Power Quality Study of a Microgrid with Nonlinear Composite Load and PV Integration

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POWER QUALITY STUDY OF A MICROGRID WITH NONLINEAR
COMPOSITE LOAD AND PV INTEGRATION

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Electrical Engineering

by
Zhanhe Liu
December 2015

Accepted by:
Dr. Elham Makram, Committee Chair
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Dr. John Gowdy
ABSTRACT

Harmonics distortion is a crucial problem in microgrid. Harmonic sources can be categorized as two main factors: renewable energy integration and nonlinear loads. Both factors are investigated in this thesis. For renewbale energy, photovoltaic (PV) power is one of the most effective solutions for energy crisis and it is showing great potential for serving customers in microgrid. A three phase PV source model is established from both mathematical equations and power electronic control schemes. A composite load model by Crossed Frequency Admittance Matrix theory is illustrated and built as well. Due to the fact that microgrid should be able to run under two different operating modes: grid-connected and stand-alone, energy storage devices are considered as neccesity. Therefore the energy storage with droop control is included in this thesis. A practical microgrid located at GA, USA is used as a study system. Instead of making the ideal assumption, the unbalanced feeder structure and historical meteorological data are considered in the study. The microgrid, PV model, nonlinear load model and energy storage are simulated in MATLAB/Simulink environment. Multiple PV sources are integrated at different locations in order to observe the impact of harmonics on the microgrid and power quality (PQ). The results show the impact of installing PV sources in both grid-connected mode and stand-alone mode considering linear and composite nonlinear loads. In addition, three PQ indices are discussed to demonstrate the numerical impacts with various perspectives. Furthermore, the mitigation of harmonics is developed by adding a active power filter on energy storage devices in the stand-alone mode.
I would like to thank my father Suyu and my mother Xinrong for their supporting and encouraging during this endeavor. Also, I would like to give thanks to my advisor Prof. Elham Makram for she has been providing precious academic help and guidance. Thank Clemson University Electric Power Research Association (CUEPRA) for funding this program. Members of CUEPRA are: Advanced Cable-bus Co., ALSTOM, Duke-Energy, South Carolina Electric and Gas (SCE&G), and Santee-Cooper.
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CHAPTER ONE

INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

Microgrids are considered as viable options for those places where main grid expansion is either impossible or has no economic justification, such as the electrification in university campuses, military installations and rural villages[1]. Some researchers regard the microgrid as a specific distribution system embedded with distributed generations, which may operate in grid-connected or islanded (stand-alone) mode [2]. Even though there are some common characteristics between distribution system and microgrid, for example, voltage level and customer types, microgrid has its own unique structure. Microgrid consists of renewable sources, backup generators, energy storage, unbalanced load demand on each phase and multiphase lines. Due to this special structure, both grid-connected mode and stand-alone mode, as one of the most important features of microgrid, are able to deliver power whether there is a power outage on grid side or not. Along with this beneficial advantage, there are potential challenges to keep the system running safely and well. One of main concerns in the microgrid study is the electrical power quality issue. From large amounts of experience, it is very necessary to assess electrical power quality for the sake of devices and users. For example, it has been reported that a 10% increase in voltage stress caused by harmonic current typically results in 7% increase in the operating temperature of a capacitor bank and can reduce its life expectancy by 30% [3]. For the purpose of saving lifetime of electric devices and
providing more reliable power to customers, harmonics study becomes significant for researchers.

Scholars who study power system used to ignore the inside functioning process of components in the large system since what the output brings are far more important. However, the situation is different. Because of the integration of renewable energy, the output of electrical sources are not conventional. Aiming to understand what can be the output of renewable energy sources, looking into the detailed model of each components can be a solution. Particularly, photovoltaic source is often integrated to local low voltage level microgrid and should be studied. Given the small scale of loads and generation in micro-grid, the amount of harmonics produced by PV will cause more significant influences than in conventional large grid, such as overheating electronic devices, poor power quality and loss of power. Apparently not just consumers but also utility companies would like to find a solution to minimize those negative influences. However, before researchers can actually find a solution for this problem, how to model, how to analyze and how to quantify harmonics in microgrid should be accomplished first.

Alternating current (AC) power, started since 1886 in North America, is the major form in electrical grid system. It operates in sinusoidal waveform to transfer electric power. In the United States, the frequency of it is 60 Hz. According to its own characteristic, every electronic devices connected to AC power is designed to function well under clean electric power. Clean power means whether voltage or current only contains components in 60 Hz. However, recent advances in technology have made the question of AC power quality even more important [4].
Human beings have been using coal as a source of electric power for over a hundred years and the pollution it brought to our society has alerted governments around the world. In order to reduce the pollution, green and renewable energy is considered as one of solutions. In a single day, enough sun shines in China to meet its energy needs for more than 10 years, at least theoretically [5]. Huge potential development stimulates both researchers and utilities working on integration renewable energy to established power system. Yet challenges are coming along with potential benefits.

Different origins can cause same results. While innovative electric devices, for example personal computers, have induced concerns on power quality, integration of renewable energy leads to some negative influences on power quality. Electric Power Quality (EPQ) is a term that refers to maintaining the near sinusoidal waveform of power distribution bus voltages and currents at rated magnitude and frequency [3].

1.2 Power System Harmonics

Harmonics was not firstly used in electric power system, but in acoustics. In electric power system, this term “harmonics” represents a component of which frequency is a certain number multiple of the fundamental frequency. It can exist both in voltages and currents. So for a $h$ order harmonic component, its frequency can be expressed as:

$$f_h = f_{\text{fundamental}} \times h$$  \hfill (1.1)

where $h$ is the order of harmonic component and $f_{\text{fundamental}}$ is the fundamental frequency of the system. Ideally power system in the United States is running at 60 Hz. However,
because of a mixture of reasons, harmonic components always exist in voltages and currents. Measured data shows, in time domain, voltage or current waveform is a superposition of fundamental frequency and different harmonics components. To apply Fast Fourier Transformation (FFT), the signal can be analyzed in frequency domain.

Due to the fact that most of time a harmonic signal contains more than one frequency or one order harmonic signal. In order to quantify the harmonics of electrical parameters, including voltages and currents, Total Harmonic Distortion (THD) is defined.

\[
THD = \sqrt{\sum_{h=2}^{\infty} \frac{X_h^2}{X_1^2}}
\]  

(1.2)

where \(X\) represents variable name. It considers the contribution of every individual harmonic component on the signal [6].

In power system, it is very necessary to monitor THD value. Majority of electrical components and devices in grid are designed for sinusoidal-wave currents and voltages in a certain rated frequency. Currents and voltages in different higher order frequency can harm components and shorten the life time. Another influence of harmonics is that they can overheat the devices, such as transformers, so that more losses are brought up. Given these negative impacts of harmonics in power system, researchers have been working on the analysis and solutions for harmonics.

This thesis focuses on microgrid study, instead of high voltage conventional power system or transmission line. However, there are some common characteristic of them in general power system field. Compared to static power flow study, harmonic research requires different modeling method which can accurately describe the behavior
of components in different frequencies. Simulation of the harmonic interaction between detailed models of the synchronous generator, power transformer and transmission system is achieved with the development of a unified multi-frequency domain equivalent [7]. Also resonance phenomena could exist in transmission line because capacitors and inductors have different reactance in higher frequency condition. Resonance happens when the reactance of capacitor and inductor cancel out. In FFT harmonic spectrum, the current near resonant frequency is much more dominant than those in other frequencies. Because of the potential possibility of resonance, a seemingly small harmonic injection at one location on the system causes significant problems some distance away such as telephone interference [8].

There are several effective solutions for compensating harmonics in power system, and among them active filters (AF) are highly focused by scholars: novel structures of active filter can have lower voltage rating, smaller size inductor and lower electromagnetic interference [9] [10]; with conventional concepts it takes one period of fundamental frequency to eliminated the harmonics after the load current has changed but newly built control scheme allows much faster harmonics reduction[11].

However, to design more suitable solutions for various conditions, it is important to analyze the origins of harmonics in power system, which can be classified as two major types: renewable energy and nonlinear loads. In this paper, only solar energy is considered for renewable energy.
1.3 Photovoltaic Source

Photovoltaic (PV) is the technology that generates DC electrical power measured in watts (W) or kilowatts (kW) from semiconductors when they are illuminated by photons [12]. For the purpose of mathematically analyzing PV module and also simulation work, a simplified model is shown in Figure 1.1.

![Figure 1.1: Simplified PV Cell Circuit](image)

Since the power of solar irradiance on the whole earth can be considered as infinite for human beings, many scholars hold the opinion that PV is the solution to energy crisis. Nowadays it is common to see solar panel (a set of PV cells) on residential rooftops. They work very well on limited housing appliances, for example heating water. Aiming to let solar energy replace more of conventional energy, utility-scale solar farm is being studied and built increasingly. Besides PV panels, converters are used to regulate DC voltage after the output of PV. Along with converters, Maximum Power Point Tracking (MPPT) is one of the most important applications for PV source. Due to the characteristic of PV cell researchers have developed various control scheme for MPPT to provide the most power from PV cell when weather condition is given. If PV source is
connected with AC system, inverters are required to install after converters. Normally the capacity of utility-scale solar farm is over 500 kW. In short duration of seven years, from 2004 to 2010, the total global grid-connected solar PV capacity has increased at an average annual rate of 55%, to a total capacity of about 40 GW [13]. Even though this new application has huge potential benefits, there are some technical concerns still existing.

