Analysis and Implementation of Grid-Connected Solar PV with Harmonic Compensation

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ANALYSIS AND IMPLEMENTATION OF GRID-CONNECTED SOLAR PV WITH HARMONIC COMPENSATION

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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>RES</td>
<td>Renewable Energy Sources</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
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<tr>
<td>MPPT</td>
<td>Maximum Power Point Tracking</td>
</tr>
<tr>
<td>C&amp;S</td>
<td>Codes and Standards</td>
</tr>
<tr>
<td>MPP</td>
<td>Maximum Power Point</td>
</tr>
<tr>
<td>THD</td>
<td>Total Harmonic Distortion</td>
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<tr>
<td>PCC</td>
<td>Point of Common Coupling</td>
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<tr>
<td>VSI</td>
<td>Voltage Source Inverter</td>
</tr>
<tr>
<td>EMI</td>
<td>Electromagnetic Interference</td>
</tr>
<tr>
<td>APF</td>
<td>Active Power Filter</td>
</tr>
<tr>
<td>PCS</td>
<td>Power Conditioning System</td>
</tr>
<tr>
<td>FRT</td>
<td>Fault Ride Through</td>
</tr>
<tr>
<td>UPS</td>
<td>Uninterruptible Power Supply</td>
</tr>
<tr>
<td>DSP</td>
<td>Digital Signal Processor</td>
</tr>
<tr>
<td>SFS</td>
<td>Sandia Frequency Shift</td>
</tr>
<tr>
<td>SMS</td>
<td>Slip Mode Frequency Shift</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>CSP</td>
<td>Concentrated Solar Power</td>
</tr>
<tr>
<td>IncCond</td>
<td>Incremental Conductance</td>
</tr>
<tr>
<td>P&amp;O</td>
<td>Perturbation and Observation</td>
</tr>
<tr>
<td>RTI</td>
<td>Real Time Interface</td>
</tr>
<tr>
<td>PLL</td>
<td>Phase Locked Loop</td>
</tr>
<tr>
<td>CVT</td>
<td>Constant Voltage Tracking</td>
</tr>
<tr>
<td>PI</td>
<td>Proportional and Integral</td>
</tr>
<tr>
<td>IRPT</td>
<td>Instantaneous Reactive Power Theory</td>
</tr>
<tr>
<td>DFT</td>
<td>Discrete Fourier Transform</td>
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ABSTRACT

A grid-connected photovoltaic (PV) system with the functionality of harmonic compensation is introduced in this thesis. Based on this, a test bed is built up to validate the practicability of the proposed scheme. Increasing interest and investment in renewable energy give rise to rapid development of high penetration solar energy. There are multiple ways to interface PV arrays with the power grid. The topology of a multi-string two-stage PV module with a centralized inverter is developed in the thesis, which is more suitable for medium power applications. However, the output of solar arrays varies due to change of solar irradiation and weather conditions. Therefore, the maximum power point tracking algorithm is implemented in DC/DC converter to enable PV arrays to operate at maximum power point. The incremental conductance algorithm is employed to control the boost converter. Then the central inverter is controlled by decoupled current control algorithm and interfaced with the utility grid via the distribution network. Besides, the current control of the inverter is independent of maximum power point control of the DC/DC converter. Finally, system performance and transient responses are analyzed under the disturbance conditions. And system stability is evaluated when solar irradiation change or system fault happens. The system is simulated in MATLAB™.

More and more use of static power converter and switched mode power supplies injects harmonic current into the power system. It’s advisable that PV can be controlled to compensate the harmonic current as well as supply the active power. The harmonic current is extracted by using time-domain current detection method, which is much easier to implement and doesn’t need any transformation comparing with the instantaneous power theory method. The system simulation is accomplished and validated by using PSCAD/EMTDC™. Meanwhile, experimental test bed is also established to verify the proposed algorithm. Eventually, the total harmonic distortion (THD) of the grid current after compensation is analyzed and compared with the standard of IEEE 519-1992.
CHAPTER 1

INTRODUCTION

1.1 Motivation

Over the past few decades, the demand for renewable energy has increased significantly due to the disadvantages of fossil fuels and greenhouse effect. Among various types of renewable energy sources (RES), solar energy and wind energy have become the most promising and attractive because of advancement in power electronic technique. Photovoltaic (PV) sources are used nowadays in many applications as they own the advantage of being maintenance and pollution free. In the past few years, solar energy sources demand has grown consistently due to the following factors: 1) increasing efficiency of solar cells; 2) manufacturing technology improvement; and 3) economies of scale. Meanwhile, more and more PV modules have been and will be connected to utility grid in many countries. Now the largest PV power plant is more than 100MW all over the world. Furthermore, the output of PV arrays is influenced by solar irradiation and weather conditions. More importantly, high initial cost and limited life span of PV panels make it more critical to extract as much power from them as possible. Therefore, maximum power point tracking (MPPT) technique should be implemented in DC/DC converter to achieve maximum efficiency of PV arrays. Several algorithms have been developed to achieve MPPT technique.

As the capacity of PV system growing significantly, the impact of PV modules on power grid can’t be ignored. They can cause problems on the grid like flicker, increase of harmonics, and aggravated stability of the power system. To both increase the capacity of PV arrays and maintain power quality, it’s necessary to comply with the technique requirements of the PV system, such as fault-ride-through capability and harmonic current regulation. Especially when a large scale PV module is connected to the grid, the effects on the grid may be quite severe. Therefore, the system operation and system stability under fault conditions should be examined when PV modules are interface with power grid.
Increasing use of static power converters like rectifiers and switched mode power supplies causes injection of harmonic currents into the distribution system. Current harmonics produce voltage distortions, current distortions, and unsatisfactory operation of power systems. Therefore, harmonic mitigation plays an essential role in grid-connected PV system. IEEE Std. 519 was first introduced in 1981 and most recently revised in 1992 to provide direction on dealing with harmonics produced by static power converters and nonlinear loads. This standard helps to prevent harmonics from negatively affecting the utility grid. In this thesis, as well as supplying active power, PV inverter can be controlled to provide harmonic currents needed by nonlinear loads so that the current on the grid side can be approximately sinusoidal, at least complies with the IEEE Std. 519. This concept is simulated successfully in the simulation environment. Then, the test bed is constructed and the components required consist of: a DC power source, a DC/AC inverter, a LC filter, and a grid voltage supply. Once validated the hardware test could provide useful insight into future test in power system at a higher power level.

1.2 Literary Review

Development in PV technology and improvement in balance of system components, as well as experience gained from thousands of system installation, PV energy cost and performance have improved to the point where a large off-grid market is flourishing and the on-grid market is nearly economic. More and more integration of PV modules may lead to some operational problems in the electric network.

Many previous works deal with high penetration of PV system into power grid. Status in identifying and reviewing photovoltaic (PV) codes and standards (C&S) was reported in [1]. Related electrical activities for grid-connected, high-penetration PV systems with utility distribution grid interconnection were also explored. It included identifying topics and concerns not yet in the scope of existing C&S documents, identifying C&S-related ongoing work and approaches, and providing recommendations related to C&S needs. Currently, interconnection C&S in the US had been developed based on passive participation of PV systems in the grid. As higher levels of PV systems were integrated into the electric power system, these PV systems could play an active role in both the technical and business operations of the utility grid and in the customer
facility and loads management. Therefore, addressing grid-integration technical and analytical issues was a necessary prerequisite for the long-term viability of the distributed renewable energy PV industry, and in particular, that was paramount for high penetration.

Impacts of large scale and high voltage level photovoltaic penetration on the security and stability of power system were discussed in [2]. The main technical impacts of large scale PV generations on power grid were: electricity quality, power flow control, voltage and frequency stability, new requirements to simulation technologies and power system test environment, codes and standards revising or supplementing of grid operation and dispatching. Several research fields were proposed to meet the practical and research requirements: 1) modeling methods of PV systems; 2) dynamic characteristics of power grid with PV systems connected; 3) power systems analyzing and calculating technology with PV systems contained; 4) control technology of grid-connected PV systems; 5) revising and supplementing of the existing power systems rules and codes. Various models and algorithms were examined, simulated and tested for the purpose of analyzing the grid-connected PV system performance. In [3], a 3 MW PV system with the distribution system was modeled in Matlab/Simulink. The modeled PV system based on the equivalent circuits of the PV cell considered the number of series and parallel connections of PV cells and the changes in the temperature and irradiation level. The oscillation of voltage and current occurred after the initiation of the fault. In all fault types, the PV array was not operating at maximum power point (MPP). The output power of the PV array in the case of the three-phase fault was the smallest, while the output power of the PV array in the case of the single line-to-ground fault was the largest. Meanwhile, islanding situation was studied in [4], which focused on the fault contribution of a grid-connected PV system in the event of an unintentional islanding. An experimental setup was created using an off-the-shelf grid-connected inverter to emulate the event of a fault occurred on a distribution feeder. The experimental results had shown that, without violating the specified criteria in the standard, the grid-connected inverter took time to detect an islanding condition and stop energizing. It also showed that higher penetration level of the PV grid-connected systems resulted in higher fault current which unavoidably had effects on the protective devices. To effectively detect islanding, feed-forward compensation was proposed in [5]. This detection scheme came into operation
when frequency, voltage, total harmonic distortion (THD), or impedance at the point of
common coupling (PCC) exceeded the set thresholds due to opening of the breaker on the
grid-side. The islanding detection capability was enhanced if any of these quantities were
used as a feed-forward signal in the control scheme. And the detection was based on the
measurement of voltage. In addition to the standard RLC load, an induction machine was
also used for studying the islanding behavior of the grid-connected PV system. Besides
the simulation and experimental results, analysis from the mathematical point of view
had been done to understand the phenomena better.

