSMC is given by,

\[
u_{eq}(k) = (C_1B^*)^{-1}(-C_1A^*x(k) - C_1E^*d(k) + lcmd_{qd})
\]

The computational delay experienced by the Digital Signal Processor (DSP) causes undesirable overshoots. In order to compensate for this delay, a first order, one-half step ahead predicted values are used. They are given as:

\[
x^p(k) = 1.5x(k) - 0.5x(k - 1)
\]

\[
d^p(k) = 1.5d(k) - 0.5d(k - 1)
\]
\[
\therefore \mathbf{u}_{eq}(k) = (\mathbf{C} \mathbf{B}^\top)^{-1}(-\mathbf{C} \mathbf{A}^\top \mathbf{x}^p(k) - \mathbf{C} \mathbf{E}^\top \mathbf{d}^p(k) + \mathbf{l}_{cmd_{qd}})
\] (2.7)

Thus, the DSMC produces a control input i.e. \(\mathbf{u}_{eq}(k)\) which utilizes \(l_{cmd_{qd}}\) to regulate \(l_{inv_{qd}}\) to \(l_{cmd_{qd}}\). \(l_{inv_{qd}}(k) = l_{cmd_{qd}}\) when sliding mode occurs. The control input is used as a PWM gating signal for the inverter.

### 2.2.2. Robust Servomechanism Controller (RSC)

#### 2.2.2.1. Why RSC?

Keyhani, et al. [17], cite the following advantages of RSC for the MG application:

- RSC is adopted for voltage control due to its capability to perform with zero steady state tracking error under unknown load and also because, it eliminates harmonics of any specified frequencies with guaranteed system stability;
- The theory behind the RSC is based on the solution of Robust Servomechanism Problem (RSP) [18] which combines the internal model principle [19] and optimal control theory for linear systems;
- The internal model principle states that “asymptotic tracking of controlled variables towards the corresponding references in the presence of disturbances (zero steady-state tracking error) can be achieved if the models that generate these references and disturbances are included in the stable closed loop systems”[19];
- In short, if the frequency modes of the references and the disturbances to be eliminated are included in the control loop, then the steady-state error will not contain these frequency modes.
2.2.2.2. RSC-based Voltage Control

We can now write the state equation as:

\[ \dot{x}_p(t) = A_p \ddot{x}_p(t) + B_p \dddot{u}(t - 0.5T_{PWM}) \]

Where an input delay of 0.5\( T_{PWM} \) is included to account for the computational delay of DSP

And, states: \( x_p = \begin{bmatrix} V_{inv_{q_d}} \\ l_{inv_{q_d}} \\ V_{load_{q_d}} \\ l_{sn_{q_d}} \end{bmatrix} \)

\[
A_p = \begin{bmatrix}
0_{2 \times 2} & (3, C_{inv})^{-1} I_{2 \times 2} & 0_{2 \times 2} & -(3, C_{inv})^{-1} T_{ri_{qd}} \\
-(L_{inv})^{-1} I_{2 \times 2} & 0_{2 \times 2} & 0_{2 \times 2} & 0_{2 \times 2} \\
0_{2 \times 2} & 0_{2 \times 2} & 0_{2 \times 2} & (C_{load})^{-1} I_{2 \times 2} \\
(L_{inv})^{-1} I_{2 \times 2} & 0_{2 \times 2} & 0_{2 \times 2} & -R_{trans}(L_{trans})^{-1} I_{2 \times 2} \\
\end{bmatrix}
\]

\[
B_p = \begin{bmatrix}
0_{2 \times 2} \\
(L_{inv})^{-1} I_{2 \times 2} \\
0_{2 \times 2} \\
0_{2 \times 2} \\
\end{bmatrix},
T_{ri_{qd}} = t_r \frac{3}{2} \begin{bmatrix} 1 & \sqrt{3} \\ -\sqrt{3} & 1 \end{bmatrix}, T_{rv_{qd}} = t_r \frac{1}{2} \begin{bmatrix} 1 & -\sqrt{3} \\ \sqrt{3} & 1 \end{bmatrix}
\]

The discretized system \((T_s = T_{PWM})\) is:

\[ \ddot{x}_p(k + 1) = \phi \ddot{x}_p(k) + \gamma_1 \dddot{u}(k - 1) + \gamma_2 \dddot{u}(k) \]

\[ \phi = e^{A_p T_s}, \quad \gamma_1 = \int_{0.5 T_s}^{T_s} e^{A_p \tau} B_p d\tau, \quad \gamma_2 = \int_{0}^{0.5 T_s} e^{A_p \tau} B_p d\tau \]

And the state-space equation in discrete-time is:

\[
\begin{bmatrix} \ddot{x}_p(k + 1) \\ \ddot{x}_a(k + 1) \end{bmatrix} = \begin{bmatrix} \phi & \gamma_1 \\ 0_{2 \times 2} & 0_{2 \times 2} \end{bmatrix} \begin{bmatrix} \ddot{x}_p(k) \\ \ddot{x}_a(k) \end{bmatrix} + \begin{bmatrix} \gamma_2 \\ 0_{2 \times 2} \end{bmatrix} \dddot{u}(k)
\]

Where \( \ddot{x}_p(k) = \dddot{u}(k - 1) = \ddot{V}_{PWM}(k - 1) \)
which in matrix form is written as,

\[ \ddot{x}_p^* (k + 1) = A_p^* x_p^* (k) + B_p^* \bar{u}(k) \]  
(2.8)

Now, the Equivalent Plant = True Plant + DSMC

\[ \ddot{x}_p^* (k + 1) = A_p^* x_p^* (k) + B_p^* \bar{u}_1(k) \]  
(2.9)

Where \( \bar{u}_1(k) = lcmd_{qd}^*(k) \),

\[ A_d = A_p^* - B_p^* (C_1 B_1^*)^{-1} (B_1^* C_{11} + E_1^* C_{12}) \],

\[ B_d = B_p^* (C_1 B_1^*)^{-1} \]

\[ C_{11} = \begin{bmatrix} I_{2 \times 2} & 0_{2 \times 2} & 0_{2 \times 2} & 0_{2 \times 2} & 0_{2 \times 2} \\ 0_{2 \times 2} & I_{2 \times 2} & 0_{2 \times 2} & 0_{2 \times 2} & 0_{2 \times 2} \end{bmatrix}, \text{ and} \]

\[ C_{12} = \begin{bmatrix} 0_{2 \times 2} & 0_{2 \times 2} & 0_{2 \times 2} & I_{2 \times 2} & 0_{2 \times 2} \end{bmatrix} \]

Then we can write the servo-compensator as,

\[ \ddot{\eta} = A_c \ddot{\bar{\eta}} + B_c \ddot{\bar{e}}_{vqd} \]

