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Modeling and Analysis of Grid-Connected Solar-Wind Hybrid Power System

Sultan Altamimi
University of Northern Iowa

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MODELING AND ANALYSIS OF GRID-CONNECTED SOLAR-WIND HYBRID POWER SYSTEM

An Abstract of a Thesis
Submitted
in Partial Fulfillment
of the Requirements for the Degree
Master of Arts

Sultan Altamimi
University of Northern Iowa
July 2012

ABSTRACT

Renewable energies are considered to be a significant part of the energy mix to assist the existing electricity demand and the future of electrical generation. Electrical power simulation software is increasingly being used to answer and determine the source of potential problems in the actual power system. To have a better understanding of an electrical power system, it is essential to validate all the components through simulation within an environment that allows accurate modeling of all power system components. This research presents modeling and analysis of an actual grid-connected solar-wind hybrid system at University of Northern Iowa campus in Cedar Falls, Iowa. A number of simulation studies were carried out in MATLAB/Simulink using the SimPowerSystems toolbox. This research covers simulations of normal operation of the actual grid-connected solar-wind hybrid power system, then compares the results to three case studies; (a) Case Study I: Analysis of PV terminal voltage fluctuations due to source and load changes, (b) Case Study II: Analysis of wind turbine terminal voltage fluctuations due to wind changes and (c) Case Study III: Analysis of voltage distortion at the utility interface. Each simulation case concentrates on the variation in voltage magnitude, sag and swell, continuous voltage operating range and transient voltage concluding with discussions of the problems that arise during fault operations.

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July 2012

This Study by: Sultan Altamimi

Entitled: Modeling and Analysis of Grid-connected Solar-Wind Hybrid Power System

has been approved as meeting the thesis requirement for the

Degree of Master of Science in Technology

6/8/2012 Date	Dr. Recayi Pecen, Chair, Thesis Committee
6/8/2012 Date	Dr. Dale Olson, Thesis Committee Member
6/12/2012 Date	Dr. Jin Zhu, Thesis Committee Member
6/8/2012 Date	Dr. Hong Nie, Thesis Committee Member
7/19/12 Date	Dr. Michael J. Licari, Dean, Graduate College

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TABLE OF CONTENTS

LIST OF TABLES vi

LIST OF FIGURES vii

CHAPTER I: INTRODUCTION 1

- Motivation and Background 1
- Statement of the Problem 1
- Purpose of Study 2
- Need and Justification 3
- Research Questions 4
- Assumptions 4
- Limitations 5
- Definition of Terms 5
- Procedure of Simulation Study 6
- Experimental Layout 7

CHAPTER II: REVIEW OF RELATED LITERATURE 8

- Introduction 8
- Efficiency of Grid-Connected Solar Photovoltaic Systems 8
- Efficiency of Grid-Connected Wind Turbine Systems 13
- Hybrid Solar-Wind Power System 16
- Summary 22

CHAPTER III: METHODOLOGY AND MATERIALS.......23

Introduction.......23

Solar System Components.......24

Wind System Components.......31

Procedure of the Simulation Study.......36

Experimental Layout.......37

SimPowerSystems Simulation Environment.......40

CHAPTER IV: SIMULATION AND ANALYSIS.......48

Overview.......48

Normal Operation.......48

Case Study I: Analysis of PV Terminal.......54

Case Study II: Analysis of Wind Turbine Terminal.......57

Case Study III: Analysis of UNI Electric Gird Terminal.......62

CHAPTER V: CONCLUSION AND RECOMMENDATION.......64

Discussion.......64

Summary.......66

Recommendation and Future Work.......66

REFERENCES.......67

APPENDIX A: DATASHEETS.......69

APPENDIX B: SIMULATION FIGURES.......73

LIST OF TABLES

1. Photovoltaic module specifications........10
2. Hybrid system operating modes........20

LIST OF FIGURES

1. Yearly averages output power 11
2. Monthly averages output power 12
3. The daily profiles of output power generated from the PV system 13
4. A general wind turbine with DFIG 14
5. Grid connected, PMG based small wind turbine system 16
6. Concept of hybrid energy system 17
7. Wind–photovoltaic hybrid system block diagram 18
8. Schematic diagram of the proposed multi-input inverter 21
9. 12-kW wind-solar power system at UNI campus 23
10. SHARP NT-175UC1 electrical characteristics 24
11. SHARP NT-175UC1 dimensional diagram 25
12. Basic system overview 27
13. Single-line circuit diagram the installed PV system at UNI campus 28
14. Wind system major components 31
15. Bergey Excel 10 power output versus wind speed 35
16. A transient voltage fluctuation in a sine waveform 38
17. (a) Clean waveform (b) a third harmonic is added 39
18. Waveform of normal, sag and swell voltage 40
19. Equivalent circuit diagram of photovoltaic 41
20. MATLAB/SimPowerSystem Grid-connected solar power system 41
21. MATLAB/SimPowerSystems implementation photovoltaic module 42
22. PV array block parameters 43
23. SimPowerSystems model for grid-connected wind turbine 44
24. SimPowerSystem wind turbine block parameters 45
25. SimPowerSystem simulation model of grid-connected solar wind power system 47
26. SimPowerSystem wind power output 49
27. SimPowerSystem Solar power output 49

28. SimPowerSystem Solar three-phase voltage and current before the filter 50
29. SimPowerSystem Solar three-phase voltage and current after the filter 51
30. SimPowerSystem wind turbine three-phase voltage and current 52
31. SimPowerSystem UNI grid side three-phase voltage and current waveform 53
32. SimPowerSystem UNI grid side frequency waveform..53
33. SimPowerSystem solar PV side three-phase voltage and current during a fault operation on the solar side of the power system...54
34. SimPowerSystem wind side three-phase voltage and current during a fault operation on the solar side of the power system..55
35. SimPowerSystem grid side three-phase voltage and current during a fault operation on the solar side of the power system..56
36. Three-phase fault connected to wind side of the power system 57
37. SimPowerSystem wind side three-phase voltage and current during a fault operation on the wind side of the power system..58
38. SimPowerSystem solar side three-phase voltage and current during a fault operation on the wind side of the power system..59
39. SimPowerSystem grid side three-phase voltage and current during a fault operation on the wind side of the power system..60
40. SimPowerSystem zoom-in grid side three-phase voltage and current during a fault operation on the wind side of the power system..60
41. SimPowerSystem zoom-in grid side three-phase voltage and current during a fault operation on the wind side of the power system..61
42. SimPowerSystem grid side three-phase voltage and current during a fault operation on the utility grid side of the power system..62
43. SimPowerSystem wind side three-phase voltage and current during a fault operation on the grid side of the power system 63
44. SimPowerSystem solar side three-phase voltage and current during a fault operation on the grid side of the power system 63
45. SimPowerSystem wind turbine...74

46. SimPowerSystem solar panel 74
47. SimPowerSystem solar panel inverter 75
48. SimPowerSystem frequency measurement...75

CHAPTER I

INTRODUCTION

Motivation and Background

The world economy and our life on a daily depend on energy, as a result we are consuming more electricity than ever and we are generating more. Renewable energies are considered to be a significant part of the energy mix to assist the existing electricity demand and the future of electrical generation. This has become an increasing concern because of the global environmental consequences of Carbon Dioxide emissions resulting from burning fossil fuel as well as from the rapidly increasing energy consumption, which leads to a higher demand and price on fossil fuel.

Electrical power simulation software is increasingly being used to answer and determine the source of potential problems in the actual power system. To have a better understanding of an electrical power system, it is essential to validate all the components through simulation within an environment that allows accurate modeling of all power system components. This research paper seeks to help further understand the behavior of grid-connected solar-wind hybrid system and investigate the reliability of distributing electric power produced by solar and wind energy sources.

Statement of the Problem

Wind speed and solar radiation levels are the key factors of solar-wind hybrid power systems; however, the electric power generated from renewable sources shows instable shortcomings due to climate conditions, including solar radiation, wind speed, air temperature and other variables. Climate conditions are continuously changing for different regions and locations. Nowadays, we cannot fully rely on renewable-based energy systems even with the combination of two renewable energy sources. The rapid changes in weather conditions might cause electrical power faults on the grid-connected solar-wind power system. These electrical power faults cannot be injected to the utility power grid, therefore the power system station has to handle and fix any electric power fault or disconnect from the utility grid if necessary in case of lightning strike.

Purpose of the Study

The purpose of this study is to investigate how to increase the reliability of hybrid solar-wind power systems. Solar and wind energy are renewable energy sources, and by combining them into one power grid system we can increase the reliability of overall electrical power generation throughout the year. Since Iowa has windy winter seasons and sunny summer seasons, it's possible to maximize electrical power generation by combining of both solar and wind power systems connected to utility power grid.

This study also helps further the understanding of the behavior of grid-connected solar-wind hybrid power system during fault operations and after they end. The study represents a useful tool in research activity and teaching on renewable energy areas for students and faculty members in the Electrical Engineering Technology program at the University of Northern Iowa.

Need and Justification

With the concerns about rising fossil fuel prices and the demand for maintaining a healthy environment with reasonable cost, the world is heading in the direction of generating electricity from renewable resources in the future. The purpose of a solar-wind hybrid power system connected to the grid would be to diversify the source of electricity generation and lead to more security and sustainable energy supply. Today's grid depends on large central power plants. These power plants remain important; however the grid must now accommodate many smaller power sources closer to the customers and homeowners. A smart grid will safely carry clean green renewable energy from wherever it made to wherever it's needed.

Chen, Kang, and Lee found that the combination of solar-wind power systems has very high power production potential because of its ability to harvest both solar and wind energy (Chen, Kang & Lee, 2010). Most of solar resources are available at times of peak electrical load. However, using two different resources together makes the hybrid Solar-Wind Power system more difficult to analyze.

Similar power systems already exist in markets with low efficiency values. In his study, Kalogirou found that the current average efficiency is about 25 percent for solar energy, and 45 percent for wind energy. Therefore, this research paper is going to investigate how to measure overall efficiency of hybrid solar-wind power systems that may lead to measure the overall system reliability (Kalogirou, 2009).

Research Questions

The research questions for this study are as follows;

1. What is the behavior of the grid-connected solar-wind hybrid power system when applying different faults in each section of the station?
2. What is the impact on the UNI grid when applying a three-phase fault at the wind side of the grid-connected solar-wind hybrid power system?
3. What is the impact on the UNI grid when applying a DC fault at the solar side of the grid-connected solar-wind hybrid power system?
4. Does the grid-connected solar-wind hybrid power system continue to operate normally after the fault in each section clears?

Assumptions

1. This research paper is going to evaluate the current status of hybrid solar-wind energy systems and find possible ways to improve their overall efficiency and performance.
2. The location of the hybrid solar-wind system selected at the University of Northern Iowa Campus has enough renewable energy resources.
3. The average operation will be generalized and estimated for large-scale hybrid solar wind power systems in different locations.
4. The digital software tool MATLAB/SimPowerSystems selected for simulations has enough precision to complete the case studies.

Limitations

The following limitations may affect the result of this study:

1. The hybrid solar-wind system at the University of Northern Iowa (UNI) campus is limited by a 12 kW installed power capacity.
2. The software SimPowerSystems, where simulations and case studies were carried out, is not fully capable of renewable energy power systems that connected to a modern electrical grid, such as smart grid.
3. The simulation software MATLAB/SimPowerSystems is able to run only one fault at a time.

Definition of Terms

SimPowerSystems: Is a power systems analysis solution that includes analytical software modules for modeling and simulating the generation, transmission, distribution, and consumption of electrical power. It provides models of many components used in these systems, including three-phase machines, electric drives, and libraries of application-specific models such as Flexible AC Transmission Systems (FACTS) and wind-power generation.

Transient voltage and current: A temporary, undesirable voltage that appears on the power supply line. Transient voltages can range from a few volts to several thousand volts, and can last from a few seconds to a few milliseconds. It also can be caused by turning off high inductive loads, switching large power factor correction capacitors or the lightning strikes hitting any part of the power system.

Sag and Swell: Voltage sags (under-voltage) can be caused when high current loads such as the start-up of large motors. Under-voltage may also occur when a power utility reduces the voltage level to conserve energy during peak usage. It is also commonly caused by overloaded transformers or undersized conductors. The voltage swells (over-voltage) can be caused when high current loads are switched off, such as when motor-driven machinery shuts down.

Data acquisition: "is the recognized name for the branch of engineering dealing with collecting information from a number of analogues sources and converting it to digital form suitable for transmission to a computer, printer or alphanumeric display" (Rosemary, 1997).

Procedure of the Simulation Study

In conducting this research, the following three main steps are undertaken:

a. Case Study I: Analysis of PV terminal voltage fluctuations due to rapid source changes and grounding failure.
b. Case Study II: Analysis of wind turbine terminal voltage fluctuations due to rapid wind changes and lightning strike.
c. Case Study III: Analysis of voltage distortion at the utility interface.

These experimental studies are modeled and analyzed using the facilities of MATLAB environment for simulation of the grid-connected solar-wind power system. MATLAB/SimPowerSystem is a power systems analysis solution that includes analytical software modules for load flow, arc flash, short circuit, motor starting, transient stability, relay coordination, cable ampacity, optimal power flow, intelligent power monitoring, energy management, system optimization, advanced automation, and real-time load and source prediction.

Experimental Layout

In order to perform the data analysis related for each case study, the design of the actual grid-connected solar-wind hybrid station at University of Northern Iowa campus in Cedar Falls, Iowa was carried out in MATLAB/Simulink using the SimPowerSystems toolbox. SimPowerSystems allows different module and subsystems to be built within any one model. The quality of electrical power that produced by the system is described as a set of values of parameters, such as:

1. Variation in voltage magnitude
2. Continuous voltage operating range
3. Transient voltage and current
4. Harmonic content in the waveforms for AC power
5. Sag and Swell

CHAPTER II

REVIEW OF RELATED LITERATURE

Introduction

In the recent years, there are a lot of research sources that have been done in solar and wind energy. The review of related literature has been divided into (a) efficiency of grid-connected solar photovoltaic systems (b) Efficiency of grid-connected wind turbine systems (c) Hybrid solar-wind power system.