In [6], a novel approach based on eigenvalue algorithm and nonlinear model
simulation was conducted to investigate both transient and steady-state performance of a
single-phase two-stage PV array connected to a utility grid. The transient responses of the
studied system under disturbance conditions were also examined. A mathematical model
of grid-connected photovoltaic (PV) energy sources suitable for stability studies was
presented in [7]. Eigenvalue analysis was mainly introduced to define regions of
attraction that determine the dynamics of the converter states. Results showed that the
system was more susceptible to instability under high loading levels, i.e. when operating
close to its maximum power point, which was due to the small margin available in order
to withstand any disturbance. However, further research needed to focus on the
determination of stability margins and operating limits, as well as the development of
better control strategies to deal with disturbances in power grid. Eigenvalue analysis was
further studied in [8] to determine the stability boundary of a grid-connected multiple PV
systems. The effect of random fluctuations on PV modules such as cloudy weather
condition was analyzed when multiple PV systems interfaced with a utility grid. The
eigenvalue schemes were very effective to determine dynamic stability limits and
transient behaviors of the studied grid-connected multiple PV systems under different
operating points and various disturbance conditions.

A new control strategy of inner current-control loop and an outer dc-link voltage-
control loop was adopted in [9]. The current-control strategy permitted dc-link voltage
regulation and enabled power-factor control. Moreover, the current-control significantly
decoupled dynamics of the PV system from those of the distribution network and the
loads. The dc-link voltage-control scheme enabled the control and maximization of the
real-power output of the PV system. And the effectiveness of the control strategy was verified through digital time-domain simulation studies conducted on a detailed switched model of the whole system. In addition, a model/sensitivity analysis was conducted on a linearized model of the system to characterize the dynamic properties of the PV system, to evaluate robustness of the controllers, and to identify the nature of interactions between the PV system and the network. In [10], DC bus model was introduced in multi-string PV system, and distribution network was also presented on grid side. Decoupled current control was employed in the voltage source inverter (VSI) to control the power injected into the network. The transient responses of the system were studied under disturbance conditions such as sudden change of solar irradiation, fault in the distribution network and fault in the DC bus. To reduce the enormous increase in DC link voltage under fault condition, the storage system was introduced in [11]. The storage system consisted of a storage capacitor, resistor and inductor in series. And the storage system controller was designed to absorb the solar power under fault conditions. Then a multi-level inverter was proposed since it offered great advantages such as lower THD, improved output waveform, lower Electromagnetic Interference (EMI) and others, compared with two-level inverter for the same switching frequency. Two symmetrical triangular carriers were employed to generate the switching decisions for the nine-switch three-level inverter.

More and more nonlinear loads like rectifier circuits and switched mode power supplies result in injection of harmonic currents into electric power distribution network. Installation of active filter could be one of the solutions to mitigate the harmonic. On the other hand, photovoltaic (PV) systems can be controlled to operate as an active power filter (APF), as well as supplying power to grid. A high performance harmonic current reduction control scheme had been presented in [12]. Its purpose was to reduce the harmonic current that flew through a power conditioning system (PCS) by outputting harmonic voltage equal to the one that contained in the grid. The control scheme did not use grid current and had low interference with the existing current control and fault-ride-through (FRT) capability. Extraction algorithm for the harmonic voltages enabled the voltage source inverter (VSI) in the PV generation system to output harmonic voltages that were very close to the harmonic voltage of the grid. A 400-kW PCS with the
proposed control scheme was installed and tested to prove the validity of the control algorithm. In [13], a compensating current by the surplus of the inverter capacity was generated in order to mitigate the voltage distortion at the load terminal. And the system could modify its compensation gain within the inverter capacity according to the solar cell output. But PV inverter was connected to power system network by a special interconnected inductance network. PV system was interfaced with an active filter to transfer the PV power to the AC local loads and improve power quality problems like current harmonics cancelation and reactive power compensation in [14]. And two configurations were presented to connect PV panel to the network. In the first configuration the output voltage of PV module was equal to the DC bus voltage in maximum power point of it, and then the PV module was connected directly to active filter. While in the second configuration, due to the low voltage of PV module, it was connected to active filter with a boost DC/DC converter. A photovoltaic (PV) grid-connected power conditioning system with the function of uninterruptible power supply (UPS) was presented in [15]. It could not only realize photovoltaic generation, but also had full function of shunt active power filter (APF). The instantaneous reactive power theory was employed in harmonics current detecting and signal synthesis algorithm of reference current. The proposed control strategy had two control modes: grid connection mode and UPS mode, which could switch to each other automatically. And a double loop control method was used in UPS mode in order to achieve fast response. A novel boost converter and dual-level four-leg inverter was proposed in [16]. Comparing with single-stage three-phase three-wire PV system, the proposed system not only allowed a wide range of input voltage, but also compensated unbalanced loads current. The key of the unified control was the current reference generation. Proposed topology and control method were applied to a 100kVA grid-connected PV system based on FPGA+DSP controller. [17] described a grid-connected PV system with the function of active power filter (APF), in which a Z-source network was employed to boost the DC bus voltage during periods when the PV array output was low. The active power was synthesized into reference current via instantaneous pq theory. However, the instantaneous pq theory couldn’t do selective harmonic detection. A novel time-domain current detection algorithm for shunt active power filters was analyzed in [18]. Comparing with existing
algorithms, this algorithm had shorter response time delay and clearer physical meaning. Different compensating current references could be accurately and easily obtained by adopting the proposed algorithm. Moreover, it was very easy to implement this algorithm in a digital signal processor (DSP). On this basis, a 100-kVA active power filter was developed, and the research of simulation and experiment was also done. The results of the simulation indicated that this algorithm can detect the active power, reactive power, positive-sequence, negative-sequence and each selected harmonics below 25\textsuperscript{th} expediently and quickly. Anti-islanding method and active power filter were combined in [19]. It was more difficult to detect islanding when multiple PV system was connected to the same distribution line than the single PV system. Two PV modules and one active power filter were connected to the same power grid. Sandia frequency shift (SFS) method and slip mode frequency shift (SMS) method were adopted for the general PV system. The effectiveness of islanding detection under multiple PV system was validated through PSCAD/EMTDC\textsuperscript{TM} based simulation model.

In the thesis, time-domain harmonic current detection is implemented and proved to have the same performance as instantaneous pq theory. More importantly, time-domain method doesn’t use any transformation and selective harmonic extraction is possible.

Finally, IEEE Std. 519 provided direction on dealing with harmonics introduced by static power converters and nonlinear loads as shown in [20]. The IEEE Std. 519 specified the permissible voltage and current distortions in a grid for efficient power transmission and distribution. And Fast Fourier Transform (FFT) was used to analyze the harmonics injected into the distribution network. These works will be discussed in following sections of the thesis.

1.3 Future Application

Over the past few decades, the photovoltaic (PV) market has grown radically and the price for PV systems has decreased rapidly due to technology development in solar cell manufacture and performance improvement on efficiency conversion. Nowadays, PV systems are usually used in three main fields:

(1) Satellite applications, where the solar panels provide power to satellite.
(2) Off-grid applications, where solar arrays are used to power remote load that are not connected to power grid.

(3) Grid-connected applications, in which solar arrays are used to supply solar energy to local loads as well as the electric grid.

Resulted from the world’s fast growing energy demand and improvement on solar technology, more and more large scale solar power station will be installed and connected to electric grid such as concentrated solar power (CSP). CSP systems use lenses or mirrors and tracking systems to focus a large area of sunlight into a small beam using the photoelectric effect. The first commercial CSP plant was developed in the 1980s. Since then large scale CSP plants are widely installed all over the world. Other applications in future for solar energy include solar chemical, solar vehicles and etc.

As the increasing installation of grid-connected PV systems, especially large systems in the order of megawatts, might lead to some operational problems in the electric network. Such negative impacts include power and voltage fluctuation problems, harmonic distortion, malfunctioning of protective devices and so on. This may still prevent further share of grid-connected PV system in electricity market. Therefore, studying the possible impacts of PV systems on the electric network is and will be becoming an important issue and receiving a lot of attention from both researchers and electric utilities. For example, different algorithms are developed to mitigate the harmonics injected into the electric network. Active power filter is one of the most used methods. However, the algorithm discussed in the thesis is the most simple, effective and easy to implement.

And more research will also focus on dynamic response and system performance when interfaced with power grid, like sudden grid voltage change, system fault both in AC and DC side, solar irradiation change and etc. Various control schemes have been developed to detect faults and to protect devices and the system. For instance, anti-islanding scheme has been equipped for solar energy interfaced with utility system to ensure personnel safety and power quality.

Another issue is that the output power of solar system depends on solar irradiance. Therefore, a lot of research will be focused on the effect of solar irradiance on the PV system. Models are going to be required to estimate the irradiance on the surface of the
PV system, for which the accuracy of the models is usually dependant on the location where the PV system is installed. Meanwhile, the fluctuations in irradiance due to pass of cloud also receives a lot of attentions.

Finally, the use of storage devices with PV systems will gain more and more attention. These devices can be used to bridge fluctuations in the output power of PV systems, shift the peak generations of the system to match the load peaks, and provide reactive power support. However, more effort needs to be put to reduce the high cost associated with their installation, as well as to increase the capacity of energy storage.
CHAPTER 2
SYSTEM DESCRIPTION

2.1 Simulation Description

A multi-string photovoltaic (PV) system interfaced with distribution network is analyzed in the thesis. Figure 2-1 illustrates the one-line schematic diagram of the system. The main building blocks of the PV system are PV modules, DC transmission line, a voltage source inverter (VSI) and a LC filter.