Where, \( \bar{e}_{vqd} = \bar{V} ref_{qd} - \bar{V} load_{qd} \)

\[ \ddot{\bar{\eta}} = [\ddot{\eta}_1, \ddot{\eta}_2, ..., \ddot{\eta}_n]^T \]

\[ A_c = \text{block diag} [A_{c1}, A_{c2}, ..., A_{cn}] \]

\[ B_c = [B_{c1}, B_{c2}, ..., B_{cn}] \]

\[ A_{ci} = \begin{bmatrix} 0_{2 \times 2} & I_{2 \times 2} \\ -\omega_i^2 I_{2 \times 2} & 0_{2 \times 2} \end{bmatrix}, \text{ ... } i = 1, 2, ..., n \]

\[ B_{ci} = [0_{2 \times 2} & I_{2 \times 2}]^T \]

The discretized servo-compensator is:

\[ \ddot{\eta}(k + 1) = A_c^* \ddot{\bar{\eta}}(k) + B_c^* \ddot{\bar{e}}_{vqd}(k) \]  
(2.10)

Where \( \ddot{\bar{e}}_{vqd}(k) = \bar{V} ref_{qd}(k) - \bar{V} load_{qd}(k) \)

\[ A_c^* = e^{A_c \bar{\tau}}, \quad B_c^* = \int_0^{T_s} e^{A_c(\bar{\tau}_s - \tau)} B_c \, d\tau \]
We now complete the control development by solving the discrete LQR problem, determining
input gains for the stabilizing controller and the servo-compensator. Writing,

Input to Perfect Robust Servomechanism Controller:

\[
\ddot{u}_1(k) = \ddot{I}cmd_{q_d}^*(k) = k_0 x_p^*(k) + k_1 \eta(k)
\]

Where, \(k_0 x_p^*(k) \rightarrow \text{stabilizing compensator}\)

\(k_1 \eta(k) = \text{servo - compensator}\)

And \(k = [k_0 \quad k_1]\) is found by minimizing the discrete performance index given by:

\[
J_e = \sum_{k=0}^{\infty} (z(k)'z(k) + \epsilon . u(k)'u(k))
\]

Where \(z = \begin{bmatrix} x_p^* \\ \eta \end{bmatrix} \)

{The gain \(k = [k_0 \quad k_1]\) is found using the Matlab command \textit{dlqr}}

The equivalent plant with servo-compensator is now given by:

\[
\begin{bmatrix}
\dot{x}_p(k + 1) \\
\eta(k + 1)
\end{bmatrix} =
\begin{bmatrix}
A_d & 0 \\
B_d C & A_c^*
\end{bmatrix}
\begin{bmatrix}
x_p^*(k) \\
\eta(k)
\end{bmatrix} +
\begin{bmatrix}
-B_d \\
-B_c^* D
\end{bmatrix}
\ddot{u}_1(k)
\]

To complete the development, Keyhani et al. [17] introduce both a current limit and saturation as,

\[
\ddot{I}cmd_{q_d}^*(k) = \begin{cases} 
\ddot{I}cmd_{q_d}^*(k), & \text{if } |\ddot{I}cmd_{q_d}^*(k)| \leq I_{\text{max}} \\
\ddot{I}cmd_{q_d}^*(k), & \text{if } |\ddot{I}cmd_{q_d}^*(k)| > I_{\text{max}}
\end{cases}
\]
When $|\tilde{I}_{cmd_q}^*(k)| > I_{max}$, the servo-compensator states will grow in magnitude due to the “break” in the control loop, an effect similar to the integrator wind-up problem in an integral-type controller. In order to compensate for this, we now define,

$$\dot{\eta}(k + 1) = A_c^*\tilde{\eta}(k) + B_c^*\tilde{e}_1(k)$$  \hspace{1cm} (2.12)

Where $\tilde{e}_1(k) = \begin{cases} \dot{e}_{vqd}(k), & \text{if } |\tilde{I}_{cmd_q}^*(k)| \leq I_{max} \\ 0, & \text{if } |\tilde{I}_{cmd_q}^*(k)| > I_{max} \end{cases}$

<table>
<thead>
<tr>
<th>Table 1: Important Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Equation</strong></td>
</tr>
</tbody>
</table>
| \[
\frac{d\tilde{V}_{inv_{qd}}}{dt} = \frac{1}{(3.C_{inv})}\tilde{I}_{inv_{qd}} - \frac{1}{(3.C_{inv})}Tr_{iqd}.\tilde{I}_{snqd}
\] | State-space equations for the power converter system (DQ reference frame) |
| \[
\frac{d\tilde{I}_{inv_{qd}}}{dt} = \frac{1}{L_{inv}}\tilde{V}_{pwm_{qd}} - \frac{1}{L_{inv}}\tilde{V}_{inv_{qd}}
\] | |
| \[
\frac{d\tilde{V}_{load_{qd}}}{dt} = \frac{1}{c_{load}}\tilde{I}_{snqd} - \frac{1}{c_{load}}\tilde{I}_{load_{qd}}
\] | |
| \[
\frac{d\tilde{I}_{snqd}}{dt} = \frac{-R_{trans}}{L_{trans}}\tilde{I}_{snqd} + \frac{1}{L_{trans}}Tr_{iqd}.\tilde{V}_{inv_{qd}} - \frac{1}{L_{trans}}\tilde{V}_{load_{qd}}
\] | |
| \[
\tilde{u}_{eq}(k) = (C_1B^*)^{-1}(-C_1A^*x^P(k) - C_1E^*d^P(k) + I_{cmd_{qd}})
\] | Control input generated by DSMC |
| \[
\begin{bmatrix} \tilde{x}_p^*(k + 1) \\ \tilde{\eta}(k + 1) \end{bmatrix} = \begin{bmatrix} A_d & 0 \\ B_c^*C & A_c^* \end{bmatrix}\begin{bmatrix} \tilde{x}_p^*(k) \\ \tilde{\eta}(k) \end{bmatrix} + \begin{bmatrix} B_d \\ -B_c^*D \end{bmatrix}\tilde{u}_1(k)
\] | State-space equations for RSC |
CHAPTER 3
STOCHASTIC MODELING OF ENERGY SOURCES AND
STRUCTURE OF SIMULATION TEST-BED

3.1. Solar PV Panel Model Validation

The stochastic modeling of the solar PV panel was accomplished using the Simscape toolbox within Simulink®. Simulink® (ver R2013b) has a built-in solar cell block which is modeled as a current source. Figure 3.1 (a) shows the solar cell block within Simulink and (b) shows its equivalent circuit diagram.