Previous work pertaining to solar PV applications in power systems can be categorized into three major categories: modeling, technical impact, and financial planning [14]. In this thesis, research focuses on the first two aspects. Various models have been built and analyzed to study PV source’s impacts on power quality in distribution systems [15-17]. One of the most important perspectives of power quality study is harmonics analysis. In PV source, inverters are considered as sources of current harmonics. Therefore, by improving control scheme of inverters, mitigation and compensation of harmonics can be achieved [18, 19]. Also because of the intermittent characteristic of solar irradiance, PV sources bring more uncertainty to systems. This uncertainty includes time-varying penetration level and its impact on voltage profile [20] and partial shading condition [21].

Large-scale PV source takes large areas. The limitation of PV farm size and proper location for solar irradiance determine that instead of connecting to transmission system directly, PV sources will have much more opportunities to serve microgrid. In the fourth part of this chapter, the characteristic of microgrid is illustrated.
1.4 Nonlinear Load

Loads usually encountered in power systems can be broadly categorized into industrial, residential, municipal and commercial loads [22]. When voltage and current in same frequency have a linear relationship, this load can be called linear load. Most of time, this type of loads is sets of linear resistors or linear inductors. However, different from classic load theory, in reality there is no load is pure constant power or pure constant impedance. So practical loads should be viewed as mixtures of linear loads and nonlinear loads. Because of massive applications of power electronics, many electrical devices are driven by multiple controllers or rectifiers. Different combinations of diodes and capacitors can cause significant nonlinearity. For example, there is a battery charger which is driven by a diode bridge rectifier (DBR) and if supplied by a pure sinusoidal AC source of 110V the current waveform is shown in Figure 1.2.

![Figure 1.2: Current Waveform of DBR](image.png)

Thus how to model loads becomes a significant topic for power system research in order to simulate systems accurately. Load models, regardless of the modeling
techniques, are divided into static and dynamic load models [23]. Static loads describe
the relationship between the power consumption, voltage and frequency [24], while
dynamic loads provide the additional advantage of representing time-sensitive behavior
of the load [25].

For static load modeling, there are two major theories: ZIP load model and
Crossed Frequency Admittance Matrix. The constant impedance, constant current, and
constant power components of a ZIP load are represented by a second-order polynomial
in bus voltage magnitude $V_i$ [26]:

$$ P_{Di}(V_i) = a_{i1}V_i^2 + a_{i2}V_i + a_{i3} $$  

$$ Q_{Di}(V_i) = b_{i1}V_i^2 + b_{i2}V_i + b_{i3} $$

where $a_{i1}$, $a_{i2}$, $a_{i3}$, $b_{i1}$, $b_{i2}$ and $b_{i3}$ are coefficients for power demand. The second order
term of voltage is for constant impedance ($Z$); the first order term of voltage stands for
constant current ($I$); and the zero order term of voltage is for constant power ($P$). This
method can give very accurate description of power consumption, voltage profile and
current flow. Nonetheless, it is not able to provide clear information of frequency
response of loads. Given the fact that harmonics study has crucial significance for power
quality, it is very necessary to consider a frequency dependent model for loads. Therefore
Crossed Frequency Admittance Matrix theory is suitable for harmonic model of loads.

This type of harmonic model takes into account the harmonic influence between
harmonic currents and harmonics voltages of different order. Equation (1.5) shows how
crossed frequency matrix represents this influence:
where voltages and currents are represented as complex numbers. The subscript $m$ stands for the harmonic order. For pure fundamental frequency voltage sources, voltage vector elements are zeroes except $V_1$. But currents flowing into loads still have harmonic distortion due to the fact that $Y_{21}$, $Y_{31}$ and $Y_{m1}$ are not all zeroes for nonlinear load. On contrary, for linear load, the crossed frequency admittance matrix becomes a diagonal matrix and the off diagonal elements are zeroes. The crossed frequency matrix models the load as a harmonic currents source.

A proper load model is very important for doing case study in power system.

### 1.5 Microgrid Characteristics

Microgrid is a new concept which is brought up within the recent ten years. There is no strict definition for microgrid, scholars share some same opinion about the characteristics of microgrid.

It is running at low voltage level, mostly same voltage level as distribution system. Microgrid concept assumes a cluster of loads and microsources as a single controllable system that provides power to its local area [27]. Normally Microgrids are considered as viable options for those places where main grid expansions is either
impossible or has no economic justification, such as the electrification in university campuses, military installations and rural villages [1].

Conventional power systems have a configuration of one-way structure, which means that there is only one source supplying the whole system. Therefore in conventional power system, the power flow is only one-directional. But in microgrid, these microsources can be installed in every possible locations, and it is also called distributed generators (DGs). The types of DGs can be bio-mass generation, small-size gas turbines, solar plant, wind plant and energy storage. The main purpose of microgrid is to serve local area and finally reach to autonomous operation with less pollution. Based on this purpose, sources of large capacity are not practical, instead small scale renewable energy can play a key role.

Some researchers regard the microgrid as a specific distribution system embedded with DGs, which may operate in grid-connected or islanded (stand-alone) mode [2]. In grid connected mode, most of the system-level dynamics are dictated by the main grid due to the relatively small size of microsources; in stand-alone mode, the system dynamics are dictated by micro sources themselves, their power regulation control and, to an unusual degree, by the network itself [28]. Also even when microgrid is running under grid connected mode, if there is a fault happening in the microgrid the connection with grid should be cut off to protect the grid. So it is not always guaranteed that energy storage and DGs can fully meet the load demand. In this condition, some loads have to be cut off power supply and these loads are considered as non-critical loads; while some
loads have to maintain power supply for 24 hours and these loads are considered as critical loads. Figure 1.3 shows a typical microgrid.

Due to this special structure, along with this beneficial advantage, there are potential challenges to keep the system running safe and well. One of main concerns in the microgrid study is the electrical power quality issue.

Researchers have been doing works on how to monitor and simulate the actual system. The first step of studying electrical power quality issues, particularly harmonics, should be modeling a microgrid with renewable sources both in grid-connected mode and stand-alone mode [15, 28, 29]. To address harmonics distortion, filters are designed and tested by scholars. Compared to active power filters, passive filters consists of only passive components and cost less. In [30] [31], several novel passive filters were designed and tested to show the improvement. Yet passive filters can be very limited when harmonic distortion is very serious and less predictable, since fixed passive filters can only help decrease harmonics on the default setting orders. Thus, active power filters
were studied for harmonics issues in [11] [32]. Unfortunately, most of these researches, which studied filter designs or inverter controls, were only focused on power electronic fields regardless of the harmonics response in the microgrid.

According to previous researches, the factors which have influence on power quality, specifically harmonics distortion, are very comprehensive. Therefore DGs, inverters, weather conditions, energy storage and load modeling should be included all together in the harmonics study in order to have better simulation results. Detailed study is presented in the following chapters.
CHAPTER TWO

MODELLING OF MICROGRID

The study of microgrid can be achieved through different research methods, including hardware test, computational programming, mathematical analysis and software based simulation. As it is known that hardware test costs a lot and computational programming is hard to describe the transient performance of some of power electronic devices. In order to study the influence of harmonics in microgrid with PV integration, software based simulation should be the best option. This thesis is based on the results which come from computer simulations and therefore it is significant to model each component in the microgrid in the most suitable ways. This chapter demonstrates the details of modelling works of PV, nonlinear load, energy storage and active power filter. Along with the process of modelling, the performances of each components are also presented to prove the practicability.

2.1 Photovoltaic Source

2.1.1 Photovoltaic Source Modeling

In this thesis KC200GT is chosen as the model of PV cell used for integration. The KC200GT data is determined by its own manufacture process. The data can be obtained from the manufacturer data sheet and some parameters are shown in Table 2.1 [33].
The basic mathematical equation of PV array to describe I-V is shown below [34]:

\[ I_m = I_{pv} - I_0 \left( e^{\frac{V + R_l I_{out}}{V_{oc}}} - 1 \right) \]  \hspace{1cm} (2.1)

\[ I_{pv} = [I_{pv,n} + K_I (T - T_n)] \frac{G}{G_n} \]  \hspace{1cm} (2.2)

\[ I_0 = I_{sc,n} + K_I (T - T_n) \frac{V_{oc,n} + K_I (T - T_n)}{a V_t e^{\frac{V_{oc,n} + K_I (T - T_n)}{a V_t}}} - 1 \]  \hspace{1cm} (2.3)

where \( I_{pv} \) is the current directly generated by one PV cell, \( I_0 \) is the reverse saturation current of the diode shown in Fig. 1.1, \( I_m \) is the source current of PV cell, \( I_{out} \) is the
output current after resistance of PV cell, $V$ is the output voltage, $a$ is the diode ideality constant, $V_t$ is the thermal voltage of PV cell, $I_{sc}$ is the short circuit current of PV cell, $T$ is the temperature and $G$ is the solar irradiance. $K_v$ is the voltage gain of solar irradiance and $K_I$ is the current gain of solar irradiance.

Based on the data in TABLE 2.1 and equation (2.1) to (2.3), mathematical model was built in MATLAB/SIMULINK platform. After PV cell, a boost converter with MPPT block was built. By comparing the output power and output voltage of PV cell on very sample time period, PMW signal can be generated to gate of IGBT. And from there, maximum power point can be traced. However, the output voltage of PV array itself is not fit for the next level inverter control and a boost converter can improve the DC voltage level. The structure is shown in Figure 2.1.