Figure 2-1: Single-line schematic diagram of a multi-string photovoltaic (PV) system interfaced with a distribution network

In the case of grid-connected PV system, the PV array is connected to the grid via a power electronic inverter, which converts the generated DC power into AC power. A number of different topologies have been developed and used over the last few decades. Among these, the multi-string topology has been the most common type of PV installation in the past [21]. Several strings are interfaced with their own DC/DC converter for voltage boost and connected to a DC bus. A common DC/AC inverter is then used for utility integration. The primary advantages of this topology are the facts
that it has independent control, better protection of power sources, greater safety during installation and maintenance, low cost and etc. This layout of a multi-string PV system is shown in Figure 2-2. Each PV module consists of 176 parallel and 150 series arrays. The characteristic of PV array is highly nonlinear and can’t be represented by a simple current or voltage source in parallel with the diode. A piecewise linear model is introduced in the thesis as shown in Figure 2-3 [22].
The maximum power point tracking (MPPT) technique is implemented in DC/DC converters to achieve maximum efficiency of PV module. Boost and buck converters are mostly used DC/DC converter topologies. However, boost converter shows advantages over buck converter, due to the blocking diodes that can prevent reverse current flow into PV array. The incremental conductance (IncCond) method is used for controlling the boost converter. The IncCond technique can keep track of previous current and voltage very accurately. Besides, there is no oscillation around the maximum power point (MPP) as compared with perturbation and observation (P&O) method. The output of the boost converter is connected to the central inverter through a DC transmission line. The DC transmission line is considered to be a short line and at an equal distance from both boost converters. The PV arrays are assumed to be located in suburban areas and need a distribution line to transmit the DC power generated. The transmission line is represented by RL equivalent circuit. And multi-string PV arrays are connected together at certain point. Then the DC common bus is interfaced with the dc-link capacitor C and the dc-side terminal of the three-phase voltage source inverter (VSI). The dc-link capacitor aims to regulate the voltage at the dc side of the inverter. And the capacitance depends on the ripple requirement on the capacitor. The VSC is controlled based on the sine-triangle modulation strategy. The interface reactor connects the ac-side terminals of the VSC to the distribution network via the point of common coupling (PCC). The interface resistor includes the resistance of the IGBT. The filter capacitor $C_f$ provides a low-impedance path for the current harmonics generated by the inverter.

The distribution network is just an example that simplifies the real distribution network. And it can be extended to be a larger and more realistic system, which is reserved to be the future work. The distribution network includes a transformer $T_{r1}$, load, two distribution line segments and capacitor $C_l$. $T_{r1}$ steps down the network voltage to a level suitable for the PV system. The high-voltage side of $T_{r1}$ has a wye winding connection and is solidly grounded. In addition, a three-phase load is connected to the line at a location between the PCC and the grid. The inductance and resistance of the distribution line segment between the PCC and the load are represented by $R_1$ and $L_1$, respectively. Similarly, $R_2$ and $L_2$, respectively represent the inductance and resistance of
the line segment between the load and the grid. While capacitor $C_1$ is used for load power factor correction and always presents with the load.

Based on the circuit scheme described above, the linear model of the system is built in MATLAB™ for stability analysis. And the model is validated by comparing the results with circuit model. The transient response of the system under disturbance conditions has also been studied. The simulation results will be illustrated and discussed later.

2.2 Experiment Description

A multi-string grid-connected PV system with the function of harmonic compensation is presented in PSCAD/EMTDC™ simulation environment. The scheme of the system is demonstrated in Figure 2-4. However, the transformers are not represented in the hardware configuration due to the fact that no large-scale transformer is needed at a low voltage level. But, a variable transformer is needed to step down the utility voltage to the required voltage level. Moreover, the transmission line is not considered in this hardware since the resistance and inductance have been included in both LC filter and connection wires. Because the PV arrays are not available in the laboratory, a controllable DC source is instead used to emulate the characteristic of PV arrays. A modified hardware scheme is then designed for validation, which is shown in Figure 2-5.

![Figure 2-4: Overall structure of PV system with active power filter](image)
As illustrated in the figure, the Sorensen DC programmable power supply is used to represent the characteristic of the PV array. The DCS series system supplies are 3kW supplies designed to provide highly stable, continuously variable output voltage and current. This model used in the experiment DCS40-75 provides output voltage range 0-40V, and output current range 0-75A. In the experiment, the voltage is set to be a constant value, while the current is dependable on the current flowing through the inverter. That’s because the DC power source is connected to Semikron three-phase inverter to convert DC to AC. The inverter can operate at a maximum switching frequency of 20 kHz and provide a maximum 18A AC current. Then inverter is interfaced with power grid via a three-phase LC filter. And a variable transformer is connected with grid to step down the voltage so that it meets the voltage level of the PV system. It’s a continuously three-phase adjustable voltage autotransformer, which has a movable brush-tap riding on a commutator. It can withstand a maximum 12A output current and automatically disconnect from the circuit under the circumstance of overcurrent. Finally, three-phase diode rectifier in parallel with a three-phase R load is connected as the nonlinear loads.
Current control is achieved by using dSPACE™ packages, which include dSPACE™ expansion box, dSPACE™ 1103 controller board, and ControlDesk™. The dSPACE™ 1103 is an all-rounder in rapid control prototyping [23]. Using with Real-Time Interface™ (RTI), the controller board is fully programmable from the simulink block diagram environment. The unparalleled number of I/O interfaces provides a great selection of interfaces, including 50 bit-I/O channels, 36 A/D channels, and 8 D/A channels. In this hardware configuration, measured voltages and currents are connected through the A/D channels as analog inputs. The current control algorithm is built and programmed by using MATLAB/Simulink™. The simulink model outputs the digital modulation signals that are passed through D/A channels to firing generation analog board. Then the modulation waveforms are compared with the reference signals to generate the firing pulses via the analog board. The modulation algorithm used here is sine triangular modulation as shown in Figure 2-6. The pulses then pass through level shifter to step up the voltage level acceptable for the Semikron. Finally, ControlDesk™ is manipulated manually to run, pause, and stop the current control program in order to enable the operation of the experiment. And the figures and data can be observed from the command window of ControlDesk™.

Actually, dSPACE™ provides us with a slave I/O on the expansion box, which can generate the firing pulses for the inverter. However, the dSPACE™ has the time step limit of 50μs. But harmonics compensation is really sensitive to the sampling time.
Therefore, in this occasion, the harmonic compensation can’t satisfy design requirement, or even worse. For example, the feedback current generated by using slave I/O doesn’t match the reference current exactly. Instead, an electronic chip circuit mounted bread board is used to generate the firing pulses. Since it has a smaller sampling time and a faster response, the compensation result is much better than that of the slave I/O.

For the future work, a much faster processor with a smaller time step, like FPGA board will be used to generate the firing pulses for the inverter. Together with dSPACE™, it will be responsible for the control of the inverter.
CHAPTER 3

Control Algorithm

Performance and reliability are essential to the PV system with a considerable power scale and voltage level. Therefore, proper modeling and control design allows for progress on hardware implementation. The whole PV system can be divided into several subsystems to facilitate the control individually. First of all, in our multi-string grid-connected photovoltaic (PV) system, equivalent circuit is modeled to represent the PV arrays.

Then maximum power point tracking (MPPT) control is implemented in boost converter to ensure the high efficiency of the distributed power generation. And the MPPT algorithms and block models are discussed in section 3.1. Three-phase inverter converts DC power to AC power to interface with distribution network. The inverter current control is so critical that it determines how well the harmonics are compensated. The voltage source inverter (VSI) control is talked about in section 3.2. For analysis and control purpose, the VSI pulse width modulation and control are synchronized to the distribution network voltage through a phase locked loop (PLL). Then the three-phase AC voltage and current are transformed into dq-axis counterparts, which is much easier to design and control. It’s explained in section 3.3 of this chapter. As to detect the harmonic components of the nonlinear loads, time-domain harmonic extraction method is proposed and illustrated in section 3.4. Finally, small signal analysis is carried out in the last section. System differential equations and eigenvalues are derived to analyze the stability of the system. The system parameter that affects the stability of the system can also be determined.

3.1 MPPT Control

It’s known that PV arrays exhibits nonlinear characteristic, which is shown in Figure 3-1. The pictures show the I/V and P/V characteristics of PV module output, respectively. While the power conversion ratio of the PV panel is still not very high, therefore, it’s significantly vital to extract as much power from the PV panels as possible.
3.1.1 Incremental Conductance Algorithm

Different kinds of MPPT algorithms have been developed and put into application. The most popular ones are: constant voltage tracking (CVT), perturbation and observation method (P&O), incremental conductance method (IncCond). The IncCond shows some advantages over others, like high tracking accuracy and no oscillation around MPP. The flowchart of IncCond is depicted in Figure 3-2.

Figure 3-1: I-V and P-V characteristics of PV arrays under different solar irradiation

Figure 3-2: Incremental Conductance algorithm
As shown in the flow chart above, the MPP can be tracked by comparing the instantaneous conductance (I/V) to the incremental conductance (∆I/∆V). \( V_{\text{ref}} \) is the reference voltage and equals to \( V_{\text{MPP}} \) at MPP. Once the MPP is reached, the operation of the PV array is maintained at this point unless there is change in ∆I, which indicates a change in solar irradiation or weather condition. The algorithm decreases or increases \( V_{\text{ref}} \) to track the new MPP [24].

### 3.1.2 MPPT Implementation

Figure 3-3 demonstrates the schematic diagram of the power circuit of the MPPT technique and its control.

![Maximum power point tracking control circuit](image)

Figure 3-3: Maximum power point tracking control circuit

In the boost converter, the input capacitor voltage is maintained between two upper and lower levels. The upper level \( V_{\text{ref}}^{\text{pv}} \) is obtained from the MPPT algorithm. The lower level is computed under the consideration of worst conditions, i.e. the switching frequency and voltage ripple do not exceed certain values. When the capacitor voltage
exceeds $V_{\text{pv}}^{\text{ref}}$, the main switch turns on, and the capacitor is discharged. The switch remains on until the capacitor voltage hits the lower limit. To limit the switching frequency, the lower limit is not taken as a constant value. However, it’s a function of the desired frequency $f^d$ and the PV current level. The lower limit can be found as follows:

$$
\Delta V_{\text{pv}} = \frac{i_{\text{pv}}}{2C_f f^d}
$$

For example, $C_f = 20 \mu F$, $f^d = 20 kHz$, $i_{\text{pv}}^{\text{max}} = 4A$, the PV voltage variation is $\Delta V_{\text{pv}} = 5V$. It’s clear from (1) that there is a trade-off between the switching frequency and the capacitor value.