Efficiency of Grid-Connected Solar Photovoltaic Systems

According to SuYan, the photovoltaic array system that converts solar energy into power has come to be one of the most promising renewable energy systems. It has a multiple growth rate of over 15 percent per year in the last few decades. Despite the fact that a photovoltaic system is capable to work and operate alone, it is normally connected to traditional grid electricity to increase the reliability of the overall electricity production system. The electrical power grid has the ability to provide a source of electricity back up if the solar photovoltaic system cannot meet the load requirement (Su Yan, 2011).

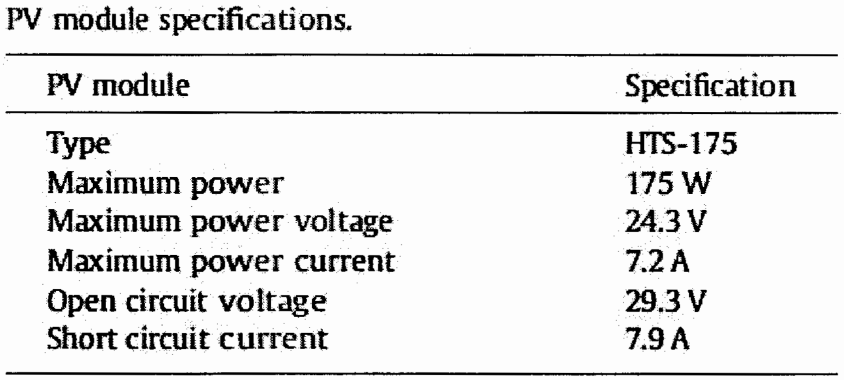
Su Yan uses real time models to calculate the energy efficiency and power output of the solar photovoltaic power system. All models were confirmed by using collected data of Su Yan's grid-connected solar photovoltaic system. Time frames that been used based monthly averages and on yearly average are measured. The result shows that the prediction model for the yearly/monthly average of the minutely output power very similar to the measured data with high value of R^2 (coefficient of determination).

When the prediction model is measuring system efficiency, it is based on the relationship between the predicted solar irradiance and the predicted output power. The relationship result shows that it's not very accurate for the growth and decay phases where the system efficiency is near zero; however it is able to fit the middle phase (9 am to 4 pm) very well. Moreover, it can still work as a valuable determination for researchers as most photovoltaic power systems operate in the most efficient method over this particular period of time. The result also shows that the maximum monthly average minutely efficiency differs over a minor range of 10.81% to 12.63% in different months (Su Yan, 2011).

Su Yan's grid-connected photovoltaic system contains of twelve Kyocera HTS-175 modules over a total land of 15.325 m2 (12 pcs × 1.29 m × 0.99 m) with an installed capacity of 2.1 kW. When the system is operating under standard test conditions (cell temperature = 25 °C, solar irradiance = 1 kW/m^2), the maximum output power of the HTS-175 module is 175 W ± 5 percent. Each of the modules includes 48 solar cells made of multi-crystalline silicon wafers. The photovoltaic module specifications are shown in Table 1. Generally, mounted solar modules help to prevent accumulation of dust on the surface and provide a natural cooling effect on the module. The photovoltaic modules were installed of an inclination angle of 10°, facing south-east.

Table 1.

Photovoltaic module specifications (Su Yan, 2011).



PV module specifications.

PV module	Specification
Type	HTS-175
Maximum power	175 W
Maximum power voltage	24.3 V
Maximum power current	7.2 A
Open circuit voltage	29.3 V
Short circuit current	7.9 A

Su Yan arranged the prediction model for output power in matrix form. *Ptd* represent the measured output power per unit area at time *t* in the day *d*. He left some elements in the matrix unfilled since some values were not available. Different categories of time averages can be calculated, depending on the time frame (one month/quarter/year) to be considered. He also measured two different of time averages while the other categories of time averages can be in the same way discussed, as well as both the yearly average and the monthly average. Su Yan calculated the yearly and monthly averages of output power at time *t* by these two equations

$$\overline{P}_y(t) = \frac{1}{N_y} \sum_{d=1}^{N_y} P_{td} \quad \text{.........} \quad (1)$$

$$\overline{P}_m(t) = \frac{1}{N_m} \sum_{d=1}^{N_m} P_{td}, \quad \text{.........} \quad (2)$$

Where:

t	Time Period
d	Day
N_y	Number of days in a year
N_m	Number of days in a month
P_{td}	Output power at time t in day d
$\overline{P}_y(t)$	Yearly average output power
$\overline{P}_m(t)$	Monthly average output power

Yan Su's model results came up as listed in Figure 1 and 2:

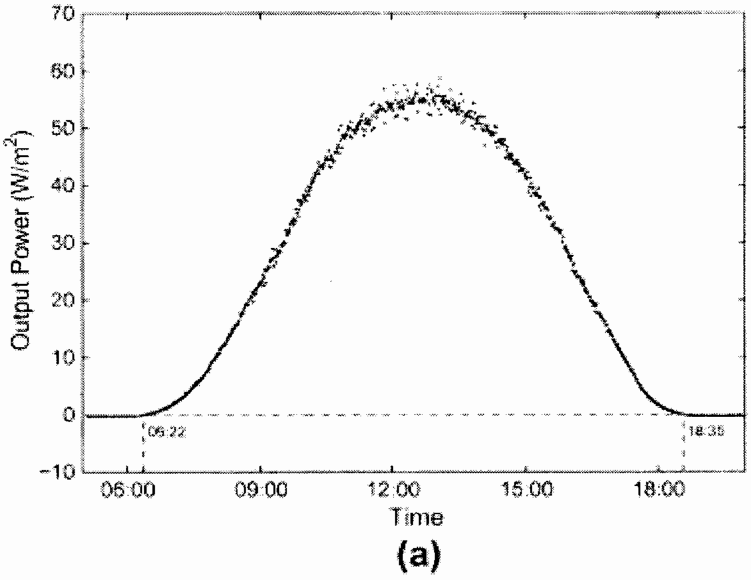


Figure 1. (a) Yearly averages of output power (Su Y et al., 2011).

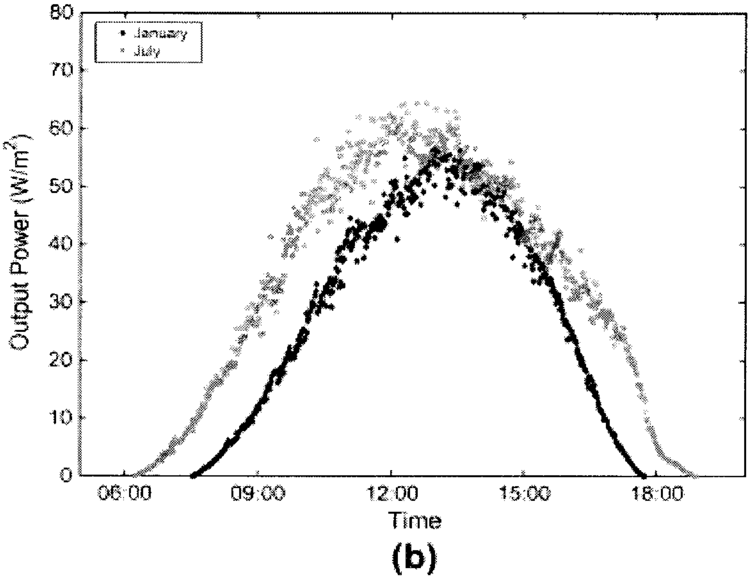


Figure 2. (b) Monthly averages output power (Su Y et al., 2011).

Yan Su also covered the daily profiles of output power produced by the solar photovoltaic system during the period of four days from March 4 to March 7, 2011. These four days were selected to show the variation of the weather patterns as broadly as possible. March 4 and March 7 were clear sunny days, March 5 was mostly cloudy day, and March 6 was sunny with some scattered cloud. Throughout the days with mostly cloudy sky and scattered cloud, the output power shows an irregular profile whereas the clear days, the output power shows a similar profile as showing in Figure 3 (Su Y et al., 2011).

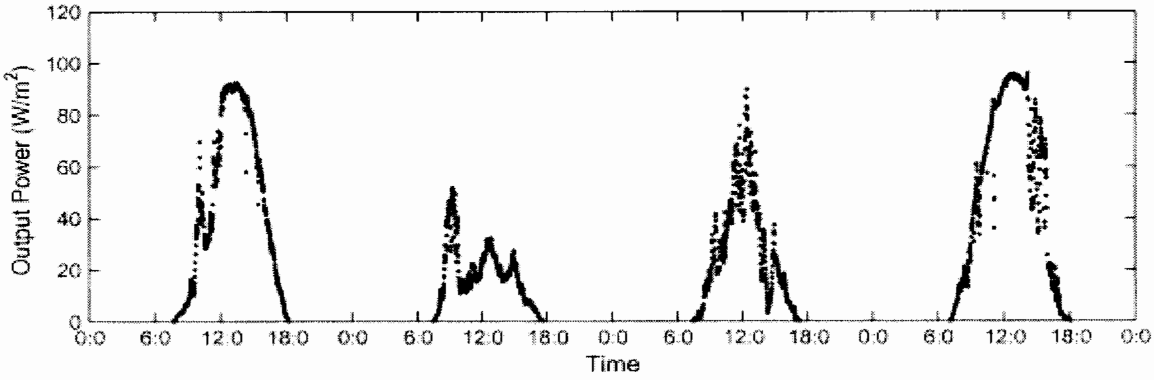


Figure 3. The daily profiles of output power generated from the PV system during the four days from March 4 to March 7. (Su Yan, 2011).

Yan Su's proposed forecast model can serve a valuable purpose for the real time expectation of system efficiency for any solar photovoltaic system. The forecast model shows that the maximum monthly average minutely energy efficiency ranges from 10.81% to 12.63%.

Efficiency of Grid-Connected Wind Turbine Systems

In present day, the most common type of wind turbines installed globally is the pitch-controlled variable speed wind turbine, which has better advantages such as controllability of speed and flexible operation compared to the other fixed speed wind turbines. Other advantages of using pitch-controlled variable speed wind turbine include speed control, enhanced power quality, decrease mechanical pressures, decoupled control of active and reactive power as well as more power production than fixed speed wind turbine under the same circumstances (Kyaw, 2010).

Min Kyaw studied two types of variable speed wind turbine, which are commonly used; first type is direct-drive synchronous wind turbine, which is entirely decoupled from the electrical grid by a power electronics converter connected to the stator winding. The electric grid side of this converter is a voltage-source converter. The wind turbine side can be a voltage-source converter or diode rectifier. The direct-drive wind turbine is excited using an excitation winding or permanent magnets. Additional type is doubly fed induction generator (DFIG), which also uses power electronics. One end of a back-to-back voltage-source converter provides the three-phase rotor winding and other end connected to stator winding or power grid as shown in Figure 4.

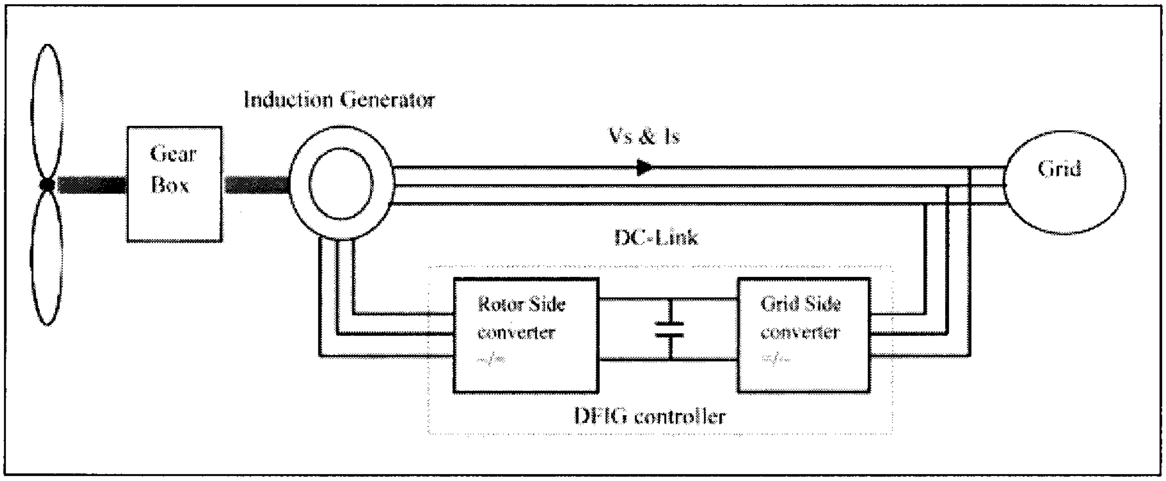


Figure 4. A general wind turbine with DFIG (Kyaw, 2010)

M. Abderrazzaq did several case studies on the analysis of a wind turbine standstill for a grid-connected wind farm. Different types of collected data were employed to analyses and find the causes of wind turbines shutdown in a grid-connected wind farm. Even though the average availability of the considered wind turbine exceeds

96%, the individual availability of some turbines does not exceed 92%. This method was based on a variation of monthly electricity generation to measure the shutdown time including the maintenance and fault hours. The low wind speed hours in summer are 60% less than the average low wind speed hours for the considered wind farm. The distribution of out of operation hours shows a 300% variance between the original and measured times of downtime. However, measured times are used to evaluate the impact of various faults causing wind turbines to shut down. The frequency spreading of the faults has shown that 42% of wind turbines shutdowns are produced by network turbulences, 70% of the network turbulences are attributed to the electric grid disconnections (Abderrazzaq, 2006).