![Figure 3.1: (a) Solar cell block, and (b) Solar cell equivalent circuit diagram in Simulink®](image)

[20]
The equations governing the solar cell block within Simulink® are obtained from [20] and are given as follows:

The output current $I$ is:

$$I = I_{ph} - I_s \ast \left( e^{\frac{V + I * R_s}{N \cdot V_t} - 1} \right) - I_{s2} \ast \left( e^{\frac{V + I * R_s}{N_2 \cdot V_t} - 1} \right) - \frac{V + I * R_s}{R_p}$$

(3.1)

where:

$I_{ph}$ is the solar-induced current:

$$I_{ph} = I_{ph0} \ast \left( \frac{I_r}{I_{r0}} \right)$$

(3.2)

and:

$I_r$ is the irradiance (light intensity) in W/m$^2$ falling on the cell.

$I_{ph0}$ is the measured solar-generated current for the irradiance $I_{r0}$.

$I_s$ is the saturation current of diode, D1.

$I_{s2}$ is the saturation current of diode, D2.

$V_t$ is the thermal voltage, $kT/q$, where:

- $k$ is the Boltzmann’s constant.
- $T$ is the device simulation temperature.
- $q$ is the elementary charge on an electron.

$N$ and $N_2$ are the quality factors (diode emission coefficient) of diodes, D1 and D2 respectively.

$R_p$ and $R_s$ are the parallel and series resistances respectively.

$V$ is the voltage across the solar cell electrical ports.

The quality factor varies for amorphous solar cells, and is $\approx 2$ for polycrystalline cells. The Simulink default value for $N$ is 1.5 for a single diode model.
The solar cell block was used to build a 60-cell panel. The electrical data for the panel, provided in Table 2, were obtained from the TSM PA05\(^2\) panel specifications. Figure 3.2 illustrates the model configuration for the 60-cell solar panel used to validate the simulated data against the expected field-data, as detailed in the manufacturer’s specifications.

**Figure 3.2: Solar Panel Model Connection Topology**

A 5-parameter based solar cell model was chosen in Simulink\(^{®}\). The cell configuration was set to be 60 cells in series in order to mimic the output of an actual 60-cell solar panel. The cell temperature dependence was set to the default values of 0 \(K^{-1}\) specified by Simulink\(^{®}\). The cell temperature (\(T_{cell}\)) and the measurement temperature (\(T_{mes}\)) were chosen to be variables in order to facilitate flexible testing.

Table 2: Electrical data for TSM PC05 230 W (60 cell) module

<table>
<thead>
<tr>
<th>Electrical Data at STC*</th>
<th>TSM – 230 (PC/PA05)²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Power Watts – Pₘₐₓ (W)</td>
<td>230</td>
</tr>
<tr>
<td>Pₘₐₓ Tolerance (%)</td>
<td>0/+3</td>
</tr>
<tr>
<td>Maximum Power Voltage – Vₘₐₓ (V)</td>
<td>29.2</td>
</tr>
<tr>
<td>Maximum Power Current – Iₘₐₓ (A)</td>
<td>7.90</td>
</tr>
<tr>
<td>Open Circuit Voltage – Vₒc (V)</td>
<td>37.1</td>
</tr>
<tr>
<td>Short Circuit Current – Iₛₑ (A)</td>
<td>8.53</td>
</tr>
<tr>
<td>Module Efficiency - ηₘ (%)</td>
<td>14.1</td>
</tr>
<tr>
<td>Series Resistance – Rₛ (mΩ)</td>
<td>10</td>
</tr>
<tr>
<td>Quality Factor – N</td>
<td>1.5</td>
</tr>
</tbody>
</table>

*STC – Standard Test Conditions (Air Mass - 1.5, Irradiance – 1000 W/m², Cell Temperature – 25°C)

The electrical data, shown in Table 2, was used to parameterize the solar cell model and the irradiance values were varied from 600 W/m² to 1000 W/m². The corresponding I-V curves were plotted as shown in Figure 3.3.

![I-V Curves for PV Solar Panel Model](image)

Figure 3.3: I-V Curves for PV Solar Panel Model
The I-V characteristics exhibit the expected solar PV cell behavior. A comparison of the solar panel model and the TSM PC05 230 W (60 cell) module performance metrics is provided in Table 3 below.

**Table 3: Electrical data verification at NOCT**

<table>
<thead>
<tr>
<th>Electrical Data at NOCT</th>
<th>TSM–230 (PC/PA05) – Specifications²</th>
<th>Simulation Data (Simulink Model)</th>
<th>Percent Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Power Watts – Pₘₐₓ (W)</td>
<td>167</td>
<td>170.11</td>
<td>1.83</td>
</tr>
<tr>
<td>Max Power Voltage – Vₘₐₓ (V)</td>
<td>26.30</td>
<td>27.32</td>
<td>3.73</td>
</tr>
<tr>
<td>Max Power Current – Iₘₐₓ (A)</td>
<td>6.35</td>
<td>6.22</td>
<td>-2.09</td>
</tr>
<tr>
<td>Open Circuit Voltage – Vₒc (V)</td>
<td>33.9</td>
<td>33.1</td>
<td>-2.42</td>
</tr>
<tr>
<td>Short Circuit Current – Iₛₑ (A)</td>
<td>6.95</td>
<td>6.82</td>
<td>-1.91</td>
</tr>
</tbody>
</table>

**NOCT - Normal Operating Cell Temperature (Irradiance - 800W/m², Ambient Temperature - 20°C, Wind Speed - 1m/s)**

NOCT refers to the Normal Operating Cell Temperature condition for a solar panel. It generally gives an accurate account of what a solar panel is expected to produce at NOCT conditions i.e. Irradiance - 800W/m², Ambient Temperature - 20°C, Wind Speed - 1m/s. The expected NOCT output values were obtained from the manufacturer’s specifications and have been documented in column two (TSM – 230 (PC/PA05) – Specifications¹) of Table 3. The third column i.e. Simulation Data (Simulink Model), details the actual data that was obtained by simulating the solar array block at NOCT conditions with the electrical data as per Table 2.
Simulation data demonstrates that the actual Pmax (170.11 W) is within the 3% tolerance specified for the ideal Pmax (167 W). Figure 3.4 is a graphical representation of the simulated electrical output data in the form of an I-V & P-V curve. It can be seen that all the other electrical data in column 3 of Table 3 correspond well with the ideal NOCT values in column 2. Since the actual electrical data (simulated) and the published electrical data (manufacturer’s specifications) are within the specified tolerance value of ±3%, the solar cell model is deemed satisfactory for use as a practical source model for the pursuit of a more realistic MG environment.

![Simulated I-V and P-V curves at NOCT for TSM-230 PA05](image)

**Figure 3.4: Simulated I-V and P-V curves at NOCT for TSM-230 PA05**
3.2. Utility Derived Supplemental DC Supply

It is well known that solar energy is an intermittent source of energy. Hence, there is a need to supplement the energy produced by the solar array using a suitable source. One of the most common methods is to use a battery which would store excess energy during the day and then supply that during the night or during a shortfall (example: cloudy conditions). Diesel generators (gensets) are also commonly used to compensate for the intermittency of energy produced by a solar array. The current research introduces a method of supplementing the solar PV DC output power using a controlled DC power supply obtained by rectifying the AC utility supply. A DC-DC converter based controlled voltage supply was modeled. Current advances in power electronics suggest that such a configuration is possible and possibly economic.\(^3\) The controlled voltage supply is connected in series with the solar PV voltage output such that it supplements the solar PV output whenever required.