The control algorithm is implemented in boost converter to feed the voltage source inverter. The boost converter topology has some advantages over the buck for MPPT application due to the following reasons. First of all, the rms current through the inductor is much less than that of the buck converter. For the selection of the power IGBT and driver, the current rating is lower in boost converter than in the buck converter. Most importantly, the capacity of solar generation systems depends on the light. At night, a current could flow back into photovoltaic cells from the grid side, which can cause leakage loss, extensive damage [25]. Blocking diodes are effective to prevent reverse current flows. In the boost converter, the diode can serve as the blocking diode to avoid reverse current. By comparing the undamped natural frequency, the boost converter shows better dynamic characteristics than the buck converter. In general, it shows advantages in terms of a wider bandwidth and smaller resonance due to the small input capacitance of the boost converter.

### 3.2 Phase-Locked Loop

The phase-locked loop technique has been used as a common way to synthesize the phase and frequency information of the electrical system, especially when it’s interfaced with power electronic devices. A simple method of obtaining the phase information is to detect the zero crossing point of the utility voltages. However, since the zero crossing point can be detected only at every half cycle of the utility frequency, the phase tracking is impossible between the detecting points and thus the fast dynamic performance can not
be obtained. An improved method using the integral of the input waveform is proposed in the thesis. In the three-phase system, the dq transform of the three-phase variables has the same characteristics and the PLL system can be implemented using the dq transform. The block diagram of the three-phase PLL system can be described in Figure 3-4.

![Figure 3-4: Block diagram of three-phase PLL](image)

The three-phase grid voltage can be represented in the synchronous reference frame. The transformation matrix $T_s(\theta)$ can be expressed in the following equation.
As shown in Figure 3-5, the three-phase voltage is transformed into two DC quantities in dq axis. Then the q-axis quantity \( v_{sq} \) is compared with the reference value zero and generates the error signal. In steady state, the reference value of q-axis is set to be zero so that only d-axis component exists to represent the AC quantity while the angular frequency becomes equal to the grid frequency. The error passes through a loop filter to derive the angular frequency. The phase shift \( \theta \) is derived by integral of the angular frequency. By properly designing the loop filter \( K_i(s) \), the PLL frequency \( \omega \) and phase \( \theta \) can be tracked accurately.

If it’s assumed that the error input is very small, the block diagram can be linearized. The linearized model of the three-phase PLL system can be described as shown in Figure 3-6.

There are various ways to design the loop filter. However, the second order loop is commonly used as a good trade-off of the filter performance and system stability [26]. The proportional-integral (PI) filter for the second order loop can be given as:

\[
K_i(s) = K_p \left(1 + \frac{1}{s\tau}\right)
\]

(3)
where $K_p$ and $\tau$ denote the gains and time constant of the PI filter, respectively. It should be considered in the design of the PI filter that the dynamic performance satisfies the fast tracking and good filtering properties. But both requirements cannot be satisfied simultaneously. Therefore, a trade-off is required in design of the dynamic behavior of the PLL system to achieve the optimization. In our model, PI parameters are tried and tested to optimize the performance of the PI filter. The proportional and integral parameters are derived as: $K_p = 1.1$, $\tau = 0.00375$, in which the system has a fast tracking and good dynamic performance.

### 3.3 VSC Current Control

As the regulation of $v_{sq}$ has the effect that the expression for the PV system real power output is simplified to

$$P_s = \frac{3}{2} v_{sd} i_d$$

Equation (4) indicates that $P_s$ is proportional to $i_d$ and can be controlled by $i_d$. $P_s$ is controlled to regulate the real power extracted from the PV array. Similarly, the reactive power is regulated by controlling $i_q$,

$$Q_s = -\frac{3}{2} v_{sd} i_q$$

The voltage and current from the PV module are measured and used to calculate the active power output of PV module generated. For the two string PV system, the real power can be calculated as follows:

$$P_{ref} = V_{pv1} I_{pv1} + V_{pv2} I_{pv2}$$

The reactive power $Q_{ref}$ pumped into the distribution network is set to zero so that the power factor of the distribution network can be adjusted. The current references in dq axis can be derived according to

$$\begin{bmatrix} I_{dref} \\ I_{qref} \end{bmatrix} = \begin{bmatrix} \frac{2}{3} V_{sd}^2 + V_{sq}^2 & V_{sd} V_{sq} & V_{sq} V_{sd} & V_{sq} - V_{sd} \end{bmatrix} \begin{bmatrix} P_{ref} \\ Q_{ref} \end{bmatrix}$$

where $V_{sd}$, $V_{sq}$ represent the voltage in dq axis at the point of common coupling (PCC). The current control algorithm is designed based on the following equations (8) and (9).
where \(i_d\), \(i_q\) are currents flowing into the PCC, respectively, \(R\) and \(L\) represents the resistance and inductance of the LC filter connect the VSC and the distribution network, respectively. \(m_d\) and \(m_q\) are modulation index in dq axis, respectively. Due to the factor of \(L\omega\), the current \(i_d\) and \(i_q\) are coupled. To decouple the dynamic of the currents, equations (8) and (9) are written in the following way:

\[
\begin{align*}
L\frac{di_d}{dt} &= -Ri_d + L\omega i_q + \frac{v_{dc}}{2}m_d - v_{ad} \quad (8) \\
L\frac{di_q}{dt} &= -Ri_q - L\omega i_d + \frac{v_{dc}}{2}m_q - v_{sq} \quad (9)
\end{align*}
\]

where \(u_d\) and \(u_q\) are two new inputs. Substituting \(m_d\) and \(m_q\) in equation (8) and (9), from (10) and (11), it can be obtained that:

\[
\begin{align*}
m_d &= \frac{2}{v_{dc}}(u_d - L\omega i_q + v_{ad}) \quad (10) \\
m_q &= \frac{2}{v_{dc}}(u_q + L\omega i_d + v_{sq}) \quad (11)
\end{align*}
\]

Equations (12) and (13) represent two decoupled, linear systems in which \(i_d\) and \(i_q\) can be controlled by \(u_d\) and \(u_q\), respectively. Figure 3-7 demonstrates the block diagram of the dq-axis current control scheme.

It’s shown in Figure 3-7 that the control signal \(u_d\) is the output of a compensator \(k_d(s)\), which processes the error signals \(e_d = i_{dref} - i_d\). Similarly, \(u_q\) is the output of a compensator \(k_q(s)\) that processes the error signals \(e_q = i_{qref} - i_q\). In order to generate the modulation signal \(m_d\) and \(m_q\), \(v_{dc}/2\) is employed as a feed-forward signal to decouple \(i_d\) and \(i_q\) from the DC-link voltage \(v_{dc}\). The feed-forward compensation decouples PV arrays from the rest of the system to enhance the PV system stability. The PWM modulation signals are produced by transformation of \(m_d\) and \(m_q\) into \(m_a\), \(m_b\), \(m_c\). The pulses for voltage source inverter are fired by using sine-triangular modulation.
The error signals are passed through a compensator to generate the control signals \( u_d \) and \( u_q \). Since the control objects are the same, then \( k_d(s) \) and \( k_q(s) \) can also be identical.

A PI controller is often selected to be the compensator, let

\[
k_d(s) = k_q(s) = k_p + \frac{k_i}{s}
\]  

where \( k_p \) and \( k_i \) are proportional and integral gains, respectively. The PI controller parameters are chosen as:

\[
k_p = \frac{L}{\tau_i}
\]  

\[
k_i = \frac{R}{\tau_i}
\]

where \( \tau_i \) is the time constant of current control loop. The time constant \( \tau_i \) should be made small for a fast response, but properly large so that \( 1/\tau_i \) is smaller than the VSC switching frequency. Thus, \( 1/\tau_i \) is taken as ten times smaller than the switching frequency.

### 3.4 Time-domain Current Detection
There are many methods developed to detect current for active power filter. Analog filter has been used to detect the harmonics. However, the accuracy of this method is not satisfactory. In 1983, instantaneous reactive power theory (IRPT) was proposed by H. Akagi for active power filter (APF). The disadvantage of IRPT is that it requires coordinate transformation between abc coordinates and dq coordinates, which increases the complexity of design. Yet it inspires many other methods based on pq theory. Besides, digital algorithms such as fast fourier transform (FFT) and discrete fourier transform (DFT) are also studied. But it needs one main cycle to track the load change completely, which is suitable for a slowly varying load.

Based on the IRPT and DFT, time-domain current detection method is developed and used in the thesis.

In a three-phase three-wire system, the load currents of three phases can be decomposed into positive-sequence and negative-sequence components according to the symmetrical weigh law. The zero-sequence component can be ignored since it’s a three-wire system.

\[
I_l(n) = \sum_{k=1}^{\infty} \left[ I_{lk} \sin\left(\frac{2\pi}{N} nk + \varphi_{lk} - \frac{2l\pi}{3}\right) + I_{2k} \sin\left(\frac{2\pi}{N} nk + \varphi_{2k} + \frac{2l\pi}{3}\right) \right]
\]  

(17)

where

\[
l = \begin{cases} 
0 & x = a \\
1 & x = b \\
2 & x = c 
\end{cases}
\]

The subscripts 1 and 2 represent the positive-sequence and negative-sequence, respectively. \( k \) represents harmonic order. \( I \) represents the peak value of the current and \( \varphi \) is the initial phase. \( N \) is the sampling point in one fundamental cycle, and \( n \) is the count value of sampling (\( n=0, 1, \ldots, N-1 \)).