Md. Arifujjaman investigated a permanent magnet generator while it is connected to the electric grid as a based wind turbine requires a power conditioning system comprising a bridge rectifier, a DC–DC converter and a grid-connected inverter. His investigation also presents the reliability examination and identification of the least reliable element of the grid-connected power conditioning system. Reliability of the configuration is examined for the worst case scenarios maximize the conversion losses at a specific wind speed. The examination discloses that the reliability of the power conditioning system of such permanent magnet generator based wind turbines as seen in Figure 5 is noticeably low and it decreases to 84% of original value within one year. Additionally, his investigation went further to identifying the least reliable element within the power conditioning system and found that the inverter has the dominant effect on the system reliability, while the DC–DC converter has the least important effect.

The reliability examination makes evident that a permanent magnet generator based wind energy conversion system is not the best choice from the point of view of power conditioning system reliability. The examination also discloses that new research is essential to determine a well power electronics structure for small wind turbine conversion (Arifujjaman, 2009).

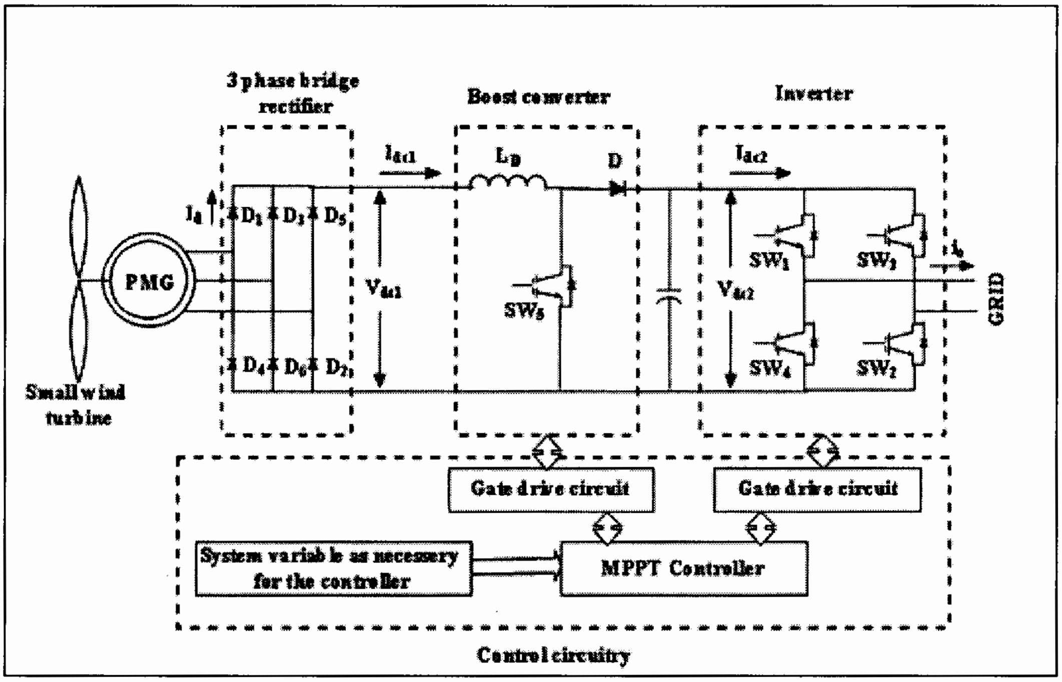


Figure 5: Grid connected, PMG based small wind turbine system (Arifujjaman, 2009).

Hybrid Solar-Wind Power System

Wind and solar power systems are worldwide available and environmental friendly. The wind energy systems may not be technically feasible at all locations because of low wind speeds and being more unpredictable than solar energy. The combinations of these two renewable energy sources, as a result, have become increasingly attractive and commonly used as substitute of fossil fuel produced energy.

Economic characteristics of these renewable energy technologies are sufficiently promising to include them for increasing power production capability. A renewable hybrid energy system contains of two or more energy sources, a power conditioning equipment, a controller and an optional energy storage system. Investigation and improvement efforts in solar, wind, and other renewable energy technologies are essential to continue for, improving their performance and production, founding methods for precisely predicting their power output and consistently integrating them with other conventional generating sources. The goal of Nema's study is to review the current state of the design, operation and control requirement of a solar–wind hybrid energy systems with conventional backup as seen in Figure 6 (Nema, 2009).

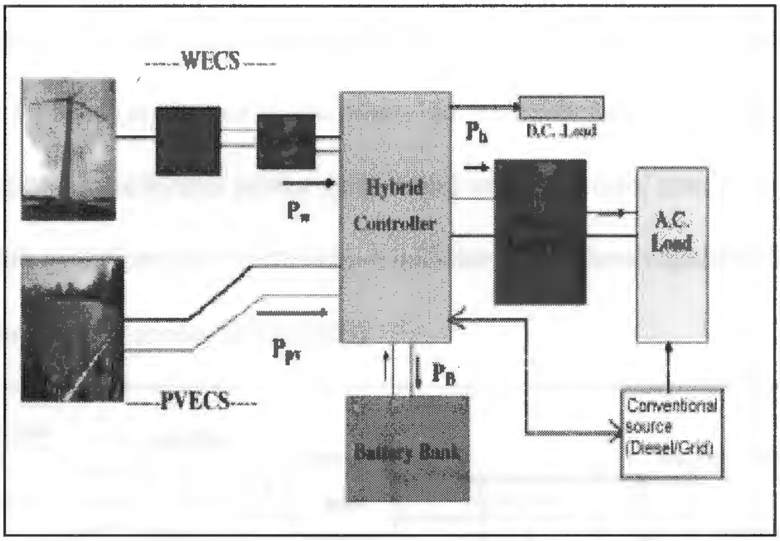


Figure 6. Concept of hybrid energy system (Nema, 2009)

A techno-economic study to implement a hybrid solar photovoltaic and wind turbine power generating system is located on the western coast of India. The system uses short-term electrical power storage using lead-acid batteries, and supplementary power from the A.C. mains power supply. The ideal system would be able to supply 84.16% of the annual electrical energy requirement of the site. The annualized cost of this power in Rs./kwh works out to be several times the present price of government supplied electricity (Bhave, 2002).

Mehdi Dali studied experimental results from the operation of a test bench constituted of a grid-connected hybrid system as seen in Figure 7. This device includes wind and photovoltaic physical emulators, battery energy storage, load and a controlled interconnection to the Low Voltage grid. Both the Wind generation unit and the PV generation unit are connected to the weak AC grid via a single phase inverter with a lead acid accumulator. The grid power inverter is suitably controlled to permit the operation of the system either interconnected to the LV grid, or in standalone mode, with a seamless transfer from the one mode to the other. His research study provides a technical explanation of the hybrid power system and of the inverter energy management, along with wide measurement results which validate the system capability to operate in the above-mentioned mode (Dali, 2010).

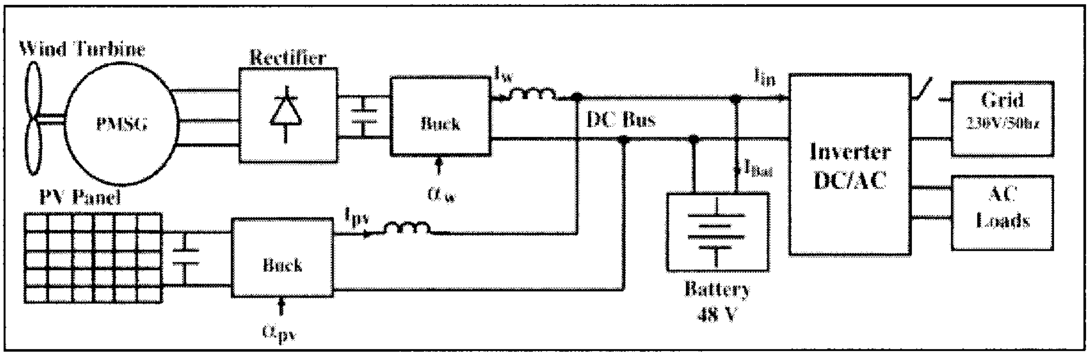


Figure 7. Wind–photovoltaic hybrid system block diagram (Dali, 2010).

Dali uses three different types of grid mode:

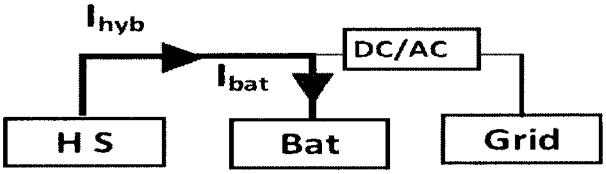
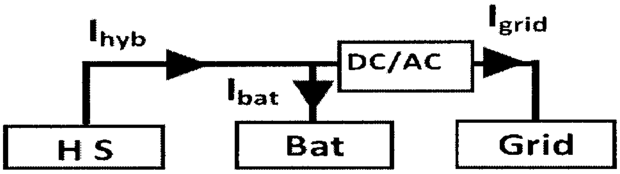
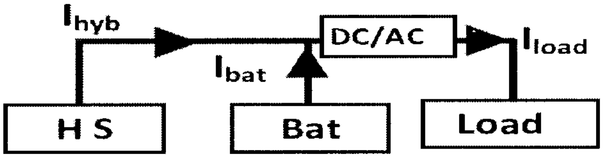
Grid mode without injection: The hybrid system first charges the batteries in standalone. If the feed-in threshold is reached (default = 52 V), the device will switch over to grid feed-in mode.

Grid mode with injection: Feeding power into grid is the standard operating mode of the inverter. The inverter can inject AC output current to the grid when the value of the DC bus voltage reaches the feed-in threshold (52 V) and remains constant for 2 min. While power is being fed to the grid, the batteries continue being charged up to their maximum charging voltage. At that point, the device ceases battery charging in order to optimize grid feed output and prevent harmful gassing of the batteries. In this mode, the consumer loads will be supplied from the grid.

Grid power outage: If there is an outage in the public power supply, the system switches over to "off-grid mode" within 5–8 ms. In "off-grid mode," the consumer loads connected to the emergency power circuit are supplied with power taken from both PV–Wind subsystems and the batteries (Dali, 2010).

Table 2.

Hybrid system operating modes (Dali, 2010).

⟨Mode1⟩ Grid operating without injection: $V_{bat} < V_{feed\text{-}in}$: charge battery $I_{hyb} = I_{bat}$ ($I_{grid} = 0$)	
⟨Mode 2⟩ Grid operating with injection: $I_{hyb} = I_{bat} + I_{grid}$	
⟨Mode3⟩ Grid power outage: supply emergency loads $I_{hyb} + I_{bat} = I_{load}$	

The system will be disconnected if the battery charge falls below the battery charge threshold and off-grid mode is not possible due to deficient solar irradiation and/or wind speed. If an outage in the grid occurs under these unusual conditions, power supply to the loads will be interrupted (Dali, 2010).

Yaow-Ming Chen argued that usually two separated inverters for the photovoltaic array and the wind turbine are used for the hybrid solar wind power system. However, an alternative approach is to use the multi-input inverter for combining these renewable energy sources in the DC end instead of the AC end. This approach can simplify the hybrid solar wind power system and reduce the costs (Chen, 2007). Multi-input inverter has the following advantages:

1. Power from the PV array or the wind turbine can be delivered to the utility grid individually or simultaneously.
2. Maximum power point tracking (MPPT) feature can be realized for both solar and wind energy.
3. A large range of input voltage variation caused by different insolation and wind speed is acceptable.

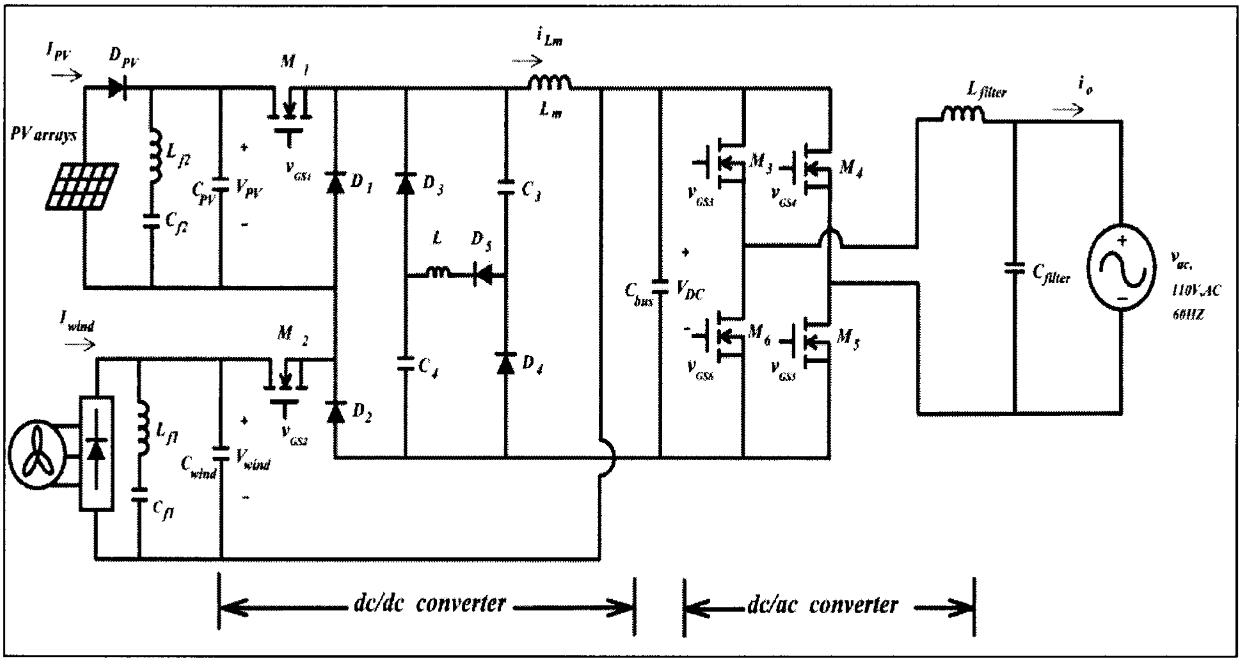


Figure 8. Schematic diagram of the proposed multi-input inverter (Chen, 2007)

Summary

Previous researchers on grid-connected solar-wind hybrid system substantiate that the combined generation of electricity by solar and wind energy is a very attractive solution to improve the system efficiency, power reliability and reduce the energy storage. This research paper presents further modeling and analysis of collected data from an actual grid-connected solar-wind hybrid system by using electrical power simulation software MATLB/SimPowerSystems.