![Figure 2.1 Boost Converter with MPPT](image-url)

**Figure 2.1 Boost Converter with MPPT**
2.1.2 Inverter Control of Photovoltaic Source

From previous researches there are two main methods for inverter control with PV integration. One is Active Power Control (or called PQ control), and another one is Voltage Frequency Control (or called VF control). When considering grid-connected mode of microgrid, PQ control is the better option for lowering the reactive power output from PV sources; when considering stand-alone mode operating, energy storage is the slack bus in the system instead of PV so PQ control can help provide the most active power for critical loads. Therefore, PQ control was built to be connected in PV source system. Figure 2.2 shows the scheme of conventional configuration of three phase active power inverter control. To be more specific, this control scheme has another name, feed-forward decoupling PQ control. The $dq$ transformation block can work as switching three parameters ($i_a, i_b, i_c$) of AC to two parameters ($i_d, i_q$) in DC. The active and reactive power signals ($P_{ref}, Q_{ref}$) are used to obtain the reference signal ($i_{dref}, i_{qref}$) of inner current control loop by the matrix solver and equation (2.4) is given [35]:

$$L \frac{d}{dt} \begin{bmatrix} i_d(t) \\ i_q(t) \end{bmatrix} = \begin{bmatrix} -R & \omega L \\ -\omega L & -R \end{bmatrix} \begin{bmatrix} i_d(t) \\ i_q(t) \end{bmatrix} - \begin{bmatrix} u_d(t) \\ u_q(t) \end{bmatrix} + \begin{bmatrix} e_d(t) \\ e_q(t) \end{bmatrix}$$  (2.4)

where $L$ and $R$ represent inductance and resistance of the impedance $Z_a, Z_b$ and $Z_c$ between three phase inverter and voltage feedback in Figure 2.2. Since the purpose of this control scheme is to force the reactive power output close to zero, the reference on q-axis set to zero. The $u_d$ and $u_q$ are the output control signals of the current control block.
2.1.3 Simulation of Photovoltaic Source

Building PV source as a simulation file is aiming to help solve practical cases and problems. In that way, it is necessary to prove the function and response of these simulation blocks. The inputs of this PV cell are solar irradiance and temperature. In spite of the fact that there are a lot of other parameters which can slightly influence the output, for example humidity, solar irradiance and temperature are still the dominant factors over all of others.
Figure 2.3: I-V Curve of Single PV Cell
under Different Solar Irradiances (at 25°C)

Figure 2.4: I-V Curve of Single PV Cell
under Different Temperatures (at 1000 W/m²)
Figure 2.5: P-V Curve of Single PV Cell
under Different Solar Irradiances (at 25°C)

Figure 2.6: P-V Curve of Single PV Cell
under Different Temperature (at 1000 W/m²)
From Figure 2.3 to Figure 2.6, curves are generated to prove the functions of PV cell simulation block. In Figure 2.3, the I-V curves show that when boosting the voltage after the maximum power point output currents drop quickly and higher irradiance can generate higher current (nominal irradiance is 1000 W/m²). In Figure 2.4, the I-V curves demonstrate that while boosting voltage after the maximum power point currents drop quickly and lower temperature can slightly cause higher currents.

Figure 2.3 to 2.6 are based on the single PV cell simulation. However, a PV source system consists of dozens of PV arrays which contains hundreds of PV cells. Here in this thesis, each single PV source has 3000 PV cells to work together. At the nominal condition which is at 25°C and 1000 W/m², the rated output active power is 600 kW, also shown in Figure 2.7. Furthermore, since the well-tuned inverter control can decrease the harmonic distortion of output current, the simulation results in Figure 2.8 and 2.9 give clear look at the output current at nominal condition when the voltage level is 4.16 kV.

Figure 2.7: Active Power Output of PV Source System at Nominal Condition
Figure 2.8: Output Current at Phase A of PV Source System at Nominal Condition

Figure 2.9: A Closer Look at

Output Current at Phase A of PV Source System at Nominal Condition
2.2 Nonlinear Composite Load

2.2.1 Nonlinear Load Modeling Method

Many theories have been proposed for nonlinear load modeling but as it is mentioned in Chapter II Crossed Frequency Matrix can demonstrate the harmonic response of different types of loads. Therefore, in this study Crossed Frequency Matrix is applied to model the load. Particularly, instead of only modeling one type of load, here a composite load is aiming to be modeled. For the purpose of composite load simulation, with given voltages, output currents can be monitored. When monitoring output currents, time domain current waveform is analyzed by the Fast Fourier Transformation (FFT) so that it can be expressed as a complex number matrix. In this complex matrix, each row stands for a current on a distinct harmonic order. In microgrid, other than resonance phenomenon, high frequency harmonic currents have quite small magnitude. It is not practical to consider every order of harmonic currents that exist in the system. In order to simplify the modeling process, here the complex matrix only includes from fundamental current up to 13th order of harmonic current. With only fundamental voltage, 60 Hz, first column elements in crossed frequency admittance matrix can be calculated. Then by superimposing 3rd, 5th, 7th, 9th, 11th and 13th order harmonic voltage sources, each one at a time, the other columns can be calculated likewise. Therefore, three 7 × 7 admittance matrixes are built for the three types of nonlinear loads. Equation (2.5) demonstrates how each harmonic order current is determined through the Crossed Frequency Matrix which is shown in equation (1.5) and m, n both represent harmonic order number. And equation (2.6) and (2.7) explain how elements in the matrix is calculated.
2.2.2 Individual Nonlinear Load Types

- Instead of making the assumption of single type load, in order to consider the practical situation of microgrid load demand, in this study a composite load is modeled, including three types of nonlinear load and one linear load. The first nonlinear load type is compact fluorescent light (CFL), which is the basic load in residential systems. Then the second one is load with diode bridge rectifier (DBR), which is widely applied to a large amount of home appliances including desktop computers, television sets, battery chargers, adjustable speed drives for heating pumps and air conditioning etc. The third type is load with phase angle AC voltage controller (PAVC), which normally used in light dimmers, heating load, single-phase induction motors. The structure of this composite load is shown in Figure 2.10.
The next step is to use simplified circuit to represent each type of load and calculate each admittance matrix according to equation (2.6) and (2.7). In Figure 2.11, each type of nonlinear load simplified circuit is given. First, to connect an AC source with only fundamental frequency to each circuit and then from simulation results currents can be recorded and divided into each frequency by FFT. From equation (2.6), elements in the first column can be found. Secondly, to superimpose one $j$ order harmonic voltage source to the previous circuit and elements on column $j$ can be calculated by equation (2.7).
Figure 2.11: Simplified Circuit of Composite Load: (a) CFL; (b) DBR;
(c) PAVC; (d) Structure

Figure 2.12 shows the simulation of a 15W CFL load, which is under 120V AC voltage level. According to the results of current FFT, the Crossed Frequency Admittance Matrix is calculated (the matrix is provided in Appendix A). In Figure 2.13, the value of Z axis shows the magnitudes of each elements in the admittance matrix while X and Y stand for the harmonic orders. Obviously, this load is far away from being linear and 5th, 7th, 11th harmonics are the main factors.
Figure 2.12: Simulation of CFL

Figure 2.13: Admittance Matrix Magnitude Distribution of CFL
Similarly, Figure 2.14 shows the simulation of 0.67 kW DBR and Figure 2.15 gives the demonstration of the magnitudes of elements in this matrix. Compared to the matrix of CFL, this one has different characteristic. Diagonal elements have the largest magnitude and this can be interpreted that there is relatively small interaction between different frequencies. Meanwhile, among diagonal elements, ones which represent for 11\textsuperscript{th} and 13\textsuperscript{th} order harmonic frequencies have larger magnitudes, which means that on high frequency this load has smaller resistance.

![Figure 2.14: Simulation of DBR](image)

Figure 2.14: Simulation of DBR
A 0.9 kW PAVC type load is simulated as Figure 2.16. Figure 2.17 shows that a load with PAVC can be close to linear load, since there is fairly small interaction between frequencies and magnitudes of diagonal terms are almost the same.
2.2.3 Simulation Model Building

After obtaining the crossed frequency admittance matrix for each type of nonlinear load, the next goal is to include these matrices into simulation. Assuming the total load demand is fixed, and with the same amount of active power and power factor the numbers of each type of loads which were described above can be estimated. In real residential system, most of house appliances are connected in parallel so that individual equipment can work independently. Thus, total current will simply be sum of the individual currents. And different loads contain nonlinear loads with different ratios. Figure 2.18 explains how this mathematical model works in the simulation of microgrid. Firstly, voltage measurement unit is able to obtain voltage information from the feeder in microgrid. And then through Fourier transformation, signals in time domain can be
transformed into frequency domain and be formed into a voltage matrix. This voltage matrix has only one column complex numbers and each row represents one harmonic order. According to equation (2.5), with both admittance matrix and voltage matrix, the current matrix can be calculated. Therefore, using the complex number in current matrix, a current signal in time domain can be generated to control the controllable current source to draw currents from the feeder. Along with the process of nonlinear load, linear load is also connected in parallel.

Figure 2.18: Composite Load Simulation Scheme Diagram
2.3 Energy Storage

Energy storage is one of the most unique part of microgrid structure. Because microgrid should be able to operate either under grid-connected mode or stand-alone mode, energy storage is necessary for stand-alone operating. In stand-alone mode, the most important requirement is to provide reliable power to customers. However, renewable energy, such as PV source, has intermittent characteristic and weather dependent restrictions. Particularly solar irradiance varies during daytime so that the output of PV source varies greatly with irradiance. Thus, other stable types of distributed sources are necessary in a microgrid. In most practical applications, batteries and diesel generators, which work as the slack bus in stand-alone mode, can supply stable voltage and frequency for the system.