Then, the fundamental current component is expressed as follows:

\[
i_{l1}(n) = I_{11} \sin\left(\frac{2\pi}{N} n + \varphi_{11} - \frac{2l\pi}{3}\right) + I_{21} \sin\left(\frac{2\pi}{N} n + \varphi_{21} + \frac{2l\pi}{3}\right)
\]

\[
= I_{11} \sin\left(\frac{2\pi}{N} n - \frac{2l\pi}{3}\right) \cos \varphi_{11} + I_{11} \cos\left(\frac{2\pi}{N} n - \frac{2l\pi}{3}\right) \sin \varphi_{11}
\]

\[
+ I_{21} \sin\left(\frac{2\pi}{N} n - \frac{2l\pi}{3}\right) \cos \varphi_{21} - \frac{2l\pi}{3} + I_{21} \cos\left(\frac{2\pi}{N} n - \frac{2l\pi}{3}\right) \sin \varphi_{21} - \frac{2l\pi}{3}
\]

(18)
The first item of equation (2) corresponds to the positive-sequence component in phase with the phase voltage, which is called the active power component of the positive-sequence fundamental current; the second item of (2) corresponds to the positive-sequence component vertical to the phase voltage, which is called the reactive power component of the positive-sequence fundamental current; the third item corresponds to the negative-sequence component in phase with the phase voltage, which is the active power component of the negative-sequence fundamental current; the last item of (2) corresponds to the negative-sequence component vertical to the phase voltage, which is the reactive power component of the negative-sequence fundamental current.

The diagram of symmetrical weigh law is shown in Figure 3-8. And Figure 3-9 shows the block diagram of the current detection algorithm.
The synchronous signal can be gained by the phase locked loop (PLL). The low-path filter determines the performance of the system. And different components will be obtained by the segregator for different purposes, which is better than the algorithm based on the instantaneous reactive power theory.

The phase voltage is expressed in per-unit. And the base voltage for per-unit value is the peak value of positive-sequence fundamental phase voltage. Then three-phase voltages can be expressed in terms of \( \sin(2n\pi/N-2l\pi/3) \). The instantaneous power of the fundamental current can be calculated by multiplying current by voltage

\[
i_{x_1}(n)\sin\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right)
\]

\[
= \frac{1}{2}\left(I_{11}\cos\varphi_{11}[1 - \cos\left(\frac{4\pi}{N}n - \frac{4l\pi}{3}\right)] + I_{11}\sin\varphi_{11}\sin\left(\frac{4\pi}{N}n - \frac{4l\pi}{3}\right) - I_{21}\cos\left(\frac{2l\pi}{3}\right)[1 - \cos\left(\frac{4\pi}{N}n - \frac{4l\pi}{3}\right)] - I_{21}\sin\left(\frac{2l\pi}{3}\right)\sin\left(\frac{4\pi}{N}n - \frac{4l\pi}{3}\right)\right)
\]

where the first item of (19) corresponds to the instantaneous active power component of the positive-sequence fundamental. The second item of the equation corresponds to the instantaneous reactive power component of the positive-sequence fundamental. The third item is the instantaneous active power component of the negative-sequence fundamental. The three-phase sum of the rest (including the posterior part of the third item and the fourth item) is not zero, and its frequency is twice the fundamental, which can be compensated by a compensator.
Similarly, the instantaneous power of harmonics can be obtained by multiplying current by \(\sin(2\pi/N - 2\pi/3)\)
\[
i_{sk}(n) \ast \sin\left(\frac{2\pi}{N} n - \frac{2\pi}{3}\right)
= \frac{1}{2} \left\{ I_{1k} \left[ \cos\left(\frac{2n\pi}{N}(k - 1) + \varphi_{1k}\right) - \cos\left(\frac{2n\pi}{N}(k + 1) + \varphi_{1k} + \frac{2\pi}{3}\right) \right] \\
+ I_{2k} \left[ \cos\left(\frac{2n\pi}{N}(k - 1) + \varphi_{1k} - \frac{2\pi}{3}\right) - \cos\left(\frac{2n\pi}{N}(k + 1) + \varphi_{2k}\right) \right] \right\}
\]  
(20)

From the equation above, it can be seen that either the negative-sequence or positive-sequence component has one part of which the three-phase sum up to zero, which can be compensated by a compensator.

In (19) and (20), the lowest frequency component is twice the fundamental frequency. The DC component can be obtained by a low-pass filter with a cutoff frequency lower than twice the fundamental frequency. Then by multiplying by 2, the following equation can be obtained:
\[
B_{z1} = I_{11} \cos \varphi_{11} + I_{21} \cos(\varphi_{21} + 4l\pi/3)
\]  
(21)

Multiplying equation (17) by \(\cos(2n\pi/3 - 2\pi/3)\), the following equation can be derived:
\[
i_{x}(n) \ast \cos\left(\frac{2\pi}{N} n - \frac{2\pi}{3}\right)
= \frac{1}{2} \left\{ I_{11} \left[ \sin \varphi_{11} + \sin\left(\frac{4\pi}{N} n + \varphi_{11} - \frac{4\pi}{3}\right) \right] \\
+ I_{21} \left[ \sin\left(\frac{4\pi}{N} n + \varphi_{21}\right) + \sin(\varphi_{21} + \frac{4\pi}{3}) \right] + i_{b} \right\}
\]  
(22)

Using the same method, the following equation can be acquired:
\[
A_{z1} = I_{11} \sin \varphi_{11} + I_{21} \sin(\varphi_{21} + 4l\pi/3)
\]  
(23)

Here, we define
\[
\begin{pmatrix}
A_{z1} & B_{z1} \\
A_{2z1} & B_{2z1}
\end{pmatrix}
\]
\[
\begin{pmatrix}
    A_{a1} + A_{b1} + A_{c1} & B_{a1} + B_{b1} + B_{c1} \\
    2A_{a1} - A_{b1} - A_{c1} & 2B_{a1} - B_{b1} - B_{c1}
\end{pmatrix}
\]

\[
\begin{pmatrix}
    I_1 \sin \phi_1 & I_1 \cos \phi_1 \\
    I_2 \sin \phi_2 & I_2 \cos \phi_2
\end{pmatrix}
\]

where \( A_{11} \) and \( B_{11} \) are the peak values of the reactive power component and active power component of positive-sequence fundamental current, respectively. \( A_{21} \) and \( B_{21} \) are the peak values of the reactive power component and active power component of negative-sequence fundamental current of phase “a”, respectively. Then the peak values for phase “b” and “c” are \( I_{21} \sin(\phi_{21} - 2\pi/3) \), \( I_{21} \cos(\phi_{21} - 2\pi/3) \) and \( I_{21} \sin(\phi_{21} + 2\pi/3) \), \( I_{21} \cos(\phi_{21} + 2\pi/3) \), respectively.

In a similar way, multiplying (17) by \( 2\sin(k(2\pi/N - 2l\pi/3)) \) and \( 2\cos(k(2\pi/N - 2l\pi/3)) \), respectively, and passing through the low-pass filter, \( A_{xk} \) and \( B_{xk} \) can be obtained:

\[
A_{xk} = I_{ik} \sin\left[\frac{2(k-1)l\pi}{3} + \phi_{ik}\right] + I_{2k} \sin\left[\frac{2(k+1)l\pi}{3} + \phi_{21}\right]
\]

\[
B_{xk} = I_{ik} \cos\left[\frac{2(k-1)l\pi}{3} + \phi_{ik}\right] + I_{2k} \cos\left[\frac{2(k+1)l\pi}{3} + \phi_{21}\right]
\]

Then, define the following equations:

\[
i_{x1l} = A_{1l} \cos\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right) + B_{1l} \sin\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right)
\]

\[
i_{x2l} = A_{2l} \cos\left(\frac{2\pi}{N}n + \frac{2l\pi}{3}\right) + B_{2l} \sin\left(\frac{2\pi}{N}n + \frac{2l\pi}{3}\right)
\]

\[
i_{xl} = A_{xl} \cos\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right) + B_{xl} \sin\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right)
\]

\[
i_{xk} = A_{xk} \cos k\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right) + B_{xk} \sin k\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right)
\]

Equations (24)-(27) compose the segregator shown in Figure 3-9, by which various results can be achieved according to different compensation goals. For instance, if the active power filter aims to compensate harmonics and the negative-sequence component of the fundamental current, the positive-sequence component of the fundamental current \( i_{x1l} \) can be obtained from equation (25), and the reference current can be gained as \( i_{ref}(n) = i_x(n) - i_{x1l}(n) \) by subtracting \( i_{x1l} \) from the load current. Another example is to compensate the selected order harmonics, the current reference can be gained by (28).
Based on the detection algorithm, various compensation goals can be achieved by using different combinations.

From the above analysis, it’s observed that the delay of this algorithm is less than half of the main cycle, which is much less than that of the method based on IRPT. Besides, the algorithm can detect the positive/negative-sequence fundamental current, active/reactive power component of positive-sequence fundamental currents, and selective harmonics. What’s more, it does not need coordinate transformation. The simulation model has been built in MATLAB™/Simulink. And it will be shown in the next chapter.
CHAPTER 4

SIMULATION RESULTS

4.1 Simulation Model and Results

4.1.1 Fault Analysis

Simulation models in MATLAB\textsuperscript{TM} and PLECS\textsuperscript{TM} are used to analyze the system responses under normal and fault conditions. The detailed system diagram was once described in Figure 2-1. A multi-string photovoltaic (PV) system is interfaced with the distribution network. A modified diagram with fault locations marked is shown in Figure 4-1. The parameters of the system are given in Table 1.

(1) Solar irradiation $S=1$ for PV$_1$ and PV$_2$

The RL load is connected to the distribution network. The load size is shown in Table 1. Both PV arrays are working at normal conditions, i.e. 1000W/m$^2$. The inverter
currents in dq axes are shown in Figure 4-2. The DC link voltage of the inverter $V_{dc}$ is shown in Figure 4-3. The current and voltage at point of common coupling (PCC) are shown in Figure 4-4.