CHAPTER III

METHODS AND MATERIALS

Introduction

This chapter provides an overview of the modeling and analysis of a 12-kW solar-wind hybrid power and instrumentation system. The research presents the modeling and analysis of an actual grid-connected solar-wind hybrid system at University of Northern Iowa campus in Cedar Falls, Iowa as shown in Figure 9.

This solar-wind hybrid system includes the following components:

- 10 kW Bergey Excel-S wind turbine with a Power Sink II utility intertie module (208 V/240V AC, 60 Hz)
- Sixteen SHARP NT-175UC1 175W solar Photovoltaic (PV) panels, and related power and instrumentation/data acquisition hardware.

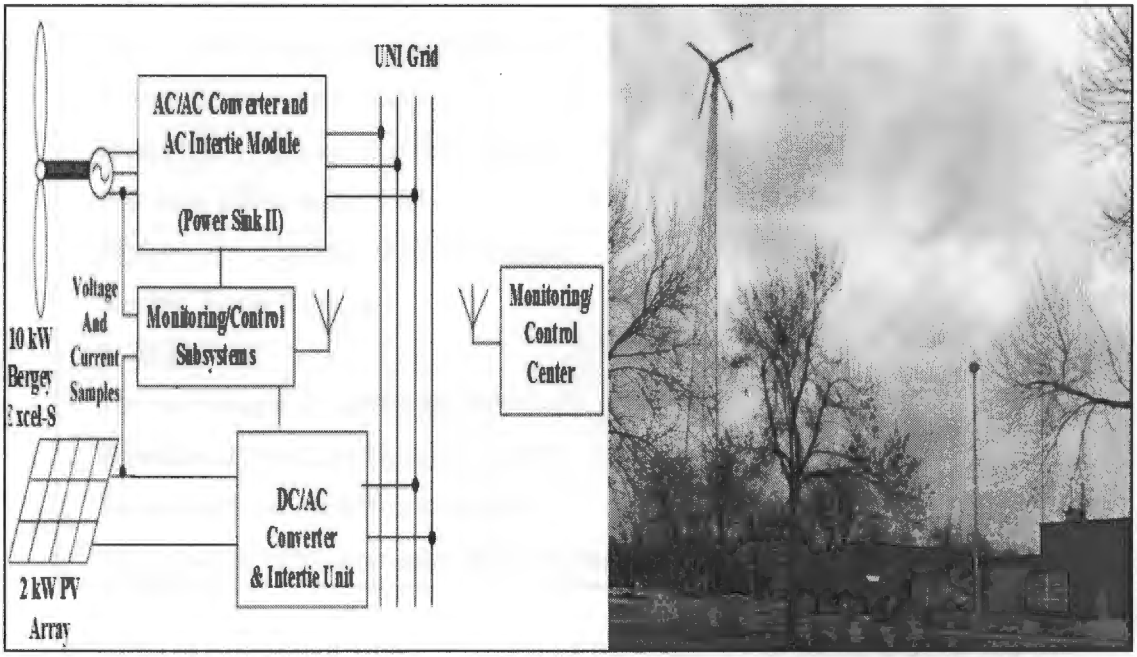
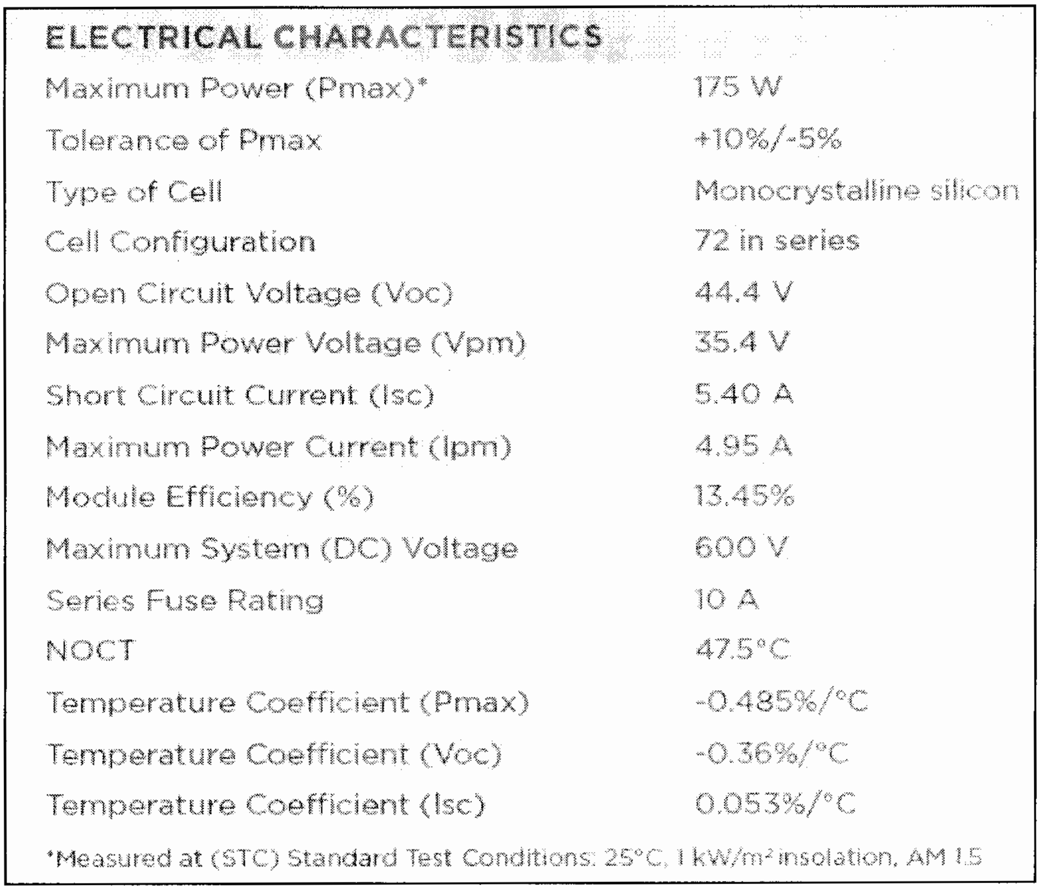


Figure 9. 12-kW wind-solar power system at UNI campus

Solar System Components

16 SHARP NT-175UC1 175 Watt Solar PV Panels

The SHARP NT-175UC1 measures the dimensions as 62.8'' x 31.1''. With the considered 8 module configuration the total area occupied by each array would measure approximately 62.2" x 124.4". The SHARP NT-175UC1 is constructed of 72 high-efficiency silicon nitride monocrystalline silicon cells with a maximum power rating of 175W as shown in Figure 10 the electrical characteristics. Figure 11 shows the SHARP NT-175UC1 dimensions.



ELECTRICAL CHARACTERISTICS	
Maximum Power (Pmax)*	175 W
Tolerance of Pmax	+10%/-5%
Type of Cell	Monocrystalline silicon
Cell Configuration	72 in series
Open Circuit Voltage (Voc)	44.4 V
Maximum Power Voltage (Vpm)	35.4 V
Short Circuit Current (Isc)	5.40 A
Maximum Power Current (Ipm)	4.95 A
Module Efficiency (%)	13.45%
Maximum System (DC) Voltage	600 V
Series Fuse Rating	10 A
NOCT	47.5°C
Temperature Coefficient (Pmax)	-0.485%/°C
Temperature Coefficient (Voc)	-0.36%/°C
Temperature Coefficient (Isc)	0.053%/°C

*Measured at (STC) Standard Test Conditions: 25°C, 1 kW/m² insolation, AM 1.5

Figure 10. SHARP NT-175UC1 electrical characteristics (Sharp, 2010)

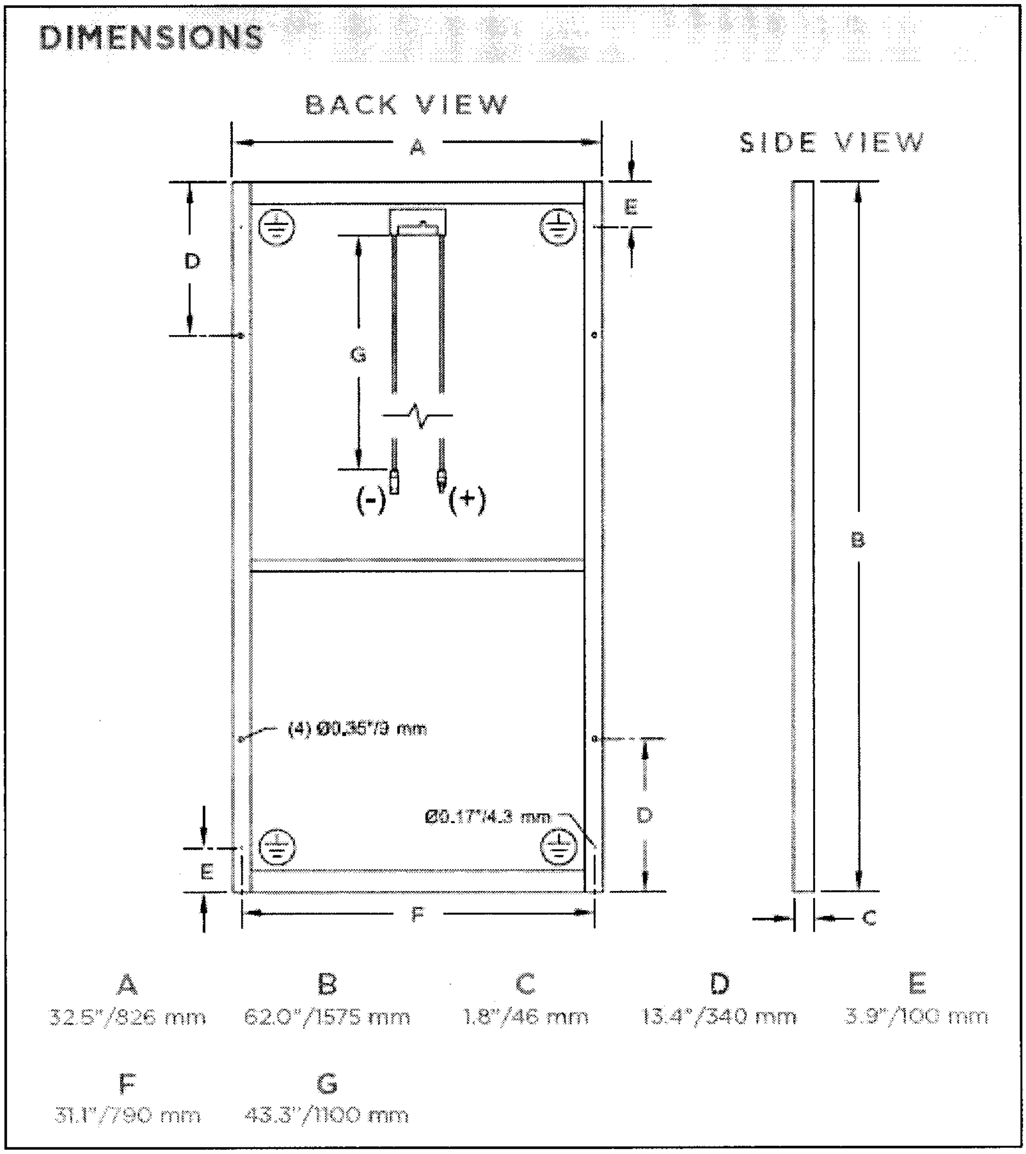


Figure 11. SHARP NT-175UC1 dimensional diagram (Sharp, 2010)

The 16 modules produce a maximum power of 2800W. The array is comprised of two strings consisting of eight modules. A string consists of multiple solar modules connected in a series configuration. Operating voltage is calculated by multiplying module voltage at maximum power by the string size. Both eight module strings will have an operating voltage of 285.6V. Operating current is found by multiplying module current at maximum power by the number of strings in the array. The operating current for this system is calculated to be 9.8 A. The open-circuit voltage will be 352V for both eight module strings. Maximum system voltage is to be less than 600V, as required by the inverter rating. This value can be calculated by multiplying the module's open-circuit voltage, number of modules (in largest string), and a coefficient of the lowest temperature on record for the site. By using the lowest temperature record of -33 degrees Fahrenheit for Waterloo, Iowa we established the maximum system voltage to be approximately 442V.

The maximum PV source circuit current is calculated by taking the rated short circuit current multiplied by 125%. This is to account for sustained periods of high sun intensity. The maximum PV source circuit current for this array is 6.75 A. The minimum source circuit conductor ampacity is calculated by taking 125% of the maximum PV source circuit current. The minimum source circuit conductor ampacity for this array is 8.4375 A. The minimum PV output circuit conductor ampacity is calculated by taking the minimum source circuit conductor ampacity multiplied by the number of strings in parallel. The minimum PV output circuit conductor ampacity for this array is 16.875 A.