Beside PQ control, $v/f$ control and droop control are often used in inverter control of distributed sources in microgrid. Since the goal of PQ control is to achieve the maximum output of active power and minimum reactive power, it is used for PV control in grid-connected mode and stand-alone mode. However, in stand-alone mode, energy storage bus should be the slack bus. Slack bus works to provide stable voltage and frequency for the system, therefore $v/f$ control and droop control are often used for inverter control of battery. Compared to $v/f$ control, droop control does not maintain the same stable voltage and frequency but varies in a small range with the output. Higher active power output can causes small drop on frequency and higher reactive power output can cause small drop on voltage.
\[
\begin{align*}
\frac{f}{ref} &= \frac{f_{ref} - k_x (P_{ref} - P)}{P} \quad (2.8) \\
V &= \frac{V_{ref} - k_y (Q_{ref} - Q)}{Q} \quad (2.9)
\end{align*}
\]

However, because of this characteristic, multiple batteries and other type of microsources can work together to communicate. So in this study, droop control is applied to the inverter control of the energy storage, which is a DC battery. The control scheme and structure is shown in Figure 2.19. Furthermore, the performance of this simulation model is going to be shown and explained in the next chapter.

![Diagram](image-url)
2.4 Active Power Filter

The design of active power filter is not the focus point of this research. Yet, when discussing harmonics distortion problem, the solution is always about filter design and installation. In a multi-battery microgrid, harmonics can be much higher in stand-alone mode than in grid-connected mode. Sometimes, too much harmonics can have quite negative influence on power devices and customers. Thus, a proper designed filter should be considered as an important part of microgrid system.

2.4.1 Structure of Active Power Filter

Harmonics can cause damages on electrical devices, such as, overheating transformers. Therefore, it is very important to monitor power quality in the grid, especially harmonic distortion levels. If harmonic distortion is beyond the regulation, it is necessary to install filters to mitigate harmonics. There are two types of filters in general: passive filters and active power filters.

Renewable energy inverters are the main source of harmonics, the magnitudes of current on each harmonic are changing all the time along with weather conditions, such as solar irradiance. However, passive filters are set to decrease the current magnitude in some specific harmonic order. If these magnitudes are changing, it is hard to choose which frequency to be tuned to improve the power quality significantly because the major harmonics distortion might not be the one from the initial design. Thus, an active power filter can help improve power quality by having an active power source with controllers, shown in Figure 2.20 [9].
2.4.2 Simulation of Active Power Filter

In order to show the performance of the active power filter mentioned above, a simple simulation study was done. The presented parallel three phase inverter can be controlled by different types of control schemes and the advantages and disadvantages are discussed in [36]. The proposed model is using a current compensation method, called Instantaneous Reactive-Power algorithm [37]. When the active power filter is connected to the grid, the power delivered on different frequencies can be calculated. By a basic 5th order Butterworth low pass filter, power that is delivered on high frequency can be detected and be considered for compensation control scheme. Therefore, the inverter can control the filter to compensate current harmonics through PWM signals, not only in one specific order but more generally. To test this active power filter simulation model, it is connected with a nonlinear load on 4.16 kV (phase to phase) voltage source. From current
waveforms shown in Figure 2.21, it can be observed that the harmonics distortion is improved significantly. By FFT, the current magnitude spectrum on frequencies is presented as follows. Figure 2.22 gives the FFT spectrum of source current without active power filter while Figure 2.23 shows the spectrum after the filter is connected. From the comparison between Figure 2.22 and Figure 2.23, Total Harmonic Distortion (THD) drops from 19.70% to 3.42% and harmonics on 5\textsuperscript{th} order drops from 15% to 0.35%.

Figure 2.21: Current Waveform (at 0.2s the active power filter is connected)

Figure 2.22: FFT Spectrum of Source Current without Active Power Filter
2.5 Summary

This chapter includes simulation modelling works for each component in this microgrid study. Specifically the structure of microgrid consists of renewable source, nonlinear load, energy storage and potential power filter. Traditional simplified model or equations which describe the relation of input and output cannot meet the requirement of harmonics study since it mainly supports steady state study. Steady-state study only gives the values and information of steady state output or parameters in the power system without considering short-time transient conditions. Nevertheless, the origins of harmonics are from inverter performance in transient status. For a long time this area studies have been regarded as the focus area for scholars who major in Power Electronics. Consequently researches in Power System area have ignored the detailed model of various types of inverters while dealing with microgrid. Therefore what makes this chapter important is while studying the harmonics influence of microgrid, the
detailed models are not ignored so that the simulation can give more practical demonstration. Especially loads and sources, which are major origins of current harmonics in microgrid, are well modelled from the view of harmonics. With the detailed models built in this chapter, more simulations results can be persuasive and solid.
CHAPTER THREE

HARMONICS IMPACTS ON MICROGRID

The research method of this thesis study is to use computer software to simulate the influence brought by PV integration in microgrid. Based on the modelling work mentioned in Chapter 2, multiple simulations can be conducted to analyze harmonic distortion influence. Specifically, both grid-connected and stand-alone mode are studied. In order to evaluate harmonics with quantified indices, several power quality indices are described in the following part.

3.1 Power Quality Indices

Power quality indices are parameters that are able to show some part of electric characteristic according to current or voltage measurements. In other words, power quality indices are defined to quantify the distortion for current or voltage. Each index has different function to describe the distortion. Therefore, multiple indices should help researchers to have a clear look at the harmonics distortion from various perspectives.

THD is the measurement of the harmonic distortion at each node on each bus in the system. In order to look at the harmonic distortion in the whole system, whole system harmonics distortion level (WSHDL) is defined as:

\[ WSHDL = \sqrt{\frac{\sum_{i=1}^{n} THD_i}{n}} \]  

(3.1)

where \( n \) is the number of nodes; \( h \) represents the harmonic order; \( m \) is the considered
maximum harmonic order. \( I_1 \) is the absolute value of fundamental (60Hz) current. The meaning of this definition is to have a great picture for the harmonics distortion trend. Also in low voltage level system, such as microgrid or distribution systems, instead of all three-phase line structure, there are many two-phase feeders or single-phase feeders. Therefore, it is important to look into each node on each bus.

In addition to the WSHDL, there are three types of PQ indices are introduced and discussed along with simulation results. Distortion power \( DP \) index is defined in (3.2) [38]. The total apparent power, fundamental active power and fundamental reactive power are defined in (3.3) to (3.5).

\[
DP = \sqrt{S^2 - P_1^2 - Q_1^2} \approx V_1 \cdot I_1 \cdot \sqrt{\text{THD}_V^2 + \text{THD}_I^2 + (\text{THD}_V \cdot \text{THD}_I)^2}
\]

(3.2)

where the total apparent power
\[
S = \sqrt{\sum_{n=0}^{m-1} V(n)^2 \times \sum_{n=0}^{m-1} I(n)^2},
\]

(3.3)

fundamental active power
\[
P_1 = V_1 \cdot I_1 \cdot \cos(\theta),
\]

(3.4)

fundamental reactive power
\[
Q_1 = V_1 \cdot I_1 \cdot \sin(\theta)
\]

(3.5)

By normalizing \( DP \) to unity, normalized \( DP_{norm} \) index can be obtained. DP index has the ability to show contributions of distortion power from individual customers to PCC. From (3.2), it is easy to estimate the power delivered not on 60 Hz simply by taking measurements of THD into the equation. This index is crucial for utility to monitor how much power is lost. Waveform distortion WD index is defined as [39]:
\[
WD = \left( \sqrt{I_{m1}^2 - I_1^2} + \sum_{i=2}^{M} I_{\text{integ}-h,i}^2 + \sum_{j=1}^{N} I_{\text{inter}-h,j}^2 \right) / I_1
\]  \quad (3.6)

where \(I_1\) is the rated current magnitude and \(I_{m1}\) is the measured fundamental current magnitude. \(I_{\text{integ}-h,i}\) is the \(i\)th integer harmonic component and \(I_{\text{inter}-h,j}\) is the \(j\)th inter-harmonic component. WD index expresses how much a component, AC current, is distorted or deviated from ideal sinusoidal waveform. WD index includes inter-harmonic components, which can take a large part of harmonics when different types of inverters involved. Also inter-harmonics cannot be presented by THD which only include integer order of harmonics. Instead of an average value, WD index gives an instantaneous distortion ratio and it can be depicted along with time axis to be monitored. Symmetrical components deviation SCD index is defined as [38]:

\[
SCD = \left( \sqrt{|I_{mp} - I_1|^2 + I_{mn}^2 + I_{mz}^2} \right) / I_1
\]  \quad (3.7)

where \(I_{mp}, I_{mn}, I_{mz}\) are the measured currents at positive, negative and zero sequences. SCD index has a significant meaning for microgrid because it can give the level of unbalance on currents. SCD index can help staff who work in substations to recognize the unbalance in each node and its impact on the whole system.

3.2 Test System Information

Study system shown in Figure 3.1 is a 14-bus 4.16 kV microgrid (located in GA, USA). The detailed feeder configuration and its impedance matrices are presented in
Appendix B. Bus 10 is the slack bus and the balance point in grid-connected mode. The slack bus voltage is set to 1.05 pu to keep all node voltages at least 0.95 pu. In Figure 3.1, three lines represent three phase feeder. Two lines represent two phase feeder and single line means one phase feeder. Load information is given in Table 3.1. The PV sources as the only type of renewable energy are integrated to the system as shown in Figure 3.1. The inverter control inputs $e_a$, $e_b$, $e_c$, $i_a$, $i_b$, $i_c$ are obtained from monitoring the integration point in microgrid. If these values are away from ideal balanced condition and changing along with time, then PV sources will provide more harmonics than running under ideal balanced condition because of the performance of inverters. Figure 3.2 shows the solar irradiance and temperature during 24 hours (average value of typical day of July within 10 years). Since in the simulation model, PV’s output is only influenced by temperature and solar irradiance, only these two factors are considered in the typical day of July. In this work, the simulation only runs during the sunniest period (7am to 6pm).