### Table 1: Multi-string PV system parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{r1}$ nominal power</td>
<td>3.5MVA</td>
</tr>
<tr>
<td>$T_{r1}$ voltage ratio</td>
<td>6.6/0.48</td>
</tr>
<tr>
<td>$T_{r1}$ leakage inductance</td>
<td>0.1 pu</td>
</tr>
<tr>
<td>$T_{r1}$ resistance</td>
<td>0.02 pu</td>
</tr>
<tr>
<td>Interface resistance</td>
<td>3e-3Ω</td>
</tr>
<tr>
<td>Interface inductance</td>
<td>250e-3H</td>
</tr>
<tr>
<td>Filter capacitance</td>
<td>600e-6F</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>3kHz</td>
</tr>
<tr>
<td>DC bus resistance</td>
<td>3e-3 per unit length</td>
</tr>
<tr>
<td>DC bus inductance</td>
<td>50e-6 per unit length</td>
</tr>
<tr>
<td>Length of DC bus to inverter</td>
<td>10 units</td>
</tr>
<tr>
<td>Length of DC bus from boost to common point</td>
<td>2 units</td>
</tr>
<tr>
<td>Grid voltage</td>
<td>6.6kV rms</td>
</tr>
<tr>
<td>Line inductance</td>
<td>0.105e-3H</td>
</tr>
<tr>
<td>Line resistance</td>
<td>5e-3Ω</td>
</tr>
<tr>
<td>Length of transmission line</td>
<td>20 units</td>
</tr>
<tr>
<td>RL load resistance</td>
<td>50Ω</td>
</tr>
<tr>
<td>RL load inductance</td>
<td>10e-3H</td>
</tr>
</tbody>
</table>

From the figures below, it’s observed that the current of the inverter can be controlled to be the value desired with q axis current given zero reference. The DC link voltage remains constant after the system gains its operational point at the maximum power point. The voltage and current at the point of common coupling are in phase with each other.
Figure 4-2: Current in dq axes of the inverter when solar irradiation $S=1$

Figure 4-3: DC link voltage when $S=1$ for both PV modules

Figure 4-4: Phase A voltage and current at PCC when solar irradiation $S=1$
(2) Solar irradiation change in PV$_2$

Solar irradiation change happens when weather conditions like rain or cloud weather occurs. It will cause decrease of power generated from PV arrays and changes of system operation point. The d axis current and DC link voltage when solar irradiation of PV$_2$ decreases to S=0.2 are shown in Figure 4-5 and Figure 4-6, respectively.

Figure 4-5: D axis current of the inverter when there is solar irradiation change for one PV module

![Figure 4-5](image)

Figure 4-6: DC link voltage of the inverter when there is solar irradiation change for one PV module

![Figure 4-6](image)

With the solar irradiation decreasing from S=1 to S=0.2, the total power generated by the PV arrays is reduced accordingly, which is verified in Figure 4-5 that the current...
decreases to a lower level after the system gains its operating point. While, the DC link voltage remains the same. Under such circumstance, the system remains stable after the transients.

(3) PV module disconnection

It’s also studied when one PV module is disconnected from the distribution network. The system response is also analyzed and the current response is shown in Figure 4-7. From the figure, it’s seen that PV power is reduced to half. However, the system remains stable although such disturbance causes a large transient in the system.

![Figure 4-7](image.png)

Figure 4-7: Current of the inverter in d axis when one PV module disconnects from the system

(4) Grid voltage drop

A grid voltage drop happens at t=0.35s and the voltage becomes normal 0.2s later. The system remains stable and gains its original state, which is shown in Figure 4-8 and Figure 4-9. The voltage at the PCC is reduced due to the voltage of the grid side drops to 80% of its original value. While the current of the inverter increases, because the inverter needs to provide more current to the load.

(5) Fault at the DC bus

There is a short circuit fault happened at the DC bus at t=0.5s. A circuit breaker opens at t=0.6s and clears the fault 0.15s later. At t=0.8s, the breaker closes to regain its normal operating point. The system response is shown in Figure 4-10.
Figure 4-8: Current of inverter in d axis when grid voltage drops

Figure 4-9: Voltage at PCC in d axis when grid voltage drops

Figure 4-10: Current in d axis when fault happens at the DC link of the inverter
4.1.2 Harmonic Compensation

PV system can compensate the harmonics generated by the nonlinear loads as well as supply active power to the power grid. The simulation scheme is established in PSCAD™ as shown in Figure 4-11.

![Figure 4-11: Grid-connected PV system with function of harmonic compensation](image)

The grid voltage is supposed to be balanced and simulated as an ideal voltage source. And the solar arrays and grid are supplying power to the diode rectifier in parallel with resistive load. The load current is very rich in harmonics and the inverter is controlled to provide harmonic compensation. The system parameters are shown in Table 2.

The DC link capacitor aims to manipulate the DC input voltage for the voltage source inverter (VSI). The value of the capacitor depends on the power variation in the three-phase side since all the power comes from the PV arrays via the DC link capacitor. In a three-phase system, the instantaneous power on the grid side varies little so that the voltage ripple in the DC link capacitor is selected as 1%. Then accordingly, DC link capacitor is selected to be 350μF.

The LC filter always comes together with the voltage source inverter (VSI), which is used to eliminate the high order voltage harmonics. However, the LC filter can not be deleted due to the fact that it determines the output voltage waveform of the VSI, which
has an important effect on the AC side. It outputs sinusoidal waveforms from pulses based on different modulation algorithms. Yet, the LC filter limits the degree of harmonics that can be compensated. Since it’s a low-pass filter, the high order current harmonics are beyond the capability of being compensated. Fortunately, the higher order harmonics are much smaller compared with lower order harmonics. For example, the switching frequency is taken as 10kHz. Then the resonant frequency is designed to be 1kHz. The fundamental frequency is 60Hz and the LC filter can pass up to 16\textsuperscript{th} harmonics. In this case, the harmonic current content on the grid side is within the IEEE 519-1992. The simulation results are shown in the following figures.

Table 2: Simulation scheme of PV system with harmonic compensation

<table>
<thead>
<tr>
<th>DC link capacitor</th>
<th>350μF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance for LC filter</td>
<td>100μH</td>
</tr>
<tr>
<td>Capacitance for LC filter</td>
<td>250μF</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>10kHz</td>
</tr>
<tr>
<td>Resistive load for diode rectifier</td>
<td>0.1Ω</td>
</tr>
<tr>
<td>Grid voltage (L-L rms)</td>
<td>4.16kV</td>
</tr>
</tbody>
</table>

The current reference and feedback are shown in Figure 4-12 and Figure 4-13 to see the tracking accuracy of the control algorithm. The d-axis current of the inverter is shown in Figure 4-12. The current reference in d-axis consists of current from the PV arrays and harmonics compensated for the nonlinear load. While the current reference in q-axis is composed of zero plus harmonics compensated. 

![Figure 4-12: Current reference and feedback of the inverter in d axis](image)
The harmonic compensation result is shown in Figure 4-13, where inverter current, nonlinear load current, and grid current are presented for comparison.

It can be seen from the above figure that the current on the inverter side is full of harmonics compared with that before compensation. However, the current on the grid side is approximately sinusoidal after compensation. The harmonic detection result is
shown in Figure 4-14, in which current in one phase is decomposed into fundamental part and harmonic part. And the harmonic contents and THD analysis are also discussed.

![Figure 4-15: Current detection using time-domain technique](image1)

![Figure 4-16: Harmonic order content chart with total harmonic distortion](image2)

The total harmonic distortion (THD) is compared for the grid current with or without harmonic compensation. The result is shown in Table 3.
Table 3: THD comparison

<table>
<thead>
<tr>
<th>Case</th>
<th>THD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without harmonic compensation</td>
<td>31%</td>
</tr>
<tr>
<td>Harmonic compensation</td>
<td>4.06%</td>
</tr>
</tbody>
</table>

The current distortion is greatly reduced after harmonic compensation. And it’s within the limit of the IEEE 519-1992, which is illustrated in Table 4 [27].

Table 4: Current Distortion Limits for General Distortion Systems (120V through 69000V)

<table>
<thead>
<tr>
<th>Individual Harmonic Order (Odd Harmonics)</th>
<th>TDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;11</td>
<td></td>
</tr>
<tr>
<td>11&lt;h&lt;17</td>
<td></td>
</tr>
<tr>
<td>17&lt;h&lt;23</td>
<td></td>
</tr>
<tr>
<td>23&lt;h&lt;35</td>
<td></td>
</tr>
<tr>
<td>35&lt;h</td>
<td></td>
</tr>
<tr>
<td>Isc/Il</td>
<td>5.0</td>
</tr>
<tr>
<td>&lt;20</td>
<td>0.3</td>
</tr>
<tr>
<td>20&lt;50</td>
<td>8.0</td>
</tr>
<tr>
<td>50&lt;100</td>
<td>12.0</td>
</tr>
<tr>
<td>100&lt;1000</td>
<td></td>
</tr>
<tr>
<td>&gt;1000</td>
<td></td>
</tr>
</tbody>
</table>

Even harmonics are limited to 25% of the odd harmonic limits. TDD refers to Total Demand Distortion and is based on the average maximum demand current at the fundamental frequency, taken at the PCC.

4.2 Small-Signal Analysis

To evaluate the stability of the PV system under the control strategy, an eigenvalue analysis is carried out on the linear model of the system. The dynamics of the PV arrays don’t affect the inverter due to the feed-forward control. Hence, the system can be decomposed into three parts: (1) Outer loop control; (2) Current control of the inverter; (3) Transmission line and load. The linear model is based on the system described in Figure 2-1.