Xantrex GT2.8 Inverter

The Xantrex™ Grid Tie Solar Inverter (GT Series) is designed to convert photovoltaic (PV) electricity produced by solar modules into utility-grade AC voltage that can be used by the home or sold to the local electrical utility. Offering high efficiency (up to 96.0 %), high reliability, and a low installed cost, through ease of installation and integrated features, the GT Series is a proven, high-frequency design in a compact enclosure. Figure 12 shows a simple diagram of a typical PV installation.

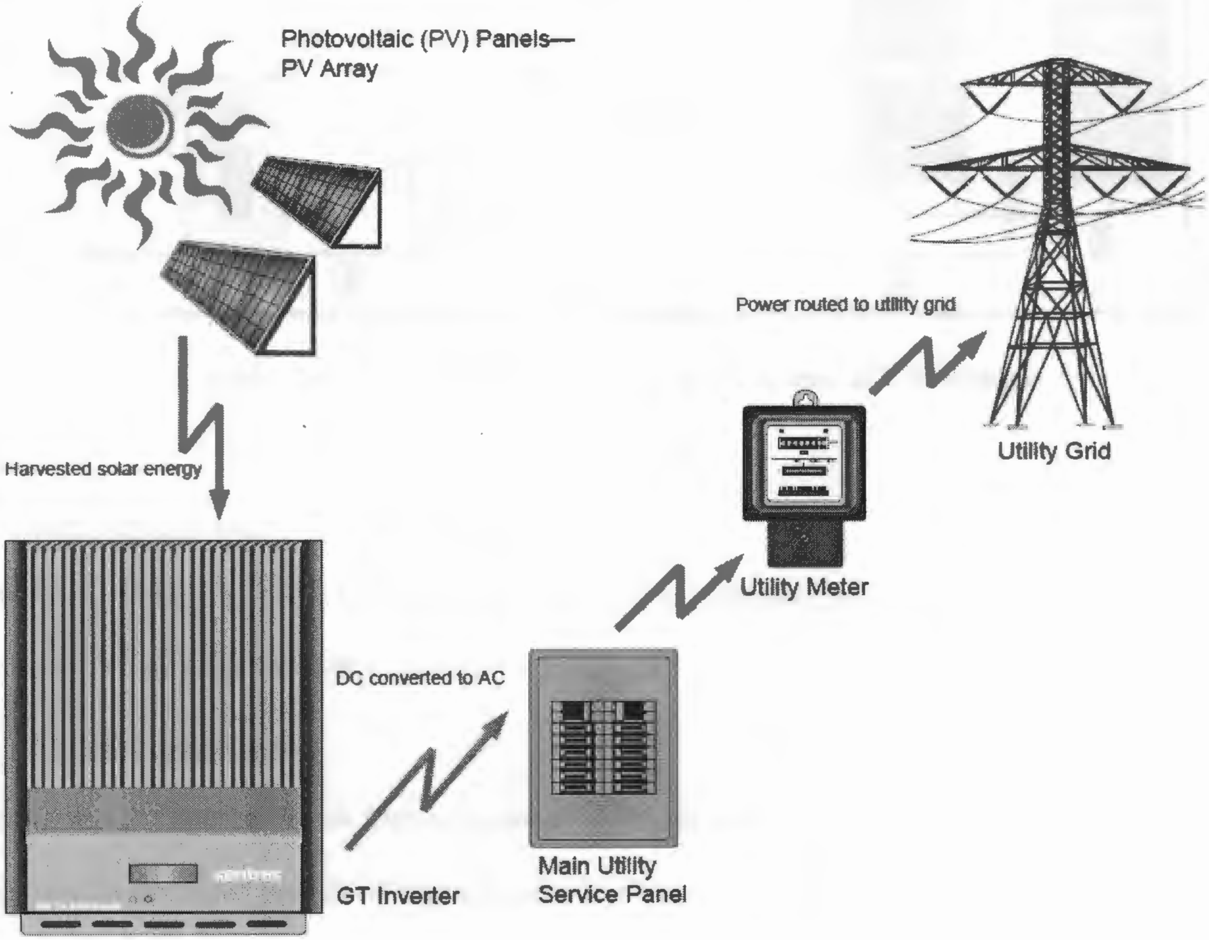


Figure 12. Basic system overview (Xantrex, 2009)

Wiring Diagram

Figure 13 shows the solar system components from the solar panels to the University of Northern Iowa electric grid.

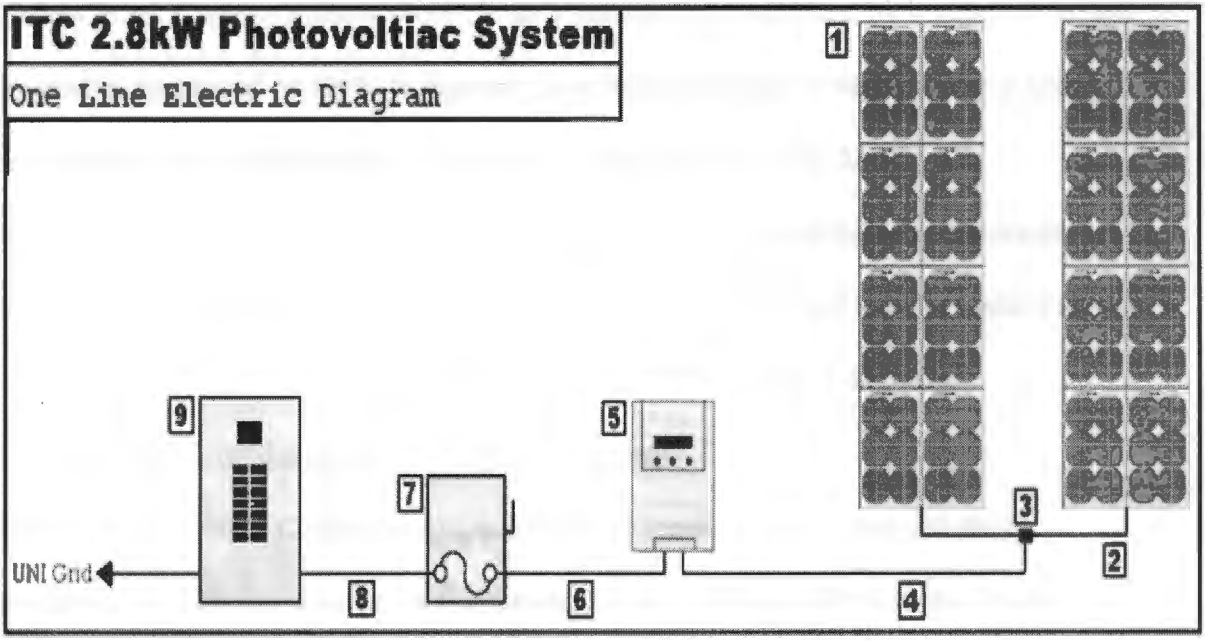


Figure 13. Single-line circuit diagram the installed PV system at UNI campus

1. Series string of eight 175W BP solar modules

Operating Voltage (module voltage at maximum power multiplied by number of modules in string) (Vpmax of 35.8V)*(8 modules) = 286.4VDC

2. #12 RHW module cable

Maximum PV Source Circuit Current (rated short-circuit current multiplied by 125% to account for sustained periods of high sun intensity) (Isc of 5.4A)*(1.25) = 6.75A

Minimum PV Source Circuit Conductor Ampacity (maximum PV source circuit current multiplied by 125% to account for continuous duty) (6.75A)*(1.25) = 8.4375A

3. String combination

Operating Current (module current at maximum power multiplied by number of strings in parallel) (Ipmax of 4.9A)*(2 strings) = 9.8A

Short-Circuit Current (module short-circuit current rating multiplied by number of strings in parallel multiplied by 125% to account for extended periods of sunlight above tested solar intensity)(NEC 690.8) (Isc of 5.4A)* (2 strings)*(1.25) = 13.5A

Maximum System Voltage (open-circuit voltage rating multiplied by temperature factor in NEC 690.7 multiplied by number of modules in a string) (record low for Cedar Falls of -34 degrees F = 1.25 factor) (Voc of 44.2V)*(1.25)*(8 modules) = 442VDC

4. #12 THWN-2 conductors from combiner to inverter

Minimum PV Output Conductor Ampacity (short-circuit current calculated above multiplied by 125% to account for the standard listing of wire to 80% of maximum circuit current for a continuous duty) (Isc of 13.5A)*(1.25) = 16.875A

5. Xantrex GT2.8

Maximum AC Power Output: 2800W

Nominal AC Output Voltage: 240V/208V

Nominal AC Frequency: 60Hz

Maximum Continuous Output Current: 11.7A

Power Factor > 0.99 (at rated power) , > 0.95 (full power range)

6. #12 THHN conductors from inverter to disconnect

Minimum Inverter Output Conductor Ampacity (inverter continuous output current rating multiplied by 125% to account for the standard listing of wire to 80% of maximum circuit current for continuous duty) (11.7A)*(1.25) = 14.625A

7. Disconnect with 15A fuse/circuit-breaker

Inverter Output Circuit Over-Current Protection is sized according to manufacturer's directions of maximum current value of 15A

8. #12 THHN conductors from disconnect to distribution panel

Minimum Inverter Output Conductor Ampacity (inverter continuous output current rating multiplied by 125% to account for the standard listing of wire to 80% of maximum circuit current for continuous duty) (11.7A)*(1.25) = 14.625A

9. Distribution Panel

Dedicated circuit breaker size is 16 A

Wind System Components

The Bergey EXCEL 10 is an upwind horizontal-axis wind turbine designed for distributed generation applications, connected to the power grid on the customer's side of the utility meter. The complete unit consists of the following major components, as shown in Figure 14:

1. Spinner
2. PowerFlex Blades
3. Alternator
4. Mainframe
5. Yaw Bearing
6. Slip-ring and Brushes
7. Tail Assembly
8. Nacelle Assembly
9. Furling Winch
10. Powersync II Inverter

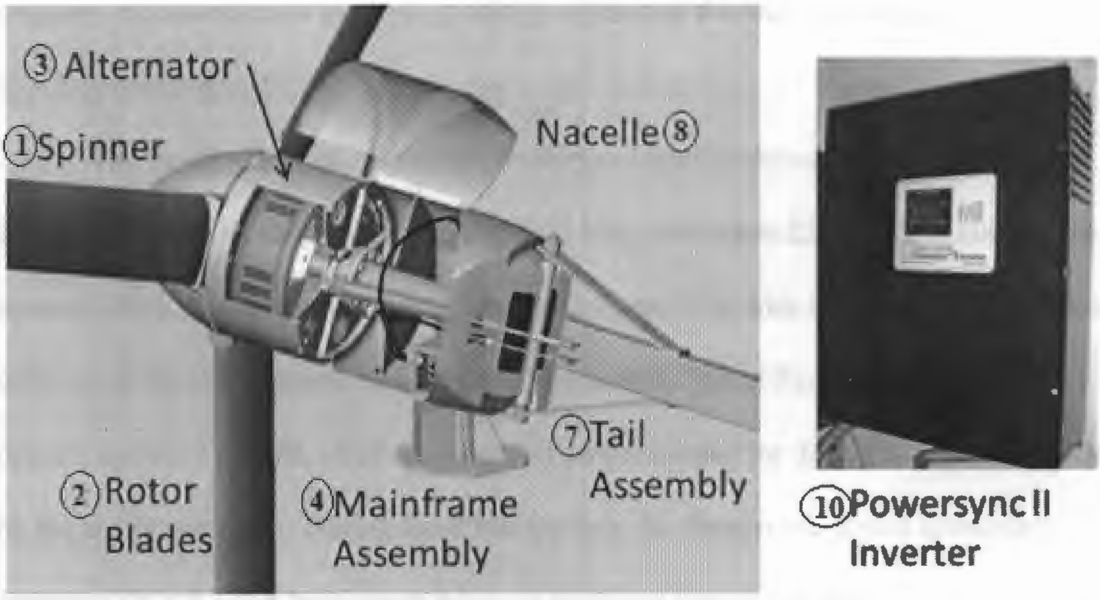


Figure 14. Wind system major components (Bergey, 2011)

Wind Turbine Rotor System

The rotor system consists of three PowerFlex® fiberglass blades. The blades convert the mechanical energy of the wind into rotational forces that drive the alternator. The PowerFlex blades are rigidly attached to the alternator and they are fixed pitch. The Excel 10 rotor blades have a proprietary airfoil, the BWC-7, which was custom designed to provide power with high efficiency and low noise.

Alternator

The alternator or generator converts the rotational mechanical energy of the rotor into electricity. The alternator utilizes permanent magnets and has an inverted configuration in that the outside housing rotates, while the internal windings are stationary. It was specifically designed for the Bergey EXCEL 10 and produces power at low speeds, eliminating the need for a speed-increasing gearbox. Since it uses permanent magnets, the alternator is generating voltage whenever the rotor is rotating.

Wind System Normal Operation

The Bergey EXCEL 10 produces utility compatible power in the form of 240VAC, 60 Hz, single phase electricity (208 VAC/60Hz and 220 VAC/50 Hz options are available). It is connected through the Powersync II inverter to the utility distribution network in the same manner as household appliances. When the wind speed is too low to operate the wind turbine, all of the electrical power needed for the home will be supplied by the utility company. During these idle periods, the Powersync II will consume approximately 0.3 (kWh) kilowatt-hours of electrical energy per day.

When the system begins producing power, the amount of power which must be purchased from the utility is reduced by an amount equal to the output of the. From the perspective of the utility company the solar-wind hybrid power system output reduces the electrical load they have to supply, just as if you turned off lights and appliances. The output of the system fluctuates with the speed of the wind solar radiation so the instantaneous amount of electricity being saved will be constantly changing.