3.2.1. DC-DC Converter-based Controlled Voltage Supply Model

A single phase 120V, 60 Hz AC supply was considered to be available from the utility as shown in Figure 3.5. A linear transformer (120V/30V, 250 VA) was connected to the utility. The output of the transformer was rectified by diode-based bridge rectifier to obtain pulsed DC across the capacitor. The pulsed DC voltage was then input into a DC-DC converter block via a current-voltage Simscape\(^\circledR\) interface. The DC-DC converter block has an output reference parameter that can be set to the required constant output voltage value. The load is connected to the model through a switch which is closed only after 0.1 ms of circuit operation. This is done to prevent very high current from flowing through the circuit when started.

\(^3\) Personal communication with Dr. Jinhui Zhang, Adjunct Professor – Power Electronics, The University of Dayton
Figure 3.5: Utility derived DC-DC converter based controlled voltage supply model

Figure 3.6 shows the constant output voltage produced by the model. The DC-DC converter sees a pulsed DC input and processes it to produce a constant DC voltage of required value. The output reference of the converter can be changed to any value within the power supply range on the input side.

Figure 3.6: Controlled voltage output (40 V here) from DC-DC Converter
Unfortunately, the DC-DC converter obtained from the Simscape® toolbox has a limitation wherein the output reference value is not a dynamically tunable parameter and hence, cannot be changed during simulation. To overcome this limitation for the current study, an alternate DC-DC converter model based on an equivalent controlled voltage source model was utilized. The related model limitations and practical issues associated with the construction of the supplemental DC source will be addressed later.

3.2.2. Supplemental DC Voltage Supply

The supplemental DC supply, modeled simply as a controlled source, was connected in series with the PV solar model to form an augmented DC source as shown in Figure 3.7.

![Figure 3.7: Supplemental DC supply connection](image)
Figure 3.8 shows the equivalent model for the regulated DC supply which acts as a supplemental voltage to the PV solar panel output voltage. \( V_{dc}(\text{actual}) \) represents the actual voltage produced by the solar panels. \( V_{dc}(\text{ref}) \) represents the reference input value to the inverter necessary to maintain a constant 120 V AC across the output load. \( V_{dc}(\text{ref}) \) was found to be 335 V. The difference between \( V_{dc}(\text{actual}) \) and \( V_{dc}(\text{ref}) \) is used to trigger a controlled voltage source which produces an output equal to the value of triggering voltage – which in this case is the difference between the expected and the actual value i.e. supplemental voltage.

Thus, a regulated and isolated DC voltage supply was obtained from the utility and was connected in series with the PV solar output voltage to form a supplemental DC voltage source to the MG. This supplemental DC voltage source is expected to account for the intermittent nature of energy generated by the PV solar panels.
3.3. Simulation Test-bed

This section describes the overall simulation test-bed representing the microgrid (MG) control system presented earlier as well as the MG model. Figure 3.9 provides the overall schematic of the simulation test-bed. The supplemental DC source block consists of an AC utility followed by a rectifier and an isolated DC-DC converter. The MG structure comprises of a solar PV array, 3-phase PWM-based inverter, the MG control system, a delta-wye transformer and a 3-phase load. The Simulink® model uses a state-space representation of this plant including the MG load. The supplemental source is connected to the MG through a Single Pole Single Throw (SPST) switch referred to as a Point of Common Coupling (PCC).

![Diagram of the simulation test-bed](image-url)

**Figure 3.9: Overall schematic of the simulation environment**
The PCC connects and disconnects the MG from the utility. The decision to connect or disconnect the MG from the utility, essentially islanding the MG, could be based on one or more factors. Some of the factors along with the reasons are listed below:

- Disconnect when the utility supply exhibits excessive harmonic content (i.e. poor power quality)
- Disconnect during a fault condition on the utility supply
- Connect to the utility when the energy produced by local DGs is insufficient to meet the load demand
- Connect to the utility based on economic reasons

Figure 3.10 & Figure 3.11 represent the simulation structure for the voltage and current controller depicted earlier in the overall schematic. The controllers were developed in Chapter 2.

Figure 3.10: Simulation structure of voltage controller [17]
As provided earlier in Figure 3.9, the output of the voltage controller (Icmd_qd) drives the current controller and the output of the current controller (Vpwm) is used as a gating control signal to a PWM-based inverter. The gating signal controls the inverter output and thus essentially maintains the rated output voltage and current.

Figure 3.11: Simulation structure of current controller [17]
CHAPTER 4
SIMULATION RESULTS

4.1. Examination of Control System Efficacy

The examination of the efficacy of the control system with an ideal source model is presented in this section. The results evaluate issues of power quality and transient stability for typical operating scenarios. The system examination is carried out on load-based cases. The load-based cases presented here are as follows:

- Full Load or Rated Load (100%)
- No Load (0%)
- Overload (500%)
- Transient Control
  - 100 to 0 and 0 to 100 % load
  - 100% to Short Circuit (SC) load and vice-versa
- **Full Load or Rated Load (100%)**

The isolated grid model was setup at full load and the following parameters were measured:

- Load Current (I\text{load})
- Load Voltage (V\text{load})
- Inverter Voltage (V\text{inv})

![Graph showing I\text{load}, V\text{load}, and V\text{inv} at Full Load - Isolated System with Ideal Source](image)

**Figure 4.1: \text{I}\text{load}, \text{V}\text{load}, and \text{V}\text{inv} at Full Load - Isolated System with Ideal Source**

As can be seen from Figure 4.1, the power system designed performs satisfactorily supplying 3-phase power to a 3-phase load by utilizing a DC power supply from an ideal source. This result verifies that the power system is capable of supplying adequate power to the load.
• No Load (0%)

When there is no load, or an open-circuit condition, on the system, the control system performs satisfactorily, as seen in Figure 4.2. As expected, there is no (negligible) load current. It can also be seen that the load and inverter voltage (Vload and Vinv) are maintained at the expected magnitude and frequency.

![Graph showing Iload, Vload, and Vinv at No Load](image)

**Figure 4.2: Iload, Vload, and Vinv at No Load - Isolated System with Ideal Source**
• **Overload (500%)**

During an overload condition, the load tends to draw a large amount of power from the grid or the MG source. In order to prevent this, the current control system includes an over-current limit. This limiter block, limits any load current over a pre-specified limit, selected to protect critical system hardware. In this case, the limit is set to be three times the rated full-load current. As can be seen from Figure 4.3, the current limiter performs satisfactorily by limiting I_{load} to a maximum of three times (300%) its full load value (100%) even though the load is 5 times its full load value.