![Test System Structure](image)

Figure 3.1 Test System Structure
Table 3.1 Load Data of the Study System

<table>
<thead>
<tr>
<th>Bus</th>
<th>Load Data for the System</th>
<th>Note</th>
<th>Active Power (kW)</th>
<th>Reactive Power (kVar)</th>
</tr>
</thead>
<tbody>
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<td>10</td>
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<td>—</td>
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<td>Three phase</td>
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<td>212</td>
<td></td>
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<tr>
<td>30</td>
<td>Three phase</td>
<td>412</td>
<td>112</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>32</td>
<td>One phase</td>
<td>37</td>
<td>12</td>
<td></td>
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<td>8</td>
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</tr>
<tr>
<td>62</td>
<td>One Phase</td>
<td>32</td>
<td>11</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.2 Meteorological Data on Typical July Day
3.3 Harmonics Impacts on Grid Connected Mode

The test system is simulated in this section in MATLAB/Simulink and analyzed considering the PV model and the composite load model explained in 2 to study the harmonic distortion and PQ indices described in section 3.1. The PV data are set as in Table 3.1. After running the power flow in the basic microgrid (without PV integration and without nonlinear loads), voltages on each node are found in the acceptable fluctuation range (0.95, 1.05 pu).

3.3.1 Considering PV with Linear Load

Two cases are studied based on PV locations. In case I, PV locations shown in Figure 3.1 are considered. Applying equation (3.1) gives the harmonics distortion data for each bus from 7:00 am to 6:00 pm. WSHDL values demonstrates the harmonics distortion in the microgrid system as shown in Figure 3.3. In Figure 3.3, the harmonic distortion is significant at noon time. In other words, as the percentage of power supplied by PV is going higher, the WSHDL is going higher. This phenomenon can be explained by the fact that inverter produces harmonics and more power coming from PV means more distorted power is generated. THD provides analysis in each bus as shown in Figure 3.4. According to the standards in [40], when voltage level is under 69 kV and $I_{sd}/I_L$ is smaller than 20, THD of current is regulated under 5% by standards. So the THD values above 5% represent nodes that largely influenced by PV integration and some potential damage might be caused by harmonics to shorten the lifetime of electrical components.
Figure 3.3 WSHDL from 7:00AM-6:00PM (Case I)

Figure 3.4 THD from 7:00AM-6:00PM (Case I)
In case II, the PV sources are integrated at buses 20, 40 and 60. Figure 3.5 shows the WSHDL of case II. In Figure 3.6, the red line (phase A of bus 50) is the most affected. However, THD value on all these nodes are under 5%, which is acceptable for microgrid system. Compared to case I, the integration locations affect the THD. In case I WSHDL is large when the penetration level is high; however in case II WSHDL is not affected much by the penetration level change. This results give a clear demonstration about how the integrations of PV affect the microgrid distortion. However, when THD is over 5% the power quality is required to be improved.

![Whole System Harmonics Distortion Level](image)

Figure 3.5 WSHDL from 7:00AM-6:00PM (Case II)
Compared to the case I, the integration locations in case II are more dispersed on this radial system. According to the theory of PQ control inverter which is introduced in Chapter 2, since each PV source are separated and slack bus can provide nearly ideal balanced power from the grid side in grid-connected mode, the inverter PQ control should be improved by less distortion reference currents and voltages. Figure 3.3 and Figure 3.5 give a clear presentation of the difference between two location choices for three PV sources.
3.3.2 Considering PV with Nonlinear Composite Load

This part investigates the effect of nonlinear loads. According to experiences from Grainger Industrial Supply [41], a normal business building can withstand up to 15% of nonlinear load without apparent negative influences. But when it comes larger than 15%, necessary devices should be installed to improve power quality. Nonlinear loads are added at different percentage w.r.t. to the linear loads. Blue solid line in Figure 3.7 shows the current waveform with 10% of nonlinear load at Bus 61, phase A. At this time, the THD is 4.0% as shown in Figure 3.8. Red solid line in Figure 3.7 represents the 15% of nonlinear load at the same node and the corresponding THD is 5.6%. Figure 3.8 shows how the current harmonic distortion increase with increasing the percentage of nonlinear load. The nonlinear load is the same as the one mentioned in Chapter 2 and each type of the admittance matrix is presented in Appendix A.

![Comparison of current waveforms with 10% and 15% nonlinear load](image)

Figure 3.7 Load Current of Bus 61A with Nonlinear Load
Figure 3.8 THD Comparison with Different Loads with PV Injection

Figure 3.9 Simplified Study System
For the purpose of PQ indices investigation, the microgrid system in Figure 3.1 is simplified as shown in Figure 3.9. An equivalent PV source is considered at the PCC point. The simplified system consists of four main loads. The composite load information is shown in Table 3.2. Bus 51 (considered as a small scale factory and because of large amount of motors and heating pumps) is a PAVC type of nonlinear loads. Buses 60 and 61 (two business buildings which contain many devices like computers) are classified as DBR. Load of bus 62 is considered residential. PQ indices in section 3.1 are applied on the simplified system. Harmonics distortion ranking (HDR) can be found through descending sorting of DP and WD indices. The simulation results are shown in Tables 3.3 and 3.4. All these results are based on currents measurement because voltage distortion is not dominant compared with currents. Table 3.3 lists the DP index which implies that the large amount of load contributing more to DP and the ranking gives the same information. However in Table 3.4, the WD index reflects that without considering power but the waveform of currents. Clearly, due to large use of motors, heating pumps and other heavy duty nonlinear loads, even load on Bus 51 does not consume the most power but it still has the worst impact on current waveform. In Table 3.4, the HDR is different with that in Table 3.3; this can give substation engineers multiple views of power quality. The SCD index can indicate how much unbalance the system have from data obtained at PCC. But before applying the SCD equation, one assumption has to be made that in this case study mutual coupling between lines can be neglected due to the short length of each feeder. According to simulation results, the magnitude of current sequences running through PCC is [25.87 12.64 10.23] Amps ([positive negative zero]). By applying
equation (3.7), the SCD index is 0.54. SCD index could weight from 0 to 1 and larger number shows more unbalanced. The contribution of harmonics from PV inverter, different types of nonlinear loads on each phase and system configuration have determined that this microgrid is very unbalanced. Engineers who work in substations can also use SCD as power quality index for regulating the system.

Table 3.2 Composite Load Information

<table>
<thead>
<tr>
<th>Bus Number</th>
<th>Phase</th>
<th>DBR</th>
<th>CFL</th>
<th>PAVC</th>
<th>Linear Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>51</td>
<td>A&amp;B</td>
<td>15%</td>
<td>15%</td>
<td>30%</td>
<td>40%</td>
</tr>
<tr>
<td>60</td>
<td>ABC</td>
<td>20%</td>
<td>20%</td>
<td>10%</td>
<td>50%</td>
</tr>
<tr>
<td>61</td>
<td>ABC</td>
<td>25%</td>
<td>25%</td>
<td>10%</td>
<td>40%</td>
</tr>
<tr>
<td>62</td>
<td>C</td>
<td>15%</td>
<td>10%</td>
<td>15%</td>
<td>60%</td>
</tr>
</tbody>
</table>

Table 3.3 Distortion Power Index

<table>
<thead>
<tr>
<th>Bus Number</th>
<th>Phase</th>
<th>$D_{Pnorm}$</th>
<th>HDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>51</td>
<td>A</td>
<td>0.0791</td>
<td>7</td>
</tr>
<tr>
<td>51</td>
<td>B</td>
<td>0.0787</td>
<td>8</td>
</tr>
<tr>
<td>60</td>
<td>A</td>
<td>0.1417</td>
<td>3</td>
</tr>
<tr>
<td>60</td>
<td>B</td>
<td>0.1798</td>
<td>1</td>
</tr>
<tr>
<td>60</td>
<td>C</td>
<td>0.1645</td>
<td>2</td>
</tr>
<tr>
<td>61</td>
<td>A</td>
<td>0.0793</td>
<td>6</td>
</tr>
<tr>
<td>61</td>
<td>B</td>
<td>0.1072</td>
<td>4</td>
</tr>
<tr>
<td>61</td>
<td>C</td>
<td>0.0977</td>
<td>5</td>
</tr>
<tr>
<td>62</td>
<td>C</td>
<td>0.0720</td>
<td>9</td>
</tr>
<tr>
<td>Bus Number</td>
<td>Phase</td>
<td>WD</td>
<td>HDR</td>
</tr>
<tr>
<td>------------</td>
<td>-------</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>51</td>
<td>A</td>
<td>0.482</td>
<td>2</td>
</tr>
<tr>
<td>51</td>
<td>B</td>
<td>0.511</td>
<td>1</td>
</tr>
<tr>
<td>60</td>
<td>A</td>
<td>0.301</td>
<td>9</td>
</tr>
<tr>
<td>60</td>
<td>B</td>
<td>0.336</td>
<td>7</td>
</tr>
<tr>
<td>60</td>
<td>C</td>
<td>0.324</td>
<td>8</td>
</tr>
<tr>
<td>61</td>
<td>A</td>
<td>0.382</td>
<td>6</td>
</tr>
<tr>
<td>61</td>
<td>B</td>
<td>0.453</td>
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</tr>
<tr>
<td>61</td>
<td>C</td>
<td>0.419</td>
<td>5</td>
</tr>
<tr>
<td>62</td>
<td>C</td>
<td>0.437</td>
<td>4</td>
</tr>
</tbody>
</table>

### 3.4 Harmonics Impacts on Stand-Alone Mode

In stand-alone mode, load demands are supported by distributed sources which are in different locations of the system. Instead of connecting Bus 10 to grid, here in stand-alone mode Bus10 is connected to energy storage as slack bus. Microsources include, in this case study, three PV sources, two batteries and one diesel generator.