The rotor of the EXCEL 10 should begin to rotate when the wind speed reaches approximately 8 mph (3.6 m/s). Once started, the rotor may continue to turn in winds below 5 mph (2.2 m/s), but the system will not be producing power below this wind speed. Similarly PV system inverter will be starting to operate after a minimum voltage of 190V from all PV panels.

The rotor speed will increase with increasing wind speed and the system will produce a higher output. This output increases rapidly because the energy available in the wind varies as the third power (cube) of the wind speed. For example, if the wind speed increased form 5 mph to 10 mph, a factor of two, the energy in the wind would increase from one unit to eight units, a factor of eight (2 to the 3rd power). One result of this relationship is that there is very little energy available in light winds. For the average site, winds in the range of 12-20 mph (5.5 – 9 m/s) will provide most of the system's energy production on an annual basis (Bergey, 2011).

High Wind Operation

During periods of high wind speeds the AutoFurl system will automatically protect the wind turbine. Furling means that the rotor is turned away from the wind. When furled, the power output of the turbine will be reduced. In winds between 33 mph (15 m/s) and 45 mph (20 m/s) it is normal for the turbine to repeatedly furl and then unfurl and then furl again. During intermittent cycling the turbine may produce output surges up to 13,000 W.

Unloaded Operation

If an abnormal condition occurs on the utility line, such as a voltage fluctuation or a complete interruption, the Powersync II inverter will automatically disconnect the wind turbine from the power grid. If sufficient wind is present, the rotor will continue to operate. Since it is unloaded it will spin at a higher speed and some increase in blade sound is to be expected. This is a perfectly safe and permissible condition as the AutoFurl system will continue to protect the turbine (Bergey, 2011).

In order to enhance the systems reliability, the power output of the Excel is limited to approximately 12.5 KW. Since this output is reached at 31 mph (14 m/s), the rotor will become progressively unloaded as wind speeds increase up to the furling point at approximately 35 mph (15.6 m/s ; Bergey, 2011).

Wind Turbine Specifications

Peak power of 10kW is 240 VAC 60 Hz Single-Phase includes Gridtek 10 inverter with no batteries needed. The BWC EXCEL is a modern 6.7 meter (22 ft) diameter, 10,000W wind turbine designed for high reliability, low maintenance, and automatic operation in adverse weather conditions. Connected to the grid, the BWC EXCEL can provide most of the electricity for an average total electric home at moderate wind sites. Figure 15 shows the power output versus wind speed.

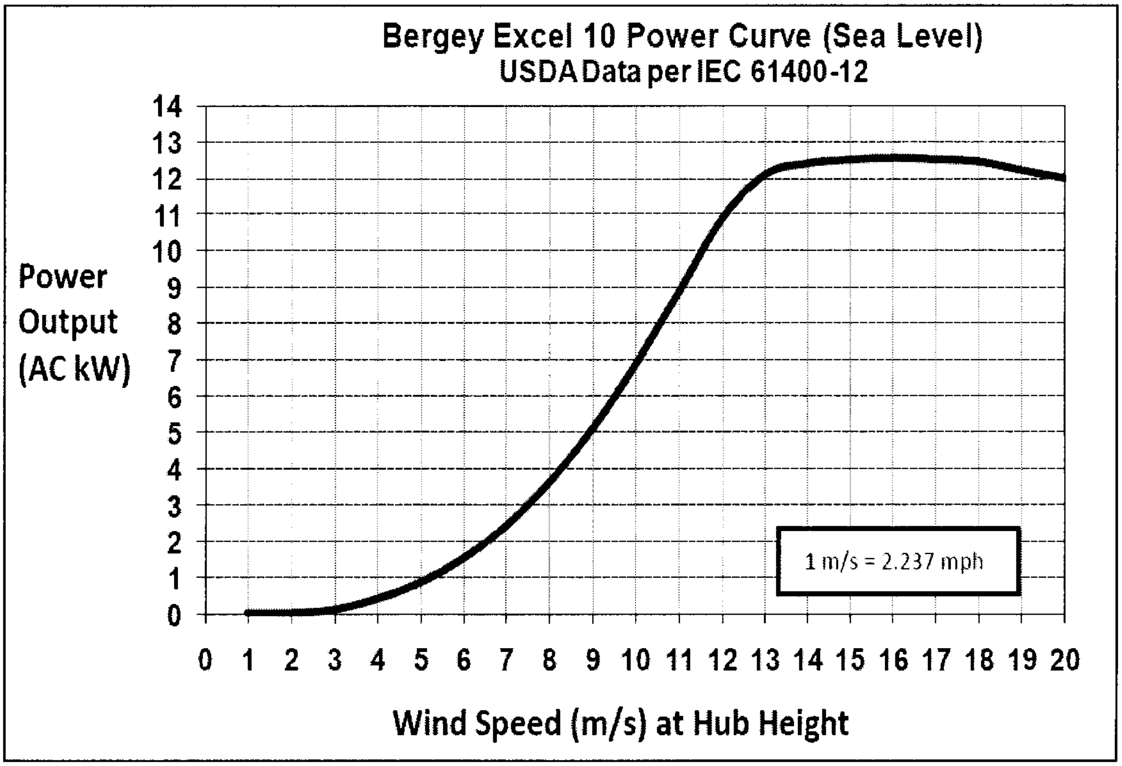


Figure 15. Bergey Excel 10 power output versus wind speed (Bergey, 2011).

Procedure of the Simulation Study

In conducting this research, the following three main steps are undertaken:

d. Case Study I: Analysis of PV terminal voltage fluctuations due to rapid source changes and grounding failure.

e. Case Study II: Analysis of wind turbine terminal voltage fluctuations due to rapid wind changes and lightning strike.

f. Case Study III: Analysis of voltage distortion at the utility interface.

These experimental studies are modeled and analyzed using MATLAB/Simulink/SimPowerSystems software environment. SimPowerSystems is a power systems analysis solution that includes analytical software modules for modeling and simulating the generation, transmission, distribution, and consumption of electrical power. It provides models of many components used in these systems, including three-phase machines, electric drives, and libraries of application-specific models such as Flexible AC Transmission Systems (FACTS) and wind-power generation. Harmonic analysis, calculation of Total Harmonic Distortion (THD), load flow, and other key power system analyses are automated. SimPowerSystems models can be discretized to speed up simulations.

Experimental Layout

In order to perform the data analysis related for each case study, modeling and analysis of the actual grid-connected solar-wind hybrid station at University of Northern Iowa campus in Cedar Falls, Iowa as shown in Figure 9 to simulate the power quality the software SimPowerSystem. The quality of electrical power is described as a set of values of parameters such as:

1. Variation in voltage magnitude

The voltage fluctuation range for pre-fault or pre-disturbance in most of the utilities is generally ±5% but it also depends on the voltage level.

2. Continuous voltage operating range

The wind turbines and the Photovoltaic system are expected to operate within typical grid voltage variations due to enhanced voltage and frequency control systems and regulators embedded in the grid-tie control unit. In most utilities, the acceptable continuous voltage range is from 0.9 to 1.1 per unit (pu).

3. Transient voltage and current

Transient voltage is defined as a temporary, undesirable voltage that appears on the power supply line. Transient voltages can range from a few volts to several thousand volts, and can last from a few seconds to a few minutes as shown in Figure 16. It also can be caused by turning off high inductive loads, switching large power factor correction capacitors and the lightning strikes hit any party of the power system.

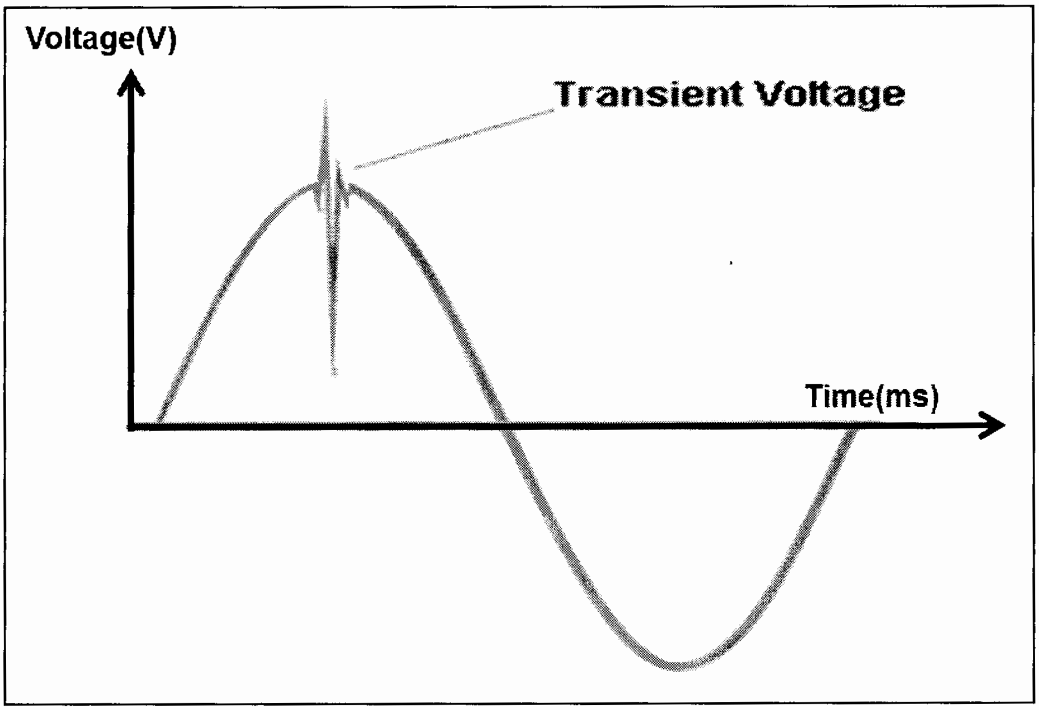


Figure 16. A transient voltage fluctuation in a sine waveform

4. Harmonic content in the waveforms for AC power

Harmonic can be produced by both wind system and solar system due to inverters that included a number of power electrics switches such as diodes, thyristors, silicon controlled rectifiers (SCRs) and power transistors. They are destructive forces in power distribution systems and could shorten the life of inverters and interfere with the operation of electronics energy. Figure 17 (a) shows a clean waveform and (b) shows a waveform destructed with harmonics content.

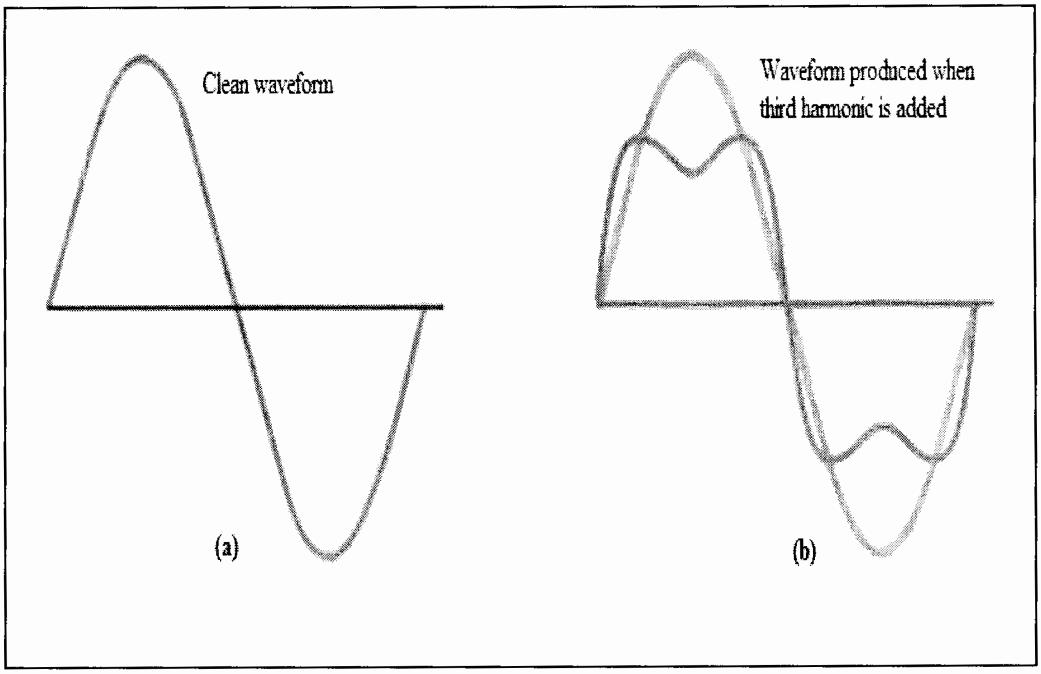


Figure 17. (a) Clean waveform (b) a third harmonic is added

5. Sag and Swell

Voltage sags and under-voltage can be caused when high current loads such a large motors are started. Under-voltage may also occur when a power utility reduces the voltage level to conserve energy during peak usage. It is also commonly caused by overloaded transformers or undersized conductors. The voltage swells overvoltage can be caused when high current loads are switched off, such as when motor-driven machinery shuts down. Figure 18 shows the waveform of normal, sag and swell voltage.