4.2.1 Outer Loop Control

The outer loop is to generate the reference currents. The current references can be calculated via a power calculator, which is shown in equation (7).
\[
\begin{bmatrix}
I_{dref} \\
I_{qref}
\end{bmatrix} = \frac{2}{3} \left( \frac{1}{V_d^2 + V_q^2} \right) \begin{bmatrix}
V_{sd} & V_{sq} \\
V_{sq} & -V_{sd}
\end{bmatrix} \begin{bmatrix}
P_{ref} \\
Q_{ref}
\end{bmatrix}
\] (29)

Where \( P_{ref} \) is equal to \( V_{pv1}I_{pv1} + V_{pv2}I_{pv2} \). \( Q_{ref} \) is set to be zero. After expansion, the current references can be acquired:

\[
I_{dref} = \frac{2}{3} \left( \frac{1}{V_d^2 + V_q^2} \right) (V_{sd}P_{ref} + V_{sq}Q_{ref})
\] (30)

\[
I_{qref} = \frac{2}{3} \left( \frac{1}{V_d^2 + V_q^2} \right) (V_{sq}P_{ref} - V_{sd}Q_{ref})
\] (31)

And it can also be derived that

\[
I_{dref} + \Delta I_{dref} = \frac{2}{3} \left( \frac{1}{V_m^2} \right) [(V_{sd} + \Delta V_{sd})(P_{ref} + \Delta P_{ref}) + (V_{sq} + \Delta V_{sq})(Q_{ref} + \Delta Q_{ref})]
\]

\[
\Delta I_{dref} = \frac{2}{3} \left( \frac{1}{V_m^2} \right) (\Delta V_{sd}P_{ref} + V_{sd}\Delta P_{ref} + V_{sq}\Delta Q_{ref})
\] (32)

Where \( V_m^2 = V_d^2 + V_q^2 \)

\[
I_{qref} + \Delta I_{qref} = \frac{2}{3} \left( \frac{1}{V_m^2} \right) [(V_{sq} + \Delta V_{sq})(P_{ref} + \Delta P_{ref}) - (V_{sd} + \Delta V_{sd})(Q_{ref} + \Delta Q_{ref})]
\]

\[
\Delta I_{qref} = \frac{2}{3} \left( \frac{1}{V_m^2} \right) (V_{sq}\Delta P_{ref} + \Delta V_{sq}P_{ref} - V_{sd}\Delta Q_{ref})
\] (33)

### 4.2.2 Current Control Loop

The d and q axes are decoupled. The current control of inverter is expressed as:

\[
\frac{I_d}{I_{dref}} = \frac{1}{1 + s\tau}
\]

\[
\frac{I_q}{I_{qref}} = \frac{1}{1 + s\tau}
\] (34)

\[
I_{dref} = I_d + s\tau I_d
\]

\[
I_{qref} = I_d + \tau I_d
\] (35)

Where \( I_d \) is used to denote \( sI_d \).

Then equation (35) can be written in the following way:
\[ I_d = \frac{I_{dref}}{\tau} - \frac{I_d}{\tau} \]

\[ \Delta I_d = \frac{\Delta I_{dref}}{\tau} - \frac{\Delta I_d}{\tau} \]

\[ \Delta I_d = \frac{2}{3} \frac{1}{\tau V_m^2} \left( \Delta V_{sd} P_{ref} + V_{sd} \Delta P_{ref} + V_{sq} \Delta Q_{ref} \right) - \frac{\Delta I_d}{\tau} \]  

(36)

Similarly,

\[ \Delta I_q = \frac{2}{3} \frac{1}{\tau V_m^2} \left( V_{sq} \Delta P_{ref} + \Delta V_{sq} P_{ref} - V_{sd} \Delta Q_{ref} \right) - \frac{\Delta I_q}{\tau} \]  

(37)

4.2.3 Transmission Line and Load

![Diagram of transmission line and RL load](image_url)

Figure 4-17: Diagram of transmission line and RL load

The filter capacitor, transformer, transmission line, grid and RL load are included in the system, which is shown in Figure 3-10.

\[ C_f \frac{dV_s}{dt} = I - NI_{g1} \]

\[ \frac{dV_s}{dt} = \frac{I}{C_f} - \frac{NI_{g1}}{C_f} \]

\[ \Delta V_{sd} = \frac{\Delta I_d}{C_f} - \frac{N \Delta I_{g1d}}{C_f} \]  

(38)

\[ \Delta V_{sq} = \frac{\Delta I_q}{C_f} - \frac{N \Delta I_{g1q}}{C_f} \]  

(39)
For the transmission line between the PCC and the RL load, the equations can be obtained as:

\[ NV_x = R_1 I_{g1} + L_1 \frac{dI_{g1}}{dt} + V_1 \]

\[ \frac{dI_{g1}}{dt} = \frac{NV_x}{L_1} - \frac{R_1 I_{g1}}{L_1} - \frac{V_1}{L_1} \]

\[ \Delta I_{g1d} = \frac{N \Delta V_{sd}}{L_1} - \frac{R_1 \Delta I_{g1d}}{L_1} - \frac{\Delta V_{1d}}{L_1} \] (40)

\[ \Delta I_{g1q} = \frac{N \Delta V_{sq}}{L_1} - \frac{R_1 \Delta I_{g1q}}{L_1} - \frac{\Delta V_{1q}}{L_1} \] (41)

Similarly, for the transmission line between the RL load and grid, the equations can also be derived.

\[ \Delta I_{g2d} = \frac{\Delta V_{1d}}{L_2} - \frac{R_2 \Delta I_{g2d}}{L_2} - \frac{\Delta V_{gd}}{L_2} \] (42)

\[ \Delta I_{g2q} = \frac{\Delta V_{1q}}{L_2} - \frac{R_2 \Delta I_{g2q}}{L_2} - \frac{\Delta V_{gq}}{L_2} \] (43)

And for the RL load and the capacitor \( C_1 \),

\[ \Delta V_{1d} = \frac{\Delta I_{g1d}}{C_1} - \frac{\Delta I_{g2d}}{C_1} - \frac{\Delta I_{1d}}{C_1} \] (44)

\[ \Delta V_{1q} = \frac{\Delta I_{g1q}}{C_1} - \frac{\Delta I_{g2q}}{C_1} - \frac{\Delta I_{1q}}{C_1} \] (45)

For the RL load alone,

\[ \Delta I_{1d} = \frac{\Delta V_{1d}}{L} - \frac{R \Delta I_{1d}}{L} \] (46)

\[ \Delta I_{1q} = \frac{\Delta V_{1q}}{L} - \frac{R \Delta I_{1q}}{L} \] (47)

**4.2.4 State Space Equations**

Based on the equations above, the state space equations can be obtained.

(1) Current Control Loop

\[ \dot{X}_c = A_c X_c + B_{c1} U_{c1} + B_{c2} U_{c2} \] (48)
\[ X_c = \begin{bmatrix} \Delta I_d \\ \Delta I_q \end{bmatrix} \]

\[ A_c = \begin{bmatrix} -\frac{1}{\tau} & 0 \\ 0 & -\frac{1}{\tau} \end{bmatrix} \]

\[ U_{c1} = \begin{bmatrix} \Delta V_{sd} \\ \Delta V_{sq} \end{bmatrix} \]

\[ B_{c1} = \begin{bmatrix} \frac{2 P_{ref}}{3 \tau V_m^2} & 0 \\ 0 & \frac{2 P_{ref}}{3 \tau V_m^2} \end{bmatrix} \]

\[ U_{c2} = \begin{bmatrix} \Delta P_{ref} \\ \Delta Q_{ref} \end{bmatrix} \]

\[ B_{c2} = \frac{2}{3 \tau V_m^2} \begin{bmatrix} V_{sd} & V_{sq} \\ V_{sq} & -V_{sd} \end{bmatrix} \]

(2) Transmission Line and RL load

\[ \dot{X}_n = A_n X_n + B_{n1} U_{n1} + B_{n2} U_{n2} \quad [49] \]

\[ X_n = \begin{bmatrix} \Delta V_{sd} & \Delta V_{sq} & \Delta I_{g1d} & \Delta I_{g1q} & \Delta I_{g2d} & \Delta I_{g2q} & \Delta V_{ld} & \Delta V_{lq} & \Delta I_{ld} & \Delta I_{lq} \end{bmatrix}^T \]

\[ U_{n1} = \begin{bmatrix} \Delta I_d \\ \Delta I_q \end{bmatrix} \]

\[ U_{n2} = \begin{bmatrix} \Delta V_{gd} \\ \Delta V_{gq} \end{bmatrix} \]

\[ B_{n1} = \begin{bmatrix} \frac{1}{C_f} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{C_f} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \]
\[
B_{n2} = \begin{bmatrix}
0 & 0 & 0 & 0 & -\frac{1}{L_2} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -\frac{1}{L_2} & 0 & 0 & 0
\end{bmatrix}
\]

\[
A_n = \begin{bmatrix}
0 & 0 & 0 & 0 & -\frac{N}{C_f} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -\frac{N}{C_f} & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{N}{L_1} & 0 & -\frac{R_1}{L_1} & 0 & 0 & 0 & -\frac{1}{L_1} & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{N}{L_1} & 0 & -\frac{R_1}{L_1} & 0 & 0 & 0 & -\frac{1}{L_1} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -\frac{R_1}{L_1} & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -\frac{R_1}{L_1} & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{C_1} & 0 & 0 & 0 & -\frac{1}{C_1} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{C_1} & 0 & 0 & 0 & -\frac{1}{C_1} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{R}{L} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{R}{L} & 0 & 0
\end{bmatrix}
\]

The overall system can be expressed as:

\[
\dot{X}_{sys} = A_{sys} X_{sys} + B_{sys} U_{sys}
\]

\[
A_{sys} = \begin{bmatrix}
A_c & B_{c1} \cdot F_1 \\
B_{n1} & A_n
\end{bmatrix}
\]

\[
U_{sys} = \begin{bmatrix}
\Delta V_{gd} \\
\Delta V_{gq} \\
\Delta P_{ref} \\
\Delta Q_{ref}
\end{bmatrix}
\]

\[
B_{sys} = \begin{bmatrix}
0_{2 \times 2} & B_{c2} \\
B_{n2} & 0_{10 \times 2}
\end{bmatrix}
\]
After obtaining the state space equations, the system eigenvalues can be calculated. It’s shown that the eigenvalues lie in the left hand side of the s-plane and the system is stable. The small signal model is validated by comparing with the circuit model built in PSCAD™.