**Figure 4.3:** I_{load}, V_{load}, and V_{inv} at Overload (500%) - Isolated System with Ideal Source
• Transient Control

○ 100 to 0 and 0 to 100 % load

Figure 4.4 shows the transition of the isolated grid from full load (100%) to no load (0%) and back to full load. It can be seen that the control system maintains a constant voltage and current profile when the power system experiences a prescribed change in the load conditions i.e. full load or no load.

Figure 4.4: Normal View of Iload, Vload, and Vinv for 100% to 0% and vice versa - Isolated Grid with Ideal Source
Figure 4.5: Detailed view of Iload, Vload, and Vinv for 100% to 0% transition - Isolated Grid with Ideal Source

Figure 4.5 & Figure 4.6 show the detailed views of the parameters Iload, Vload, and Vinv, during the moment of transition from 100% to 0% and 0% to 100% respectively.

Figure 4.6: Detailed view of Iload, Vload, and Vinv for 0% to 100% transition - Isolated Grid with Ideal Source
In Figure 4.5, when the load transitions from 100% to 0%, it is seen that \( I_{\text{load}} \) falls to zero immediately as expected. On the other hand, \( V_{\text{load}} \) and \( V_{\text{inv}} \) exhibit perturbations from their regular, sinusoidal form. It is worth noting that the control system restores the system to its normal operating state within one cycle of operation, indicating that the transient effects are sufficiently and quickly damped. In Figure 4.6, when the load transitions from 0% to 100%, the transient deviations observed in \( V_{\text{load}} \) and \( V_{\text{inv}} \) are very negligible as compared to when the load transitions from 100% to 0%. As a result, the control system restores system to steady state more quickly as compared to Figure 4.5.

- **100% to Short Circuit (SC) load and vice-versa**

  The transition of the system from full load to a short circuit condition is examined in detail here. The expected results reveal the robustness of the system even under short-circuited load conditions. Figure 4.7 shows the overall view of \( I_{\text{load}} \), \( V_{\text{load}} \), and \( V_{\text{inv}} \) when the short circuit occurs close to 1.5 sec into the simulation. \( I_{\text{load}} \) experiences a very large spike in its value at this moment as expected. This can be seen much more clearly in Figure 4.8 where \( I_{\text{load}} \) is shown in isolation. It can be seen from Figure 4.7 that the control system maintains a stable voltage profile before, during, and after the short circuit.

![Graph showing Iload, Vload, and Vinv for different scenarios](image)

**Figure 4.7:** Normal View of \( I_{\text{load}} \), \( V_{\text{load}} \), and \( V_{\text{inv}} \) for 100% to short circuit load and vice versa - Isolated Grid with Ideal Source
Figure 4.8: Spike in Iload when short circuit occurs

So how does the control system deal with this sudden short circuit in the load and how does it control $V_{\text{inv}}$, $V_{\text{load}}$, and $I_{\text{inv}}$? Figure 4.9 shows that $I_{\text{inv}}$ (inverter current) is maintained close 1500 A during short circuit which is 3 times its value at full load (approximately 500 A). Additionally, note the absence of harmful current spikes or surges in all three phases of the inverter. The results illustrate that the control system effectively controls the maximum current during short-circuit conditions and transitions well from full load to short circuit load; thus preventing potential damage to the power electronic components as well as maintaining the overall reliability of the isolated MG.

Figure 4.9: Detailed view of $I_{\text{inv}}$ during the moment of short circuit – Note the absence of large current spikes in all three inverter phases
4.2. Examination of Control System Efficacy for an Improved MG Model

The examination of the control system efficacy during load transients for a MG with a stochastically modeled energy source is now examined. The improved MG model, with a stochastically modeled solar PV array, is simulated to validate system operation during transient load conditions. The solar PV model is subject to actual TMY3 hourly irradiance data for the city of Dayton, OH. The maintenance of power quality during the change in load from full load to no load and vice-versa in conjunction with a change in solar PV voltage (due to change in irradiance) is presented here.

Solar PV Results

Figure 4.10 shows the TMY3 hourly irradiance data for Dayton, OH during the months of January and July. TMY3 is an industry standard used by solar energy professionals to size solar arrays all over the world. January and July data have been considered because they typically receive the least and most irradiance respectively in a calendar year.

![TMY3 Hourly Irradiance Data – Dayton, OH](image)

Figure 4.10: TMY3 hourly horizontal irradiance data for Dayton, OH
The hourly horizontal irradiance value has been used as an input into the solar array model to provide a more realistic account of the actual total irradiance experienced by a solar cell.

\[
I_r(\text{horizontal}) = I_r(\text{direct}) + I_r(\text{reflected i.e. ground}) + I_r(\text{diffused}) \quad (4.1)
\]

The corresponding voltage produced for the month of July by the solar PV array modeled using TSM PC05 (230 W) solar panel electrical data and scaled as per load requirements is represented in Figure 4.11 as \(V_{dc} – \text{Solar}\). Voltage produced during every time step of simulation time is directly related to an hourly value of irradiance i.e. 24 hourly irradiance values produce 24 solar PV voltage data points. As expected, \(V_{dc} – \text{Solar}\) is zero during night hours and increases with the increase in irradiance value. It is also affected by shading and cloudy conditions. As was described in Chapter 3, a supplemental energy source is needed to compensate for the lack of power generated by the solar PV. \(V_{dc} – \text{Supplemental}\) represents the voltage produced by the supplemental voltage source developed in Chapter 3. The sum total of \(V_{dc} – \text{Supplemental}\) and \(V_{dc} – \text{Solar}\) is seen by a 3-phase PWM-based inverter. It is represented by \(V_{dc} – \text{Total}\).

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**Figure 4.11:** DC voltage produced by solar PV for July: \(V_{dc} – \text{Solar}\), supplemental DC voltage: \(V_{dc} – \text{Supplemental}\), and total DC voltage: \(V_{dc} – \text{Total}\)

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4.2.1. **Cost-based Approach to Switching to the Utility**

Based on earlier data, it is clear that the solar PV power is not enough to sustain the load throughout the day. It needs to be supplemented by energy from a storage device (example: battery bank) or a supplemental source (derived from the utility), as in this case. The supplemental source suffers loss of energy due to the process of conversion (AC-DC converter) and inversion (PWM-based inverter). This leads us to the following questions:

Until when is it economically feasible to be supplementing solar power? When should the energy supply to the MG load be switched from the solar PV array to the AC grid (utility) directly? Whilst the primary purpose for a MG structure is supply security, is there an economic benefit in managing MG operation as a quasi-autonomous system?