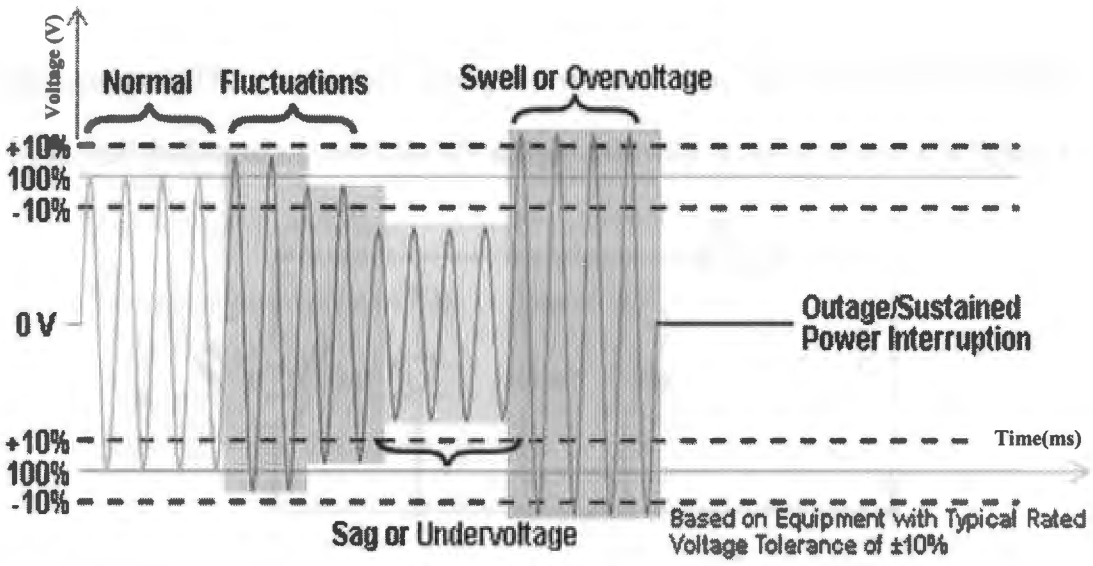


Figure 18. Waveform of normal, sag and swell voltage modified from Electric Power Systems Quality (Dugan, McGranaghan, Santoso & Beaty, 2003)

SimPowerSystems Simulation Environment

This section describes the software package developed for simulation of grid-connected solar power system, and called SimPowerSystems toolbox. Its main features and module structure are explained. The functionality and performance of the developed model is illustrated.

Modeling the Solar Power System

Solar cells made of semiconductor materials such as silicon, which are specially treated to form an electric field, positive on one side (backside) and negative on the other (towards the sun). When solar energy (photons) hits the solar cell, electrons are knocked loose from the atoms in the semiconductor material, creating electron-hole pairs (Loern, 1994). If electrical conductors are then attached to the positive and negative sides, forming an electrical circuit, the electrons are captured in the form of electric current (photocurrent). The model of the solar photovoltaic can be realized by an equivalent circuit that consists of a current source and parallel with diode as showing in Figure 19.

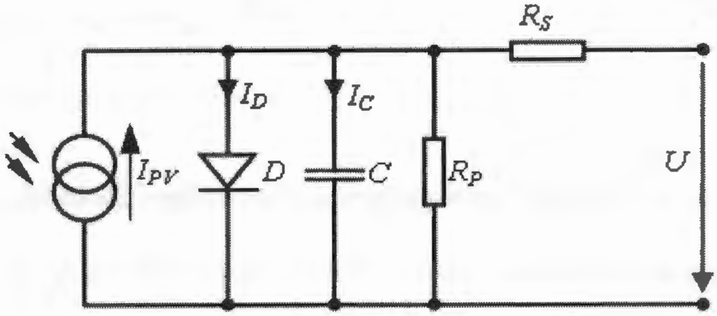


Figure 19. Equivalent circuit diagram of photovoltaic

The development of Matlab SimPowerSystems model for the PV module presented in Figure 20.

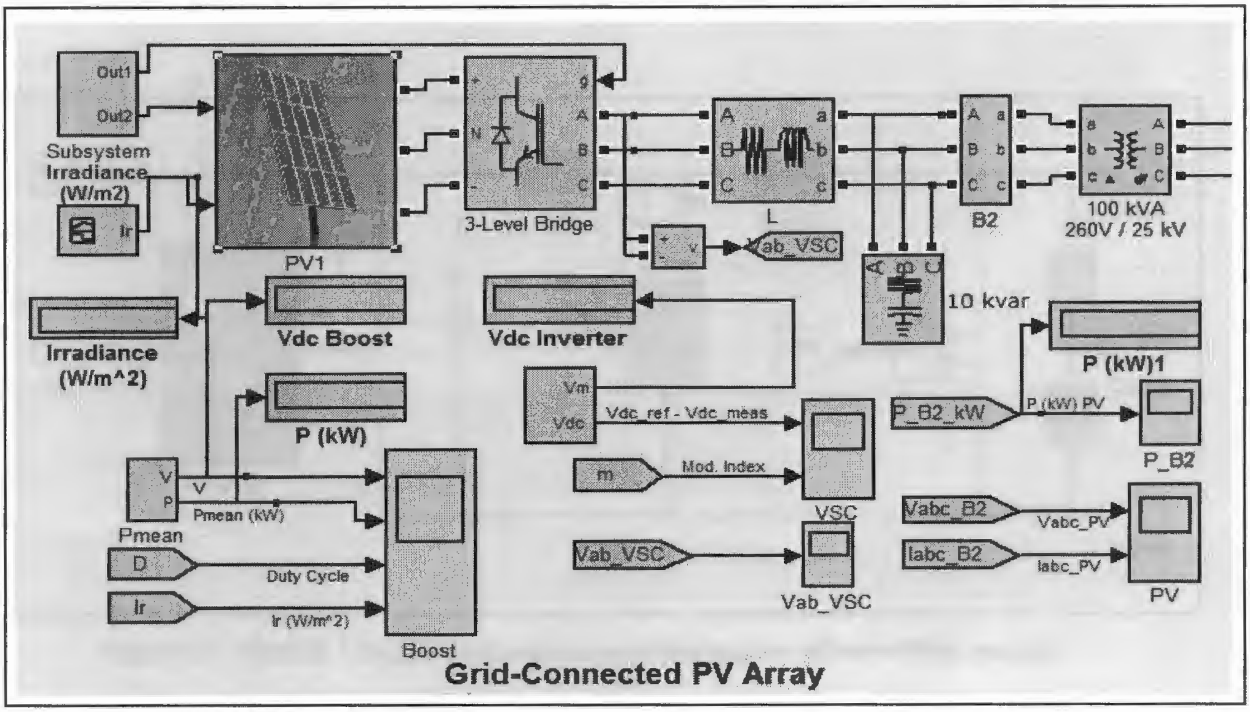


Figure 20. Matlab/SimPowerSystem Grid-connected solar power system

The solar system model consists of three SimPowerSystems blocks:

1. Solar model block
2. Photovoltaic model block
3. Energy conversion modules

The solar model block implements the mathematical model of the solar radiation. This is done by using standard SimPowerSystems and Matlab modules and functions. This block allows selecting different type of patterns for the solar radiation.

The Photovoltaic module implements the equivalent circuit of a solar cell, shown in Figure 19. Standard functions and blocks of MATLAB and SimPowerSystems were used to obtain this model. Its functional block diagram is presented in Figure 21.

The output of the photovoltaic module is processed by an energy conversion block implemented with a PWM IGBT inverter block from standard SimPowerSystems library.

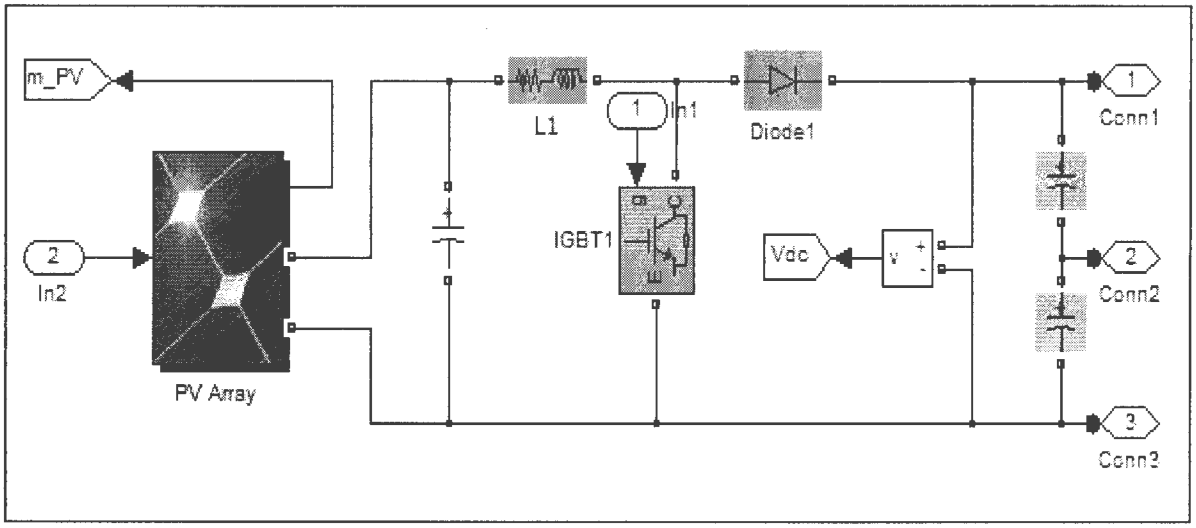
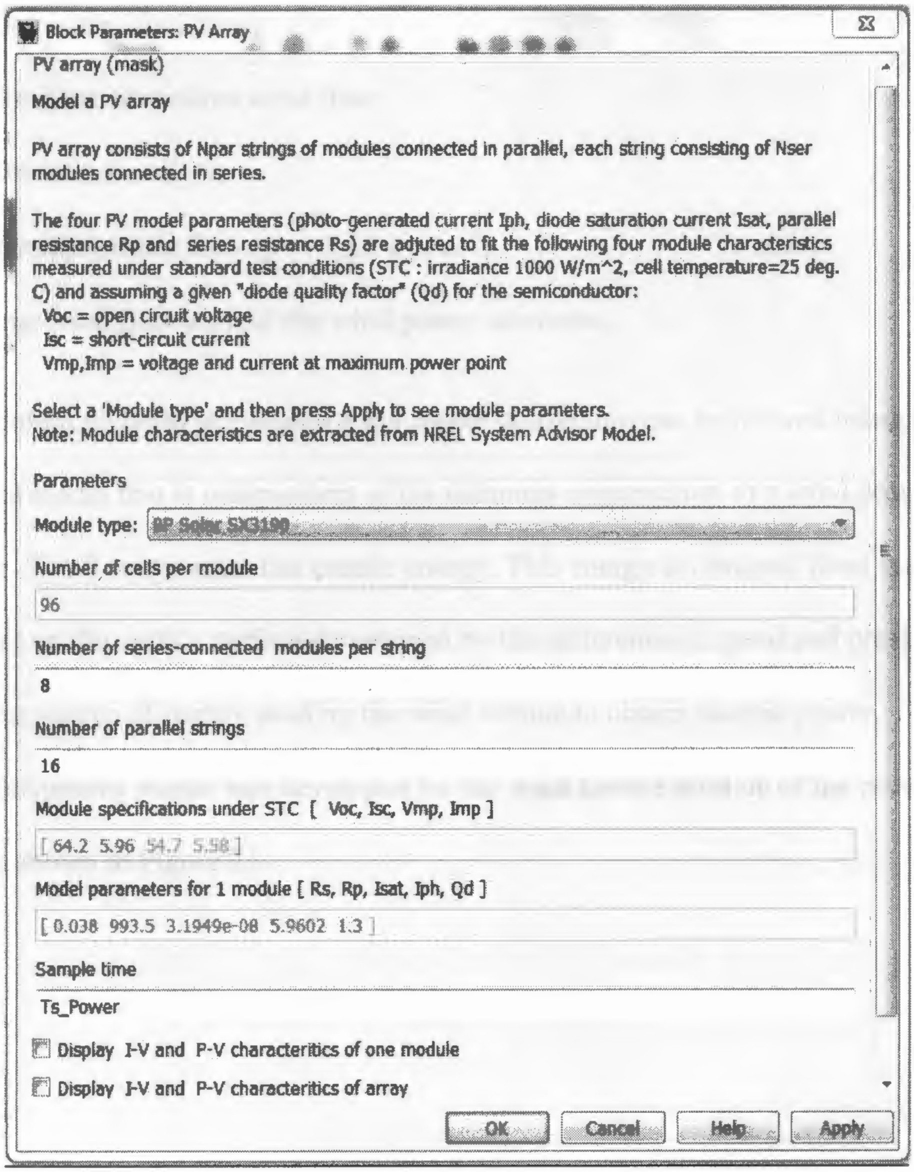


Figure 21. Matlab / SimPowerSystems implementation photovoltaic module

The output of the photovoltaic module is processed by an energy conversion block implemented with a PWM IGBT inverter block from standard SimPowerSystems library. Figure 22 shows related PV array block parameters.



PV array (mask)

Model a PV array

PV array consists of Npar strings of modules connected in parallel, each string consisting of Nser modules connected in series.

The four PV model parameters (photo-generated current Iph, diode saturation current Isat, parallel resistance Rp and series resistance Rs) are adjuted to fit the following four module characteristics measured under standard test conditions (STC : irradiance 1000 W/m^2, cell temperature=25 deg. C) and assuming a given "diode quality factor" (Qd) for the semiconductor:

Voc = open circuit voltage
Isc = short-circuit current
Vmp,Imp = voltage and current at maximum power point

Select a 'Module type' and then press Apply to see module parameters.
Note: Module characteristics are extracted from NREL System Advisor Model.

Parameters

Module type: BP Solar SX3190

Number of cells per module
96

Number of series-connected modules per string
8

Number of parallel strings
16

Module specifications under STC [Voc, Isc, Vmp, Imp]
[64.2 5.96 54.7 5.58]

Model parameters for 1 module [Rs, Rp, Isat, Iph, Qd]
[0.038 993.5 3.1949e-08 5.9602 1.3]

Sample time
Ts_Power

☐ Display I-V and P-V characteritics of one module

☐ Display I-V and P-V characteritics of array

Figure 22. PV array block parameters

Modeling the Wind Turbine Power System

Modeling the wind turbine power converter is made considering the following assumptions

1- Friction is neglected;
2- Stationary wind flow;
3- Constant, shear-free wind flow;
4- Rotation-free flow;
5- Incompressible flow ($p = 1.22\ kg/m^3$)
6- Free wind flow around the wind power converter.