It’s observed that circuit model and linear model have the same response when solar irradiation changes. The only difference is that the circuit model shows a larger transient current and a longer settling time. However basically, the circuit model is validated by comparing with the derived linear model.
CHAPTER 5

EXPERIMENTAL RESULTS

5.1 Experimental setup

The whole setup of the experimental implementation is already described in Figure 2-5. Due to the limitation of facilities available in the laboratory, the experimental model is modified down to a lower level but still achieve the same goal. First of all, the solar cells are not available in our lab. Therefore, an independent DC power supply is presented to act as the PV power generator. The Sorensen™ DCS 40-75 supplies maximum 40V and 75A, respectively. The model is shown in Figure 5-1.

![Figure 5-1: Sorensen model DCS 40-75](image)

This model is used to simulate the output characteristics of the PV module with MPPT. The voltage output of the DC source can be set as a constant, and the current can be controlled by the inverter. In other words, if the maximum power of the PV array is given, then the current can be controlled while the voltage remains constant.

The Semikron™ three-phase inverter is used to converter DC voltage to three-phase AC voltage and to interface with grid. The inverter is shown in Figure 5-2.

![Figure 5-2: Semikron™ three-phase inverter](image)
The inverter can be fed by a maximum of 800V DC voltage, and output 18A rms AC current. And the inverter works at an absolute maximum switching frequency of 20kHz. An equivalent DC capacitor bank is provided in the Semikron™ at 940μF. Although it’s different from the capacitance designed in the simulation model, the experimental results show that the difference has little effect on the performance of the system.

The current control is designed via using dSPACE™. The controller board is fully programmable from the simulink block diagram environment by Real-Time Interface™ (RTI). The only difference in the RTI™ model is that the measured current and voltage are represented by ADC blocks. And the output digital signals are connected to hardware facility via DAC blocks. The algorithm is shown in Figure 5-3.

![Figure 5-3: Current control algorithm designed by dSPACE™](image)

The issue that needs to be considered is that both ADC and DAC channels have turning ratio. Hence, in order to reproduce the original value, a corresponding gain should be added in the simulink block. At the beginning, slave I/O port was used to generate the PWM for the inverter. Although it’s easy to use and implement, it’s not clear what’s going on inside the block. Besides, the dSPACE has a limit of sampling time of 50μs, which is larger than the time step requirement in our simulation. And it’s observed that under this circumstance, it’s not possible for the current feedback to track the current reference accurately. Unfortunately, the harmonic is very sensitive to the phase shift so
that the performance could be even worse. Then, an analog pulse generation board was
developed to produce the firing pulses for the Semikron™. Since it has a smaller time
step, the current tracking is much faster and the compensation performance is better than
slave I/O.

The function of the LC filter is talked about in the previous chapter. Due to the fact
that power and voltage level are both lower in the experiment than those in the simulation,
there is no need for the transformers and the distribution line. The variable transformer is
utilized to step down the grid voltage to a lower level suitable for the experimental
system. And the Variac is shown in Figure 5-4. The system parameters are shown in
Table 3.

![Variable transformer](image)

**Figure 5-4: Variable transformer**

<table>
<thead>
<tr>
<th><strong>Table 5: Experiment system parameters</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DC link voltage</strong></td>
</tr>
<tr>
<td><strong>DC equivalent capacitance</strong></td>
</tr>
<tr>
<td><strong>IGBT R&lt;sub&gt;on&lt;/sub&gt;</strong></td>
</tr>
<tr>
<td><strong>Diode forward voltage drop</strong></td>
</tr>
<tr>
<td><strong>Inductance for LC filter</strong></td>
</tr>
<tr>
<td><strong>Capacitance for LC filter</strong></td>
</tr>
<tr>
<td><strong>Diode rectifier resistive load</strong></td>
</tr>
<tr>
<td><strong>Parallel three-phase resistive load</strong></td>
</tr>
<tr>
<td><strong>Grid voltage (per phase)</strong></td>
</tr>
<tr>
<td><strong>Switching frequency</strong></td>
</tr>
</tbody>
</table>
The resonant frequency for the LC filter can be calculated as follows:

\[ f = \frac{1}{2\pi\sqrt{LC}} \]

The resonant frequency of the low-pass filter is around 600Hz so that it can pass up to 10\textsuperscript{th} harmonics flowing through. Although it’s better to have a relatively higher resonant frequency to allow more harmonics, the resonant frequency should be several times smaller of the switching frequency.

The nonlinear load is represented by diode rectifier in parallel with three-phase resistive load, which is shown in Figure 5-5.

![Figure 5-5: Diode rectifier nonlinear load model](image)

The diode rectifier feeding a resistor is used to serve as the nonlinear load. The purpose of the three-phase resistive load is to reduce the harmonic content of the diode rectifier so that compensation effect will be much easier to observe. Moreover, it’s more realistic in industry.

### 5.2 Experimental Data

The experimental results are shown in the following figures. The current reference and feedback in dq axes are shown in Figure 5-6 and Figure 5-7 to check the accuracy of
the control algorithm. The nonlinear current and grid current are also depicted to show the compensation performance of the proposed algorithm. For validation, the experimental results are compared with the corresponding simulation results in MATLAB™.

Figure 5-6: Current in d axis from the inverter side

Figure 5-7: Current in q axis from the inverter side
From the above figures, it’s shown that the current feedback matches the reference signal to a large extent with some oscillation. The oscillation may come from the zero shift of the voltage/current sensor board, loose connection for hardware component, and etc. The d axis current is controlled to be some constant value plus harmonic component of the nonlinear current. And the q axis current is controlled to be zero plus harmonic component of the nonlinear current. The current is controlled by the inverter via using dSPACE™. The nonlinear current is shown in Figure 5-8 compared with the one in simulation. The currents are measured by connecting the ideal voltage supply to the diode rectifier. The fundamental component can be seen from the figures. However, the currents are very rich in harmonics. The situation will be worse if only the diode rectifier is connected without three-phase resistive load.

Figure 5-8: Nonlinear current produced by diode rectifier (Left: Experiment, Right: Simulation)

Figure 5-9: Grid side current and voltage of one phase
It’s shown that the phase voltage on the grid side is sinusoidal, since it’s directly connected to the utility power supply. Meanwhile, the sinusoidal frame can be observed from the phase current shown above, which is achieved by harmonic compensation. Although the current is not totally sinusoidal, it’s much better than that without harmonic compensation. However, it’s seen that current spikes still occur in every cycle. And it’s known that the harmonics can’t be absolutely compensated due to the limit of the LC filter, time step limit of dSPACE™, and others. For comparison, the current on the inverter side, grid side and load side are presented in Figure 5-10. The top one shows the grid current after compensation. And the figure in the middle is the inverter of the inverter, which is controlled to provide the harmonic current. The amplitude of the inverter current is around 2A because the d-axis current is controlled to be 2A plus the harmonic current. The bottom figure shows the nonlinear current, which is equal to the inverter current plus the grid current.

Figure 5-10: Currents on the inverter side, grid side and load
For validation, the current of the grid side is compared with that modeled in the MATLAB™, which is shown in Figure 5-11. As discussed before, the voltage is connected directly to the utility grid so that the waveform is sinusoidal. The figure on the left is gained from experimental test bed, which shows some spikes in the current. In contrast, the figure on the right is from the MATLAB™ simulation. The difference between the two situations is that the time step in simulation is much smaller than that in experimental setup. And it’s obvious that the performance is better with a smaller time step.

Figure 5-11: Grid current and voltage (Left: experiment, Right: simulation)
CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

In this thesis, a multi-string grid-connected photovoltaic (PV) system with harmonic compensation was presented. For the general configuration, a novel topology of central inverter with individual DC/DC converter was introduced to model the grid interface of solar arrays. Then DC transmission lines were also proposed to emulate the short distance between solar arrays and the central inverter. For the distribution network, two segments of distribution lines with three-phase resistive load were developed to simplify the real distribution network. The system performance and transient response under disturbance conditions were analyzed in MATLAB™. Later on, small signal analysis was also carried out to validate the simulation model. The results showed that the system remained stable under the disturbance and the performance was acceptable.

Harmonic compensation test bed was configured with dSPACE™ to achieve current control algorithm. Diode rectifier in parallel with resistive load was presented to generate the harmonic. Time-domain current detection algorithm was proposed in the thesis to extract the harmonics of the nonlinear load. Controllable DC source was selected to represent the characteristics of the output of solar PV arrays. The Semikron inverter was used to convert DC to AC, which was controlled by analog signal firing board. Although the LC filter had limitation for the degree of harmonic compensated, it always existed with the voltage source inverter to improve the voltage waveform on the AC side. The inverter was controlled by the dSPACE™ to generate the harmonic current needed for the nonlinear load so that the current on the grid side could be approximately sinusoidal, at least within the standard set by the IEEE 519-1992. Experimental result and corresponding simulation results were compared under the harmonic compensation scheme. Finally, it’s found out that the system performance of harmonic compensation was satisfied and applicable.

6.2 Future Work
For the future research, the following improvement can be implemented. For the hardware configuration, the current control was accomplished in dSPACE™ which had a time step limit of 50μs. A smaller time step device such as FPGA or DSP can be utilized to achieve the control algorithm. In this case, the current feedback should track the reference more quickly and exactly. Then a better performance of harmonic compensation could be expected.

Solar panels and boost converters should be used instead of Controllable DC source to better represent the characteristics of the PV arrays and achieve MPPT. The LC filters needs to be redesigned so that it approaches compromise of a high resonant frequency and an acceptable voltage waveform on the AC side. And it’s advisable to increase the voltage level of the system to a higher level so that it can emulate the real scenario of power system as close as possible.

Recently, anti-islanding and fault protection for PV system are receiving more and more attention. They will be studied in future from both simulation and experimental tests.
REFERENCES


BIOGRAPHICAL SKETCH

Jianwu Cao was born in Taizhou, Jiangsu Province, China on July 18, 1987. He received his B.S. degree in Electrical Engineering in June 2009 from Huazhong University of Science and Technology, in Wuhan, Hubei Province, China. He joined the Florida State University in 2009 to purse his MS in the department of Electrical and Computer Engineering at Florida State University. Since September 2009, he has been working as a graduate research assistant under Dr. Chris S. Edrington at the Center for Advanced Power Systems.