To answer these questions it is important to understand the following:

\[
S = (E_{\text{solar}} - E_{\text{losses}}) \times C
\]

\[
L_{\text{supp}} = (E_{\text{conv}} + E_{\text{inv}} + E_{\text{losses}}) \times C
\]  

(4.2)

Where,

- **S** – Solar Savings, in USD
- **L_{\text{supp}}** – Loss of money due to losses experienced by the supplemental source setup, in USD
- **E_{\text{solar}}** – Energy produced by solar array, in kWh
- **E_{\text{losses}}** – Energy loss due to transmission, in kWh
- **E_{\text{conv}}** – Energy loss due to conversion (AC-DC converter), in kWh ~ 5-10%
- **E_{\text{inv}}** – Energy loss due to inversion (PWM-based inverter), in kWh ~ 5-10%
- **C** – Cost to customer per kWh, in USD ~ *average 11 cents/kWh for OH*
One of the reasons to switch to the AC utility directly would be when the process of supplementing the solar power becomes a loss-making exercise. In other words if the energy savings provided by the solar power are insufficient to compensate for the losses that occur due to conversion and inversion, the MG would not be profitable for the customer. For economic reasons, it would be best to switch the load to the AC utility directly to overcome the energy processing losses experienced by the MG, assuming the utility supply has satisfactory power quality. Bad power quality (i.e. high THD and coupling between real and reactive power) could potentially damage the load appliances. In case of poor power quality, the customer may want to continue supplementing the solar power and utilize the good power quality it delivers due to the use of control systems. In conclusion, this cost-based approach supplements the solar power and maintains a constant input to the PWM-based inverter as long as the process is profitable (based on the above formulae) to the customer. This ensures the maximum use of the incident solar energy and the profitability of the MG.

To summarize:

If $S > L_{supp}$, then the customer could continue using solar power and supplement it when there is a lack of power production. It could be supplemented by the current design, a battery bank, a diesel generator, a fuel cell, among others.

If $S < L_{supp}$, then the customer may want to disconnect from solar power and switch to the AC grid directly as long as the local utility power quality is satisfactory. The solar power in turn can be stored in a battery bank, or other energy storage devices.
4.2.2. Transient Performance Assessment

The maintenance of power quality amidst changes in load and solar PV voltages is examined here. The load transition from full load to no load and vice-versa accompanied with the change in solar PV voltage is studied in detail.

Figure 4.12 shows the load current, load voltage and inverter voltages for a load transition from full load to no load. The control system restores the normal operating state of the system within one cycle. The Total Harmonic Distortion (THD) content of the output was observed to be 0.2\% or lower. The result demonstrates that the power quality is maintained even when the load transitions. Additionally, the load voltage ($V_{load}$) and load current ($I_{load}$) profile remain constant when there is a change in solar PV voltage at $t_{TMY3} = 12$ hours, demonstrating that the control system performs effectively despite a change in input solar PV voltage.

**Full Load to No Load Transition**

![Image of load transition graphs]

Figure 4.12: Power quality maintained despite load transition (100\% to 0\%) and change in solar PV voltage at $t_{TMY3} = 12$ hours
Figure 4.13 shows the transient performance of the system when the load changes from no load to full load. The transients at the moment of load transition are reduced almost immediately and the THD content continues to remain under 0.2%. Additionally, the system maintains a steady voltage and current profile even when the solar PV voltage changes, similar to Figure 4.12. This shows the efficacy of the control system which maintains the output power quality during a load transient as well as during a change in solar PV voltage.

Figure 4.13: Power quality maintained despite load transition (0% to 100%) and change in solar PV voltage at $t_{TMY3} = 14$ hours

Figure 4.14 displays the tracking performance of the control system under both transient load conditions as well as a change in solar PV voltage. It can be seen that the control system restores the tracking to its normal operating state within a cycle of the change in load from full
load to no load. Similarly, the tracking continues to perform well under a change in the input solar PV voltage at $t_{\text{TMY3}} = 12$ hours.

**Tracking during Full Load to No Load Transition**

![Tracking Diagram](image)

**Figure 4.14:** Tracking of $V_{\text{load}}$ to $V_{\text{ref}}$ under transient load

The examination of the overall efficacy of the control system under a change in load as well as a change in input solar PV voltage shows that the system is able to consistently maintain satisfactory power quality in the MG. Additionally; Equation (4.2) presents a cost-based model to connect or disconnect the MG from the utility supply. It ensures that the available solar energy is utilized to its maximum potential and also maintains profitability to the MG’s customer(s). Thus, the MG topology presented in this research facilitates real-time cost-based decision making whilst maintaining satisfactory overall power quality, provided that the supplemental DC source model is practically realizable.
CHAPTER 5
SUMMARY AND FUTURE WORK

5.1. Summary

The efficacy of a control system for power quality maintenance during transient load conditions has been examined in the current research via the use of an improved stochastic model of a MG. A simulation based MG model is developed in Matlab Simulink®. A stochastic model of a solar PV array is presented as a renewable energy source in the MG. Its output data is successfully validated against field data of solar panels as detailed in the manufacturer’s specifications. A novel supplemental DC voltage source model is also presented in the current research. It is connected in series to the solar PV array and helps to compensate for the lack of power generated by the solar PV array due to environmental factors. A Robust Servomechanism Controller in conjunction with a Discrete Sliding Mode Controller is employed to achieve voltage and current regulation in the MG. The performance of this control system as a part of the improved MG under load transients coupled with source voltage changes was found to be satisfactory. The control system managed to quickly reduce the transients generated during load changes and restored the system to a normal operating state within a cycle from the instant of change. The associated Total Harmonic Distortion content was found to be under 0.2 %. This guarantees that the power quality is maintained throughout.
Additionally, a constant voltage and current profile was maintained despite a change in the source voltage due to a change in solar PV voltage. The tracking performance was restored almost immediately after the occurrence of a load transient and it was found to be unaffected during source voltage changes. A cost-based model to connect or disconnect the MG from the utility supply whilst ensuring the maximum use of incident solar energy was also presented in this research. Therefore, the MG topology presented in this research facilitates real-time cost-based decision making whilst maintaining satisfactory overall power quality, provided that the supplemental DC source model is practically realizable. The simulated results also indicate that the system performs consistently and could be pursued as a part of a practical MG setup in future.

5.2. Future Work

- Practical MGs are expected to consist of more than one DG connected to it at the same time. Thus, the next step would be to model the MG with more than one DG. A wind turbine(s), diesel generator, and/or fuel cells, among others could be modeled and integrated into the MG. Additional energy storage models such as batter banks could also be incorporated to make the MG structure self-sustained.

- It would be extremely valuable to test the practical efficacy and feasibility of the supplemental DC source model presented in this research by building it from an AC source via the use of rectifiers and converters and then connecting its output in series to the output produced by a solar panel.