For the models proposed in Chapter 2, the rate output power of battery on 4.16 kV voltage level is presented in Figure 3.10. It is proven that the simulation models are well tuned to be able to give steady output. Batteries are charged by PV sources when the microgrid is running under grid-connected mode, while PV’s output varies along with time, batteries give maximum output and the diesel generator covers the rest of the load demand. In this case, total load demand is 2,426 kW and it is also assumed that only 80% of loads is critical load in stand-alone mode. The power curve of this system is given in Figure 3.11.
Figure 3.10 Battery Rated Output Active Power

Figure 3.11 Active Power Curve of Microgrid in Stand-alone Mode
Both nonlinear loads and inverters generate harmonics and the harmonic distortion is able to influence the output current of energy storage. Figure 3.12 demonstrates how THD of battery output current changes during the day from 7:00 AM to 6:00 PM. In Figure 3.12, the red line stands for THD values without active power filter while the green line stands for THD values with active power filter. Without filter, harmonics value can be higher than 5%, which can potentially harm the transformer located between the battery and the microgrid. Even when the nonlinearity ratio of load increases, this THD value could be much higher. After being connected with the active power filter, the THD values are largely decreased. In this case, the highest value of THD is not over 1%. Though active power filter can work effectively, it is not practical to install many active power filters in one microgrid considering the cost. Installing one active filter on the slack bus to protect energy storage is practical since the initial cost of battery and larger size transformer are more expensive.

Figure 3.12 THD of Battery Current Output from 7:00AM to 6:00PM
In Figure 3.13, WSHDL is plotted from 7:00 AM to 6:00 PM. While the solar irradiance is increasing along with time, the increase of WSHDL means that the harmonic distortion gets worse. For a grid-connected system, if the value of WSHDL is above 1%, that means some of nodes are suffering from significant harmonic distortion. Because when system is running under grid-connected mode THD near PCC is very small if assuming the grid does not deliver much harmonics, there must be some buses which suffer from high THD. Nevertheless, in Figure 3.13, it is easy to notice that WSHDL is keeping above 2%. This can be viewed as one of the major difference between grid-connected mode and stand-alone mode. Since the slack bus in stand-alone mode is the one which is connected with the energy storage and generators, there are always a certain amount of high frequency currents from the slack bus. If the nonlinearity of load becomes more significant, it is even harder to keep THD lower than 5% on each node. When the average THD of each node is 5%, WSHDL is 2.236%. Figure 3.14 presents THD on each node along the same time period.

According to the comparison between Figure 3.13 and Figure 3.14, WSHDL has the advantage of showing the trend of the whole system with one simple parameter based on THD values. Without looking into every line in Figure 3.14, how the harmonics distortion varies in the whole microgrid can be found in Figure 3.13. However, THD plots provides a more accurate close look at each current, which can be analyzed individually.
Figure 3.13 WSHDL of Study System from 7:00AM to 6:00PM in Stand-alone Mode

Figure 3.14 THD of Study System from 7:00AM to 6:00PM in Stand-alone Mode
3.5 Summary

This chapter discussed the impact of two harmonic sources: PV sources and nonlinear load, in a microgrid in both grid-connected mode and stand-alone mode. Firstly the PV source integration is studied using linear loads; then PV sources are combined with nonlinear loads. While considering only linear loads, this study provides a comparison between two types of PV integrating locations. Then the whole system harmonics distortion level as well as the THD are considered as the main measures to evaluate the power quality and impact of PV integrations. Instead of single PV source, this study investigates mutual influences with multiple PV sources. An actual microgrid with historical-based weather conditions is used as a study system. Simulation results can indicate a discernible look at these negative impacts on the microgrid power quality. In order to make numerical comparison and ranking power quality indices are used to estimate the current distortion from several different perspectives. Three PQ indices are applied and compared to investigate the power distortion, waveform distortion and system unbalance. And using the same models that were applied in grid-connected mode study, stand-alone mode was investigated mainly by THD and WSHDL. Because the slack bus in stand-alone mode is the energy storage battery and diesel generators, it cannot provide power of the same quality as from the grid side. From multiple figures, the microgrid suffers much more from harmonics distortion in stand-alone mode. Simulation models and used matlab codes are shown in Appendix C.
CHAPTER FOUR

CONCLUSION AND FUTURE WORK

The initial motivation of this thesis study is from the special structure of microgrid which might be the future solution of power delivery. As it has been presented above, microgrid is a low-voltage power system with small size capacity and complicated feeder configuration. While analyzing the whole microgrid system, different with simplified mathematical model, detailed models are able to present better view on monitoring and assessment of harmonics. An accurate harmonics study can help reduce power loss, financial loss and operating stability of microgrid.

Given the fact that microgrid is aiming to serve local area, it becomes one of the most promising application platform of renewable energy. Specifically in this thesis, PV integration is analyzed. The major issue of the PV integration is harmonics distortion which is the focus point in this research.

In Chapter One, some related basic background knowledge were presented as the foundation of the research. In addition, previous works by other scholars were mentioned as literature review to give a clear picture of what has been accomplished and what need to be improved. These foundation explains the significance of electrical power system harmonic study, what is microgrid and why it is different from conventional distribution system. In Chapter Two, the main content is that how the components in microgrid are modelled for simulation. PV cell and nonlinear loads were modelled from mathematical
Mathematical equations express the relationship between input and output, mostly in steady state condition. However, the Crossed Frequency Admittance Matrix is able to describe the load response in different harmonic orders. At the same time, control blocks in Simulink can simulate the transient response of inverters. In Chapter Four, the research demonstrated the harmonic distortion monitoring and assessment in an actual microgrid. In order to get valuable data for practical uses, the study system was modeled based on actual load demand, line configuration and meteorological information. An index named as WSHDL is proposed to evaluate the impact of harmonics distortion in both grid-connected and stand-alone mode. Besides WSHDL, there are other three power quality indices, which are Distortion Power Index, Waveform Distortion Index and Symmetrical Components Deviation Index. Each of them can present how electrical power is distorted by harmonics from three different perspectives.

There are three directions for future study: 1) optimization of PV locations in unbalanced microgrid; 2) improvement on renewable energy focused active power filter; 3) communication and control scheme between multiple distributed sources. Given the fact that PV sources can be installed for individual customers or for different locations in microgrid level, then the choices of locations becomes important. As it is studied in this thesis, the mutual influence between two solar inverters cannot be ignored when the capacity is large enough. Therefore the optimization might be able to help improve in both power quality and load sharing aspects. Another direction is to do research in
developing novel active power filter specifically for microgrid. As it was shown in this thesis, harmonics of PV sources can vary a lot and there is no fixed dominant harmonic order because of various inverters’ performance. Future work can be extended on adaptive control scheme of filters. The third direction is also focused on the special structure of microgrid. The biggest difference between microgrid and distribution system is the existence of multiple distributed sources. Because each of the distributed sources has different capacity and weather-dependent characteristic, it is not practical to assume that they will cover the load with stable output in the most optimal way. For renewable energies, for example PV and wind turbines, the output can drop down a large amount within a short time period and meanwhile some other sources, for example batteries or diesel generators, should be able to cover the drop to maintain the power delivery. For this reason, a flexible and optimal communication scheme between distributed sources might show the benefits in the future as well.
REFERENCE


63
Appendix A

Crossed Frequency Admittance Matrix of Composite Load

Table A-1 DBR Matrix

(DBR: 0.67kW with 120V AC power)

<table>
<thead>
<tr>
<th></th>
<th>0.08∠22.00°</th>
<th>0.15∠-145.39°</th>
<th>0.12∠4.36°</th>
<th>0.04∠-128.50°</th>
<th>0.07∠-96.07°</th>
<th>0.04∠-97.07°</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06∠-137.00°</td>
<td>0.38∠49.34°</td>
<td>0.29∠-163.58°</td>
<td>0.17∠13.94°</td>
<td>0.07∠-63.94°</td>
<td>0.10∠99.93°</td>
<td>0.18∠65.00°</td>
<td></td>
</tr>
<tr>
<td>0.03∠76.00°</td>
<td>0.27∠-125.28°</td>
<td>0.38∠40.04°</td>
<td>0.32∠-168.50°</td>
<td>0.06∠-23.73°</td>
<td>0.03∠-45.48°</td>
<td>0.05∠145.87°</td>
<td></td>
</tr>
<tr>
<td>0.01∠-25.00°</td>
<td>0.06∠59.86°</td>
<td>0.24∠-132.11°</td>
<td>0.41∠35.77°</td>
<td>0.31∠177.78°</td>
<td>0.14∠-33.37°</td>
<td>0.05∠-42.37°</td>
<td></td>
</tr>
<tr>
<td>0.01∠-90.00°</td>
<td>0.08∠84.92°</td>
<td>0.09∠61.91°</td>
<td>0.25∠-139.35°</td>
<td>0.48∠33.26°</td>
<td>0.31∠174.67°</td>
<td>0.08∠-7.74°</td>
<td></td>
</tr>
<tr>
<td>0.01∠142.00°</td>
<td>0.06∠-85.55°</td>
<td>0.03∠97.14°</td>
<td>0.09∠56.82°</td>
<td>0.31∠-134.84°</td>
<td>0.46∠37.03°</td>
<td>0.29∠-178.74°</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.02∠-70.87°</td>
<td>0.05∠-76.69°</td>
<td>0.03∠72.41°</td>
<td>0.09∠73.95°</td>
<td>0.29∠-133.32°</td>
<td>0.52∠34.79°</td>
<td></td>
</tr>
</tbody>
</table>
Table A-2 CFL Matrix