- The current research deals with a 3-phase resistive load. It would be worthwhile to model the control system for a non-linear load and study the corresponding effects.

- Study of other commercially available power systems design software such as PS-CAD, PowerFactory, or the PLECS toolbox integrable within Simulink® might help in overcoming the limitations in design and functionality faced by the current research.
[1] The Lawrence Berkeley National Laboratory, California. URL: http://der.lbl.gov/


APPENDIX

MATLAB script to

- Calculate Control Gains using RSP Voltage Controller and Discrete Sliding Mode Current Controller,
- Initialize solar PV model, and
- Initialize matrices parameters for simulations

Initial Author: Nanda Marwali [17]

Updated by: Thanigasalam Chettiyar

clear all

% Define fundamental output frequency;
ffun=60;
wfun=2*pi*ffun;
% Define control sampling time
Tsamp=1/60/51; %6536/20e6;
Cinv=540e-6; % Inverter capacitor filter
Linv=298e-6; % Inverter inductor filter
Cload=90e-6; % Grass capacitor
Ltrans=0.03*208*208/80e3/wfun; % 3% p.u transformer inductance
Rtrans=0; %0.03*208*208/80e3; % 3% p.u transformer resistance
tr=120/245; % Inverter To Output Turn ratio
Ilimit=3*80e3/245*sqrt(2); % 300% inverter current limit in Line-Line Amp peak
% Define harmonics frequencies
w1=wfun;
w2=2*wfun;
w3=3*wfun;
w5 = 5*wf
w4 = 4*wf
w7 = 7*wf
T1 = 1/ff

% Define Delta-Wye Transformer Voltages and Currents Transfer Matrices
Tri_qd = 3/2*tr*[1 sqrt(3);
-sqrt(3) 1];
Trv_qd = 1/2*tr*[1 -sqrt(3);
sqrt(3) 1];

%% Solar Panel Initialization - Thani

%% TSM-PA05
% Electrical Data at STC
% Peak Power from panel = 230 W
% Vmax = 29.2 V
% Imax = 7.90 A
Isc = 8.53;
Voc = 37.1/60;
N = 1.5; % Quality Factor (typically 1-2)
% added to account for imperfect junctions as observed in real transistors
Rs = 10e-3; % Series Resistance (ohm)
Ir = 1000; % Solar Cell irradiance base value
Tmes = 20; % Measurement temperature
Tcell = 20; % Cell temperature (Simulation temp)

%% Start design of discrete SM current controller
% Define the plant for the current controller
A = [zeros(2,2) eye(2,2)/(3*Cinv) ;
-1/Linv*eye(2) -0.01/Linv*eye(2)];
B = [zeros(2,2);
\[ I = \frac{1}{L_{inv}} \text{eye}(2); \]
\[ E = [-\frac{\text{Tri} \ qd}{3C_{inv}}; \]
\[ \text{zeros}(2,2)]; \]
\[ F = [\text{zeros}(2,2); \]
\[ -\text{eye}(2)]; \]
\[ C = [\text{zeros}(2,2) \ \text{eye}(2)]; \]
\[ D = \text{zeros}(2,2); \]

%% Discretize the plant for the current controller
sysc = ss(A, B, C, zeros(size(C,1), size(B,2)));  
syd = c2d(sysc, Tsamp, 'zoh');  
[Acurrd, Bcurrd, Ccurrd, Dcurrd] = ssdata(syd); 
CBinv = inv(Ccurrd * Bcurrd); 
CA = Ccurrd * Acurrd; 
CD = Ccurrd * F; 

%% End Discrete sliding mode controllers gains calculation

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Start design of Perfect RSP voltages controllers
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%% Define the true plant
Ao = [zeros(2,2) \text{eye}(2,2)/(3Cinv) zeros(2,2) -\text{Tri} \ qd/(3Cinv); 
-\text{eye}(2,2)/L_{inv} zeros(2,2) zeros(2,2) zeros(2,2); 
zeros(2,2) zeros(2,2) zeros(2,2) \text{eye}(2,2)/C_{load}; 
\text{Trv} \ qd/L_{trans} zeros(2,2) -\text{eye}(2,2)/L_{trans}; 
R_{trans} \text{eye}(2,2)/L_{trans}]; 
Bo = [zeros(2,2); 
\text{eye}(2,2)/L_{inv}; 
zeros(2,2); 
zeros(2,2)];
Co=[zeros(2,2) zeros(2,2) eye(2) zeros(2,2)];

%% Define the analog servo compensator
Ch0=zeros(2,2);
Ch1=[zeros(2,2) eye(2);
-w1^2*eye(2) zeros(2,2)];
Ch5=[zeros(2,2) eye(2);
-w5^2*eye(2) zeros(2,2)];
Ch7=[zeros(2,2) eye(2);
-w7^2*eye(2) zeros(2,2)];
Ch_star=[Ch1 zeros(size(Ch1)) zeros(size(Ch1)) ;
zeros(size(Ch1)) Ch5 zeros(size(Ch1)) ;
zeros(size(Ch1)) zeros(size(Ch1)) Ch7 ];
Bh_star=[zeros(2,2);
eye(2,2);
zeros(2,2);
eye(2,2);
zeros(2,2);
eye(2,2)];

% Discretize true plant
sysc=ss(Ao,Bo,Co,zeros(size(C,1),size(B,2)));
sysd=c2d(sysc,Tsamp,'zoh');
[Aod,Bod,Cd,Dd]=ssdata(sysd);

% Calculate equivalent plant + DSM current controller
C1=[eye(4) zeros(4,4)];
C2=[zeros(2,4) eye(2) zeros(2,2)];
Ad=Aod-Bod*(CBinv*CA*C1+CBinv*CE*C2);
Bd=Bod*CBinv;

% Discretize the controller
csysc=ss(Ch_star,Bh_star,eye(size(Ch_star,1)),zeros(size(Ch_star,1),size(Bh_star,2)));
[csysbc,T]=ssbal(csysc);
csysd=c2d(csylbc,Tsamp, 'zoh');
[Aon_d,Bcon_d,Ccon_d,Dcon_d]=ssdata(csylsd);

% Form the augmented equivalent plant and the servocompensator
Ad_big=[Ad zeros(size(Ad,1),size(Aon_d,2));
-Bcon_d*Cd Aon_d];
Bd_big=[Bd ; -Bcon_d*Dd];

% Define the weighting matrices
epsilon=1e-5;
Q2=eye(size(Aon_d,1));
state_W=0.2; % 80 kVA
Q1=state_W*eye(size(Ad,1));
Q=[ Q1 zeros(size(Ad,1),size(Aon_d,2));
zeros(size(Aon_d,1),size(Ad,2)) 5e5*Q2];
R=epsilon*eye(2);

% Now perform the optimal calculations of the gains
[Kd,S,E]=dlqr(Ad_big,Bd_big,Q,R);
Kd=-Kd;

% Create matrices parameters for the plant states equations
Rfl=208*208/(80e3*0.8);
Rtrans=0.03*208*208/80e3;
Tri=[1 -2 1;
1 1 -2;
-2 1 1];
Trv=[0 0 -1;
-1 0 0;
0 -1 0];
Tri_qd0=3/2*tr*[1 sqrt(3) 0;
-sqrt(3) 1 0];
Trv_qd0=1/2*tr*[1 -sqrt(3);
   sqrt(3) 1 ;
   0 0];
Ks=2/3*[cos(0) cos(0-2*pi/3) cos(0+2*pi/3);
    sin(0) sin(0-2*pi/3) sin(0+2*pi/3);
    1 1 1 ];
Ksinv=inv(Ks) ;

% Define the B and D matrices
Bsim=[zeros(2,2);
     eye(2,2)/Linv;
     zeros(3,2);
     zeros(3,2)];
Dsim=zeros(13,2);

% Full load
Rload33=[ Rfl 0 0;
    0 Rfl 0;
    0 0 Rfl];
Afl=[ zeros(2,2) eye(2,2)/(3*Cinv) zeros(2,3) -Tri_qd0/(3*Cinv);
     -eye(2,2)/Linv zeros(2,2) zeros(2,3) zeros(2,3);
     zeros(3,2) zeros(3,2) -Ks*inv(Rload33)*Ksinv/Cload
     eye(3,3)/Cload; Trv_qd0/Ltrans zeros(3,2)
     -eye(3,3)/Ltrans -Rtrans*eye(3,3)/Ltrans];
Cfl=[ [eye(10)];
     [zeros(3,4) Ks*inv(Rload33)*Ksinv zeros(3,3)]];  

% No load
Rload33=[ 100 0 0;
    0 100 0;
    0 0 100];
Anl=[ zeros(2,2) eye(2,2)/(3*Cinv) zeros(2,3) -Tri_qd0/(3*Cinv);
     -eye(2,2)/Linv zeros(2,2) zeros(2,3) zeros(2,3);
     zeros(3,2) zeros(3,2) -Ks*inv(Rload33)*Ksinv/Cload
     eye(3,3)/Cload; Trv_qd0/Ltrans zeros(3,2)
     -eye(3,3)/Ltrans -Rtrans*eye(3,3)/Ltrans];
Cnl=[ [eye(10)]];
\[ \text{zeros}(3,4) \text{ \( Ks\)}\text{inv}(\text{Rload33})\text{\( Ks\)}\text{inv} \text{zeros}(3,3) \];

\% 500\% load
Rload33=[ sqrt(0.2*Rfl) 0 0;
0 sqrt(0.2*Rfl) 0;
0 0 sqrt(0.2*Rfl)];
Aov=[ zeros(2,2) eye(2,2)/(3*Cinv) zeros(2,3) -Tri qd0/(3*Cinv);
-\text{eye}(2,2)/Linv zeros(2,2) zeros(2,3) zeros(2,3);
zeros(3,2) zeros(3,2) -Ks\text{inv}(\text{Rload33})\text{\( Ks\)}\text{inv}/\text{Cload}
\text{eye}(3,3)/\text{Cload}; \text{Trv qd0}/\text{Ltrans} \text{zeros}(3,2)
-\text{eye}(3,3)/\text{Ltrans} -\text{Rtrans}\text{\( eye\)}(3,3)/\text{Ltrans};
Cov=[ [\text{eye}(10)];
\text{[zeros}(3,4) \text{\( Ks\)}\text{inv}(\text{Rload33})\text{\( Ks\)}\text{inv} \text{zeros}(3,3)]\];

\% Short circuit
Rload33=[ 0.001 0 0;
0 0.001 0;
0 0 0.001];
Asc=[ zeros(2,2) eye(2,2)/(3*Cinv) zeros(2,3) -Tri qd0/(3*Cinv);
-\text{eye}(2,2)/Linv zeros(2,2) zeros(2,3) zeros(2,3);
zeros(3,2) zeros(3,2) -Ks\text{inv}(\text{Rload33})\text{\( Ks\)}\text{inv}/\text{Cload}
\text{eye}(3,3)/\text{Cload}; \text{Trv qd0}/\text{Ltrans} \text{zeros}(3,2)
-\text{eye}(3,3)/\text{Ltrans} -\text{Rtrans}\text{\( eye\)}(3,3)/\text{Ltrans};
Csc=[ [\text{eye}(10)];
\text{[zeros}(3,4) \text{\( Ks\)}\text{inv}(\text{Rload33})\text{\( Ks\)}\text{inv} \text{zeros}(3,3)]\];
Initialization of Simulink based MG model

The above Matlab® script needs to be run to initialize all the data required for the Simulink® model to run. Table 1 details some of the important system parameters used in the Simulink® model. Table lists the state-space constants that need to be changed during simulation to account for the change in system load. Matrices C & D remain constant during all the four load conditions.

Table 1: System Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC bus voltage ($V_{dc}$)</td>
<td>335 V (min)</td>
</tr>
<tr>
<td>Load Voltage ($V_{load}$)</td>
<td>120 V (LN)</td>
</tr>
<tr>
<td>Frequency ($f$)</td>
<td>60 Hz</td>
</tr>
</tbody>
</table>

**Inverter Filter**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{inv}$</td>
<td>540 μF</td>
</tr>
<tr>
<td>$L_{inv}$</td>
<td>300 μH</td>
</tr>
</tbody>
</table>

**Delta-Wye Transformer**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{trans}$</td>
<td>48 μH</td>
</tr>
<tr>
<td>$R_{trans}$</td>
<td>0.02 Ω</td>
</tr>
</tbody>
</table>

**Output Filter**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{grass}$</td>
<td>90 μF</td>
</tr>
</tbody>
</table>

Table 2: Load Parameters

<table>
<thead>
<tr>
<th>Load Type</th>
<th>A Matrix</th>
<th>C Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Load</td>
<td>Afl</td>
<td>Cfl</td>
</tr>
<tr>
<td>No Load</td>
<td>Anl</td>
<td>Cnl</td>
</tr>
<tr>
<td>Over Load</td>
<td>Aov</td>
<td>Cov</td>
</tr>
<tr>
<td>Short Circuit Load</td>
<td>Asc</td>
<td>Csc</td>
</tr>
</tbody>
</table>
Table 3 contains the simulation parameters that help in the quick and accurate simulation of the MG model. The simulation time is considered to be 24 to account for the 24 TMY3 data points, representing the 24 hours in a day.

Table 3: Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation Time</td>
<td>24</td>
</tr>
<tr>
<td>Solver</td>
<td>ode23t (mod.stiff/Trapezoidal)</td>
</tr>
<tr>
<td>Solver type</td>
<td>Variable step</td>
</tr>
</tbody>
</table>