(CFL: 15W with 120V AC power)

<table>
<thead>
<tr>
<th>0.0016∠38.00°</th>
<th>0.0023∠133.36°</th>
<th>0</th>
<th>0.0015∠97.12°</th>
<th>0.0018∠88.29°</th>
<th>0.002∠57.10°</th>
<th>0.0023∠79.83°</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0012∠-81.00°</td>
<td>0.0058∠83.31°</td>
<td>0.0037∠-148.97°</td>
<td>0.0036∠63.03°</td>
<td>0.0045∠-113.27°</td>
<td>0.0034∠144.30°</td>
<td>0.0049∠139.50°</td>
</tr>
<tr>
<td>0.0008∠172.00°</td>
<td>0.0059∠-60.59°</td>
<td>0.0076∠78.08°</td>
<td>0.0079∠-123.18°</td>
<td>0.0076∠-22.81°</td>
<td>0.0019∠-50.85°</td>
<td>0.0039∠7.03°</td>
</tr>
<tr>
<td>0</td>
<td>0.0034∠107.18°</td>
<td>0.0145∠-31.62°</td>
<td>0.0207∠71.80°</td>
<td>0.0069∠-152.46°</td>
<td>0.0101∠33.42°</td>
<td>0.0094∠-57.11°</td>
</tr>
<tr>
<td>0</td>
<td>0.0011∠108.69°</td>
<td>0.0073∠-171.54°</td>
<td>0.0132∠-64.63°</td>
<td>0.0134∠80.29°</td>
<td>0.0149∠-143.40°</td>
<td>0.0098∠-27.19°</td>
</tr>
<tr>
<td>0.0026∠-86.56°</td>
<td>0.0259∠-44.56°</td>
<td>0.0469∠-4.72°</td>
<td>0.0457∠69.96°</td>
<td>0.0286∠-8.84°</td>
<td>0.0665∠80.06°</td>
<td>0.0423∠-52.52°</td>
</tr>
<tr>
<td>0</td>
<td>0.0020∠-61.40°</td>
<td>0.0025∠-23.92°</td>
<td>0.0028∠98.85°</td>
<td>0.0075∠-166.76°</td>
<td>0.0136∠-46.33°</td>
<td>0.0230∠80.89°</td>
</tr>
</tbody>
</table>
**Table A-3 PAVC Matrix**

(DBR: 0.9kW with 120V AC power)

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0966° -5.00°</td>
<td>0.0178°-174.81°</td>
<td>0.0101°164.85°</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.0080°156.00°</td>
<td>0.0071°3.7301°</td>
<td>0.0137°96.76°</td>
<td>0.0030°173.73°</td>
<td>0</td>
<td>0.0012°86.00°</td>
<td>0</td>
</tr>
<tr>
<td>0.0046°7.00°</td>
<td>0.0118°-6.60°</td>
<td>0.0839°5.01°</td>
<td>0.0034°68.28°</td>
<td>0.0016°98.91°</td>
<td>0.0008°-153.50°</td>
<td>0.0003°-113.10°</td>
</tr>
<tr>
<td>0.0010°-86.00°</td>
<td>0.0011°59.29°</td>
<td>0.0028°-61.91°</td>
<td>0.0908°5.54°</td>
<td>0</td>
<td>0</td>
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</tr>
<tr>
<td>0</td>
<td>0.0010°68.94°</td>
<td>0.0007°-73.71°</td>
<td>0.0009°-72.93°</td>
<td>0.0929°4.3399°</td>
<td>0</td>
<td>0</td>
</tr>
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<td>0.0010°32.54°</td>
<td>0</td>
<td>0</td>
<td>0.0286°-8.84°</td>
<td>0.0940°80.06°</td>
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</tr>
<tr>
<td>0</td>
<td>0.0006°10.60°</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.0945°2.80°</td>
</tr>
</tbody>
</table>
Appendix B

Line Data Calculation of the Study System

Line Construction Types:

A

Ground wire position is at 45 feet for all pole types

B

C

D

Same for A and B phases
### Table B-1 Line Data of the Study System

<table>
<thead>
<tr>
<th>Line Number</th>
<th>From Bus</th>
<th>To Bus</th>
<th>Line Length (Miles)</th>
<th>Phasing</th>
<th>Conductor Type and Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>20</td>
<td>0.48</td>
<td>ABC</td>
<td>A 336</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>30</td>
<td>0.4</td>
<td>ABC</td>
<td>A 336</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>31</td>
<td>0.2</td>
<td>AB</td>
<td>D 4/0</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>34</td>
<td>0.45</td>
<td>ABC</td>
<td>B 4/0</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>40</td>
<td>0.5</td>
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<td>B 336</td>
</tr>
<tr>
<td>5</td>
<td>31</td>
<td>32</td>
<td>0.2</td>
<td>A</td>
<td>C 4/0</td>
</tr>
<tr>
<td>6</td>
<td>31</td>
<td>33</td>
<td>0.2</td>
<td>B</td>
<td>C 4/0</td>
</tr>
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<td>7</td>
<td>40</td>
<td>41</td>
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<td>ABC</td>
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<tr>
<td>8</td>
<td>40</td>
<td>50</td>
<td>0.6</td>
<td>ABC</td>
<td>B 336</td>
</tr>
<tr>
<td>9</td>
<td>50</td>
<td>51</td>
<td>0.4</td>
<td>AB</td>
<td>D 4/0</td>
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<tr>
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<td>50</td>
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<td>0.55</td>
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<td>B 336</td>
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<td>60</td>
<td>61</td>
<td>0.4</td>
<td>ABC</td>
<td>B 4/0</td>
</tr>
<tr>
<td>12</td>
<td>60</td>
<td>62</td>
<td>0.6</td>
<td>C</td>
<td>C 4/0</td>
</tr>
</tbody>
</table>

In the initial design all phase conductors are either 336,400 - 26/7 strands ACSR or 4/0 - 6/1 strands ACSR. See line data for each line section’s configuration and size. Neglect line capacitance. Ground conductors are all 2/0 – 6/1 strands ACSR.

Type A336 Impedance:

\[
Z_{abc} = \begin{bmatrix}
0.4503 + 1.0721i & 0.1722 + 0.5045i & 0.1723 + 0.4265i \\
0.1722 + 0.5045i & 0.4501 + 1.0728i & 0.1722 + 0.5045i \\
0.1723 + 0.4265i & 0.1722 + 0.5045i & 0.4503 + 1.0721i
\end{bmatrix} \quad (\Omega/\text{mi})
\]
Type B4/0 Impedance:

\[ Z_{abc} = \begin{bmatrix}
0.5450 + 1.4311i & 0.1021 + 0.4886i & 0.1053 + 0.3924i \\
0.1021 + 0.4886i & 0.5497 + 1.4134i & 0.1082 + 0.4665i \\
0.1053 + 0.3924i & 0.1082 + 0.4665i & 0.5574 + 1.3863i
\end{bmatrix} \text{ (Ω/mi)} \]

Type B336 Impedance:

\[ Z_{abc} = \begin{bmatrix}
0.3780 + 1.2981i & 0.1021 + 0.4886i & 0.1053 + 0.3924i \\
0.1021 + 0.4886i & 0.3827 + 1.2804i & 0.1082 + 0.4665i \\
0.1053 + 0.3924i & 0.1082 + 0.4665i & 0.3904 + 1.2533i
\end{bmatrix} \text{ (Ω/mi)} \]

Type C4/0 Impedance:

\[ Z_c = [0.3333 + 0.9913i] \text{ (Ω/mi)} \]

Type D4/0 Impedance:

\[ Z_{ab} = \begin{bmatrix}
0.5560 + 1.3908i & 0.1110 + 0.3378i \\
0.1110 + 0.3378i & 0.5560 + 1.3908i
\end{bmatrix} \text{ (Ω/mi)} \]
Appendix C

Simulation Models and Matlab Codes

1. Test System Simulation Model

Figure C-1: Microgrid Test System
2. Composite Nonlinear Load Simulation Model

Figure C-2: Three Phase Nonlinear Load Connection

Figure C-3: Nonlinear Load by Cross Frequency Admittance Matrix
3. Active Power Filter Inverter Control

Figure C-4: Voltage Matrix Formation

Figure C-5: Active Power Filter Inverter Control
4. DC Battery Droop Control Blocks

![Diagram of DC Battery Droop Control Blocks]

Figure C-6: Active Power Calculation

![Diagram of Active Power Calculation]

Figure C-7: Voltage Reference in dq Axis

![Diagram of Voltage Reference in dq Axis]
Figure C-8: PWM Signal Generation

5. System Impedance Calculation Example (from Bus 10 to Bus 30)

```matlab
%%Calculate impedance from Bus 10 TO BUS 30

%%Phase ABC
%%From Bus 10 To Bus 20 length 0.48mi
%%A336

%% Impedance ohms per mile
Zaa=0.3733+i*1.413;
Zbb=0.3733+i*1.413;
Zcc=0.3733+i*1.413;
Zab=0.09528+i*0.8451;
Zac=0.09528+i*0.7674;
Zbc=0.09528+i*0.8451;

Zww=0.8013+i*1.603;
Zwa=0.09528+i*0.7857;
Zwb=0.09528+i*0.7848;
Zwc=0.09528+i*0.7857;

Zabc=[Zaa Zab Zac Zwa;
      Zab Zbb Zbc Zwb;
      Zac Zbc Zcc Zwc;
      Zwa Zwb Zwc Zww;]

%****************************************
%Kron Reduction
%```
\[ K = Z_{abc}(1:3,1:3); \]
\[ L = Z_{abc}(1:3,4); \]
\[ M = Z_{abc}(4,4); \]
\[ L_t = Z_{abc}(4,1:3); \]
\[ Z_{abc\_sim} = K - L*\text{inv}(M)*L_t \]
\[ \text{Length 0.48 mi} \]
\[ Z_{abc\_10\_20} = Z_{abc\_sim}*0.48; \]
\[ \text{From Bus 20 To 30 length 0.4mi} \]
\[ Z_{abc\_20\_30} = Z_{abc\_sim}*0.4; \]
\[ Z_{abc\_com} = [Z_{abc\_10\_20} \quad Z_{abc\_20\_30}; \]
\[ \quad \quad Z_{abc\_20\_30}.' \quad Z_{abc\_10\_20} + Z_{abc\_20\_30};] ; \]
\[ \text{Impedance from Bus 10 To Bus 30} \]
\[ Z_{abc\_10\_30} = Z_{abc\_com} \]

6. Crossed Frequency Admittance Matrix Calculation Example (PAVC)

\\texttt{%%%%%%%%%%%%%%%%%%PAVC Matrix 0.9kW %%%%%%%%%%%%%%%%%}

\\texttt{in this case only 1st, 3rd, 5th, 7th, 9th, 11th, 13th, 15th} \n\\texttt{120 V rms} \n\\texttt{V1=120;}

\\texttt{I1=zeros(1,7);} 
\\texttt{I1(1,1)=16.4*cos(-5/180*pi)+16.4*sin(-5/180*pi)*j; \}
\\texttt{I1(1,2)=1.36*cos(156/180*pi)+1.36*sin(156/180*pi)*j; \}
\\texttt{I1(1,3)=0.78*cos(7/180*pi)+0.78*sin(7/180*pi)*j; \}
\\texttt{I1(1,4)=0.172*cos(-86/180*pi)+0.172*sin(-86/180*pi)*j; \}
\\texttt{I1(1,5)=0.057*cos(171/180*pi)+0.057*sin(171/180*pi)*j; \}
\\texttt{I1(1,6)=0.044*cos(72.8/180*pi)+0.044*sin(72.8/180*pi)*j; \}
\\texttt{I1(1,7)=0.034*cos(-1/180*pi)+0.034*sin(-1/180*pi)*j; \}
\\texttt{for k=1:1:7; \}
\\texttt{Y2(k,1)=I1(1,k)/sqrt(2)/V1; \}
\\texttt{end} 

\\texttt{120*10% V rms 60degree 3rd harmonics}
V3=120*0.1*cos(60/180*pi)+120*0.1*sin(60/180*pi)*j;

I2=zeros(1,7);
I2(1,1)=16.3*cos(-6/180*pi)+16.3*sin(-6/180*pi)*j;
I2(1,2)=1.85*cos(111/180*pi)+1.85*sin(111/180*pi)*j;
I2(1,3)=0.93*cos(16/180*pi)+0.93*sin(16/180*pi)*j;
I2(1,4)=0.174*cos(-80/180*pi)+0.174*sin(-80/180*pi)*j;
I2(1,5)=0.07*cos(162/180*pi)+0.07*sin(162/180*pi)*j;
I2(1,6)=0.06*cos(78.2/180*pi)+0.06*sin(78.2/180*pi)*j;
I2(1,7)=0.038*cos(12.5/180*pi)+0.038*sin(12.5/180*pi)*j;

for k=1:1:7;
    Y2(k,2)=(I2(1,k)/sqrt(2)-Y2(k,1)*V1)/V3;
end

%%120*5% V rms 100degree 5th harmonics
V5=120*0.05*cos(100/180*pi)+120*0.05*sin(100/180*pi)*j;

I3=zeros(1,7);
I3(1,1)=16.4*cos(-5.3/180*pi)+16.4*sin(-5.3/180*pi)*j;
I3(1,2)=1.45*cos(159/180*pi)+1.45*sin(159/180*pi)*j;
I3(1,3)=0.98*cos(53/180*pi)+0.98*sin(53/180*pi)*j;
I3(1,4)=0.16*cos(-79/180*pi)+0.16*sin(-79/180*pi)*j;
I3(1,5)=0.052*cos(167/180*pi)+0.052*sin(167/180*pi)*j;
I3(1,6)=0.045*cos(69/180*pi)+0.045*sin(69/180*pi)*j;
I3(1,7)=0.035*cos(1/180*pi)+0.035*sin(1/180*pi)*j;

for k=1:1:7;
    Y2(k,3)=(I3(1,k)/sqrt(2)-Y2(k,1)*V1)/V5;
end

%%120*5% V rms 50degree 7th harmonics
V7=120*0.05*cos(50/180*pi)+120*0.05*sin(50/180*pi)*j;

I4=zeros(1,7);
I4(1,1)=16.4*cos(-5/180*pi)+16.4*sin(-5/180*pi)*j;
I4(1,2)=1.37*cos(157/180*pi)+1.37*sin(157/180*pi)*j;
I4(1,3)=0.77*cos(9/180*pi)+0.77*sin(9/180*pi)*j;
I4(1,4)=0.645*cos(46/180*pi)+0.645*sin(46/180*pi)*j;
I4(1,5)=0.05*cos(173/180*pi)+0.05*sin(173/180*pi)*j;
I4(1,6)=0.04*cos(69/180*pi)+0.04*sin(69/180*pi)*j;
I4(1,7)=0.034*cos(-5/180*pi)+0.034*sin(-5/180*pi)*j;
for k=1:1:7;
    Y2(k,4)=(I4(1,k)/sqrt(2)-Y2(k,1)*V1)/V7;
end

%%120*5% V rms 45degree 9th harmonics

V9=120*0.05*cos(45/180*pi)+120*0.05*sin(45/180*pi)*j;
I5=zeros(1,7);
I5(1,1)=16.4*cos(-5/180*pi)+16.4*sin(-5/180*pi)*j;
I5(1,2)=1.36*cos(156/180*pi)+1.36*sin(156/180*pi)*j;
I5(1,3)=0.77*cos(7.7/180*pi)+0.77*sin(7.7/180*pi)*j;
I5(1,4)=0.165*cos(-85/180*pi)+0.165*sin(-85/180*pi)*j;
I5(1,5)=0.76*cos(53/180*pi)+0.76*sin(53/180*pi)*j;
I5(1,6)=0.042*cos(68/180*pi)+0.042*sin(68/180*pi)*j;
I5(1,7)=0.035*cos(-4/180*pi)+0.035*sin(-4/180*pi)*j;
for k=1:1:7;
    Y2(k,5)=(I5(1,k)/sqrt(2)-Y2(k,1)*V1)/V9;
end

%%12*0.1 rms  70 degree  11th harmonics

V11=120*0.1*cos(70/180*pi)+120*0.1*sin(70/180*pi)*j;
I6=zeros(1,7);
I6(1,1)=16.4*cos(-5/180*pi)+16.4*sin(-5/180*pi)*j;
I6(1,2)=1.38*cos(156/180*pi)+1.38*sin(156/180*pi)*j;
I6(1,3)=0.78*cos(6/180*pi)+0.78*sin(6/180*pi)*j;
I6(1,4)=0.17*cos(-88/180*pi)+0.17*sin(-88/180*pi)*j;
I6(1,5)=0.063*cos(165/180*pi)+0.063*sin(165/180*pi)*j;
I6(1,6)=1.64*cos(72/180*pi)+1.64*sin(72/180*pi)*j;
I6(1,7)=0.038*cos(1/180*pi)+0.038*sin(1/180*pi)*j;
for k=1:1:7;
    Y2(k,6)=(I6(1,k)/sqrt(2)-Y2(k,1)*V1)/V11;
end

%%120*0.05 rms  30 degree  13th harmonics

V13=120*0.05*cos(30/180*pi)+120*0.05*sin(30/180*pi)*j;
I7=zeros(1,7);
I7(1,1)=16.4*cos(-5/180*pi)+16.4*sin(-5/180*pi)*j;
I7(1,2)=1.36*cos(156/180*pi)+1.36*sin(156/180*pi)*j;
I7(1,3)=0.78*cos(6.8/180*pi)+0.78*sin(6.8/180*pi)*j;
I7(1,4)=0.172*cos(-86/180*pi)+0.172*sin(-86/180*pi)*j;
I7(1,5)=0.06*cos(170/180*pi)+0.06*sin(170/180*pi)*j;
\[ I_7(1,6)=0.045\cos\left(\frac{73}{180}\pi\right)+0.045\sin\left(\frac{73}{180}\pi\right)j; \]
\[ I_7(1,7)=0.83\cos\left(\frac{31.5}{180}\pi\right)+0.83\sin\left(\frac{31.5}{180}\pi\right)j; \]

\[
\text{for } k=1:1:7; \\
\quad Y_2(k,7)=\left(\frac{I_7(1,k)}{\sqrt{2}}-Y_2(k,1)*V_1\right)/V_13; \\
\text{end}
\]

\[ Y_2 \]

\[
\text{for } x=1:1:7 \\
\quad \text{for } y=1:1:7 \\
\quad \quad \text{fprintf('%4.4f %4.4f
',abs(Y_2(x,y)),angle(Y_2(x,y))/\pi*180);} \\
\quad \text{end} \\
\text{end}
\]