The maximum physical achievable wind power conversion can be derived using a theoretical model that is independent of the technical construction of a wind power converter. The flow air mass has certain energy. This energy is obtained from the air movement on the earth's surface determined by the difference in speed and pressure. This is the main source of energy used by the wind turbine to obtain electric power. SimPowerSystems model was developed for the wind turbine module of the power system is shown in Figure 23.

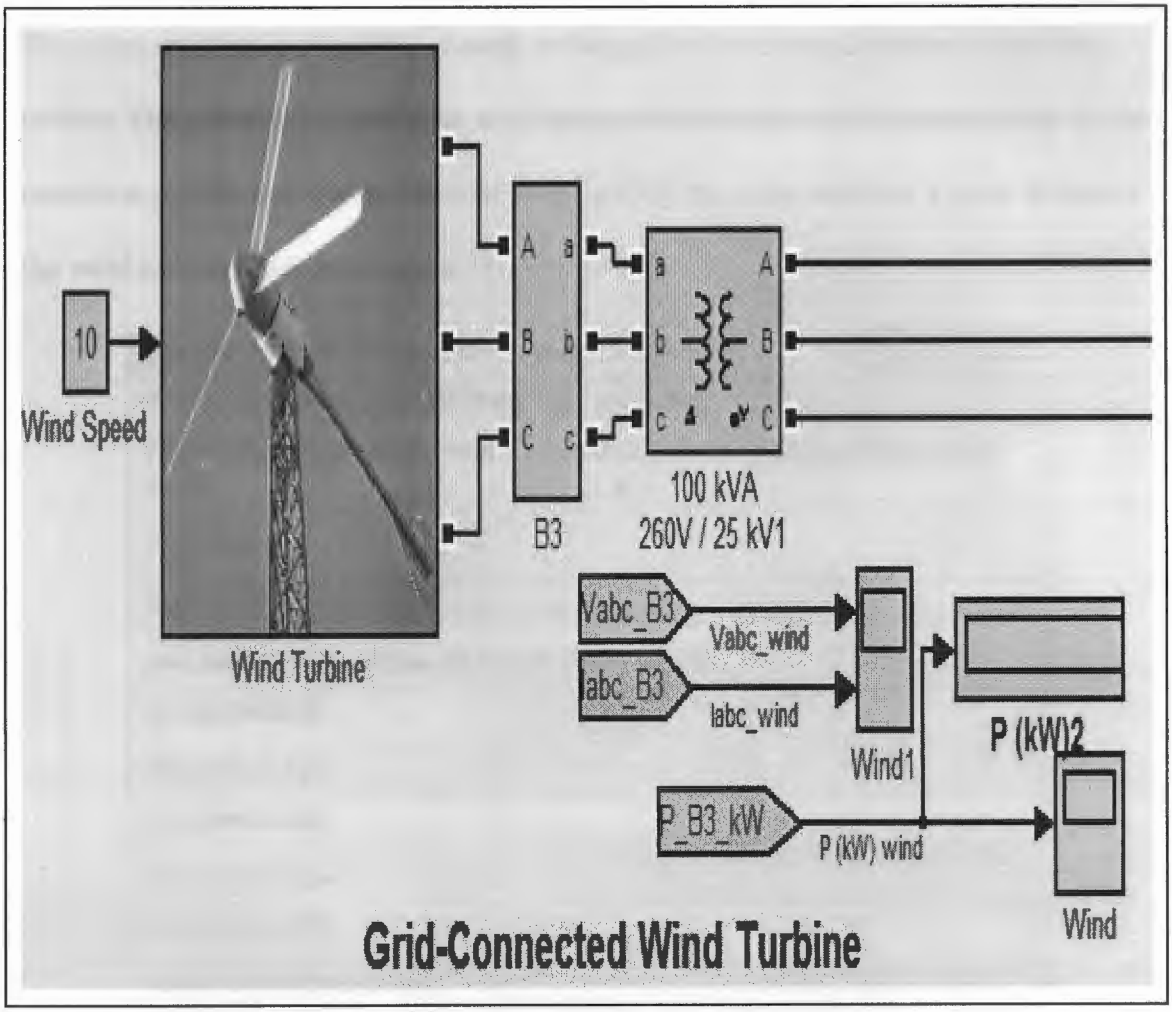
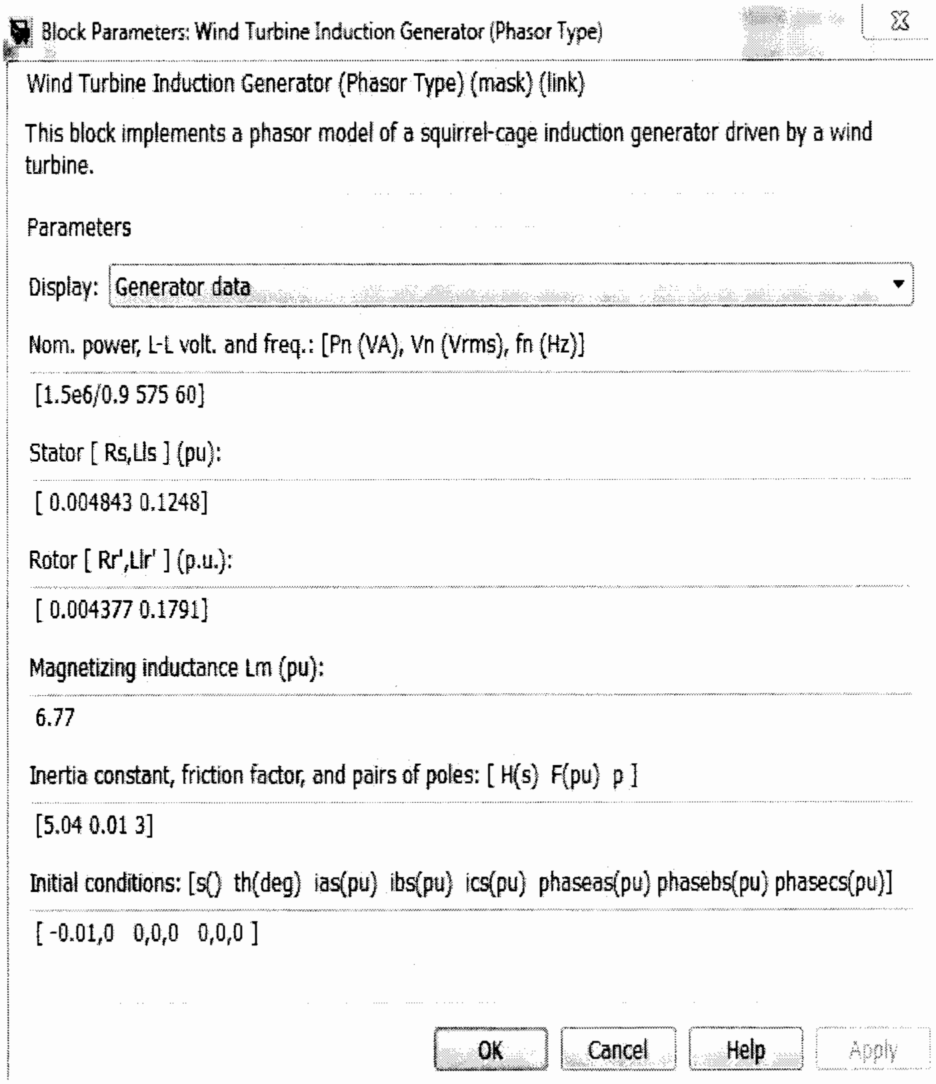


Figure 23. SimPowerSystems model for grid-connected wind turbine

The stator winding is connected directly to the grid and the rotor is driven by the wind turbine. The power captured by the wind turbine is converted into electrical power by the induction generator and is transmitted to the grid by the stator winding. Figure 24 shows the wind turbine block parameters.



Wind Turbine Induction Generator (Phasor Type) (mask) (link)

This block implements a phasor model of a squirrel-cage induction generator driven by a wind turbine.

Parameters

Display: Generator data

Nom. power, L-L volt. and freq.: [Pn (VA), Vn (Vrms), fn (Hz)]
[1.5e6/0.9 575 60]

Stator [Rs,Lls] (pu):
[0.004843 0.1248]

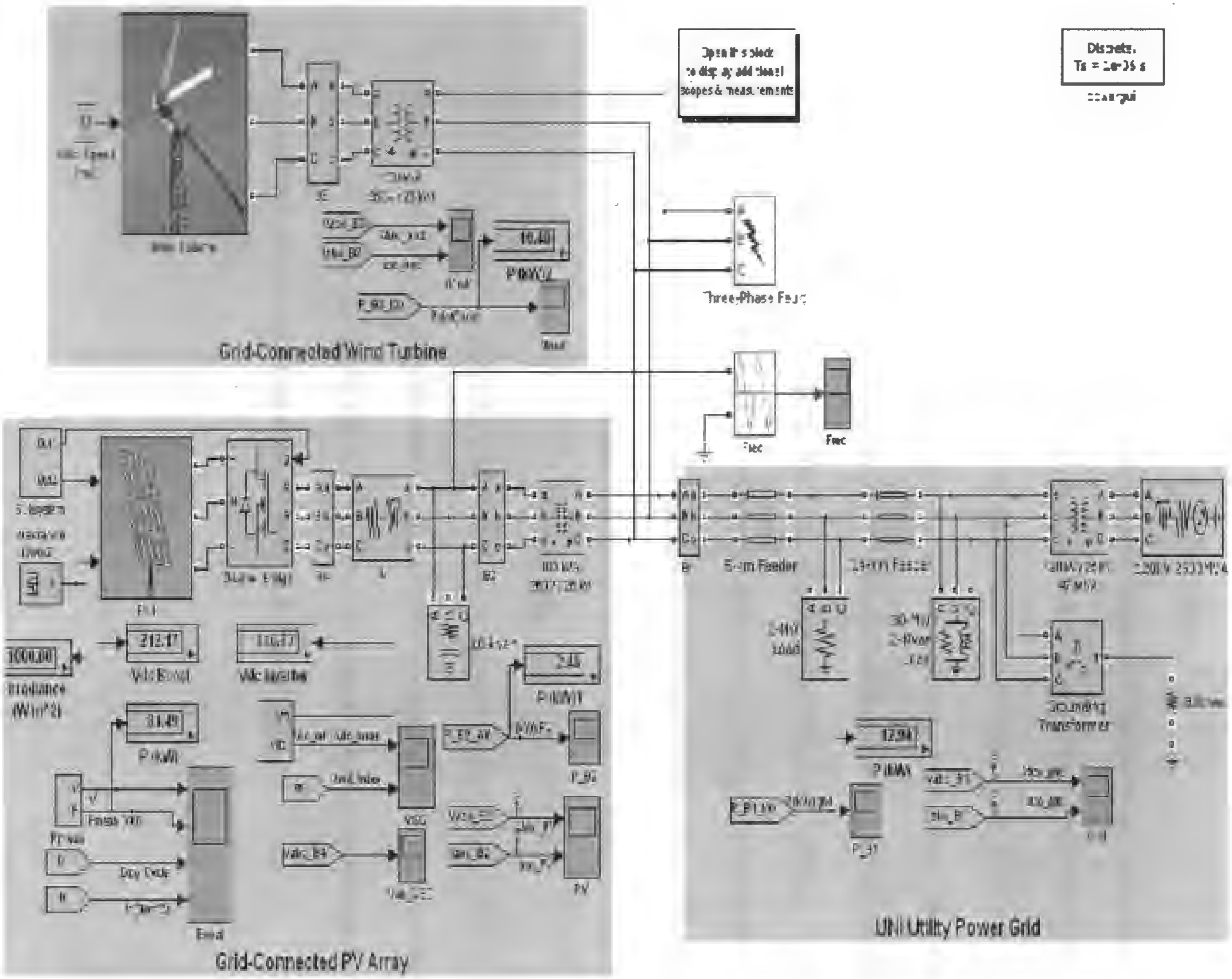
Rotor [Rr',Llr'] (p.u.):
[0.004377 0.1791]

Magnetizing inductance Lm (pu):
6.77

Inertia constant, friction factor, and pairs of poles: [H(s) F(pu) p]
[5.04 0.01 3]

Initial conditions: [s() th(deg) ias(pu) ibs(pu) ics(pu) phaseas(pu) phasebs(pu) phasecs(pu)]
[-0.01,0 0,0,0 0,0,0]

Figure 24. SimPowerSystem wind turbine block parameters



Figurer 25. SimPowerSystems simulation model of grid-connected solar wind hybrid power system

CHAPTER IV

SIMULATION AND ANALYSIS

Overview

To confirm the operation of the grid-connected solar-wind station, a number of simulation studies were carried out in SimPowerSystems using the model described in Chapter 3. This chapter covers the simulations of normal operation of the actual grid-connected solar-wind hybrid power system, then compares the result to three case studies; (a) Case Study I: Analysis of PV terminal voltage fluctuations due to source and load changes, (b) Case Study II: Analysis of wind turbine terminal voltage fluctuations due to wind changes and (c) Case Study III: Analysis of voltage distortion at the utility interface. Each simulation case concentrates on the output power, three-phase voltage and three-phase current as well as discusses the problems that arise during fault operations.

Normal Operation

In normal operation the grid-connected solar-wind hybrid power station generates about 12 kW; 10 kW from the wind turbine when it is running at constant wind speed of 10 m/s and 2.8 kW from the PV solar panels. The power output does not stabilize until few seconds after the starting time as, shown in Figure 26.

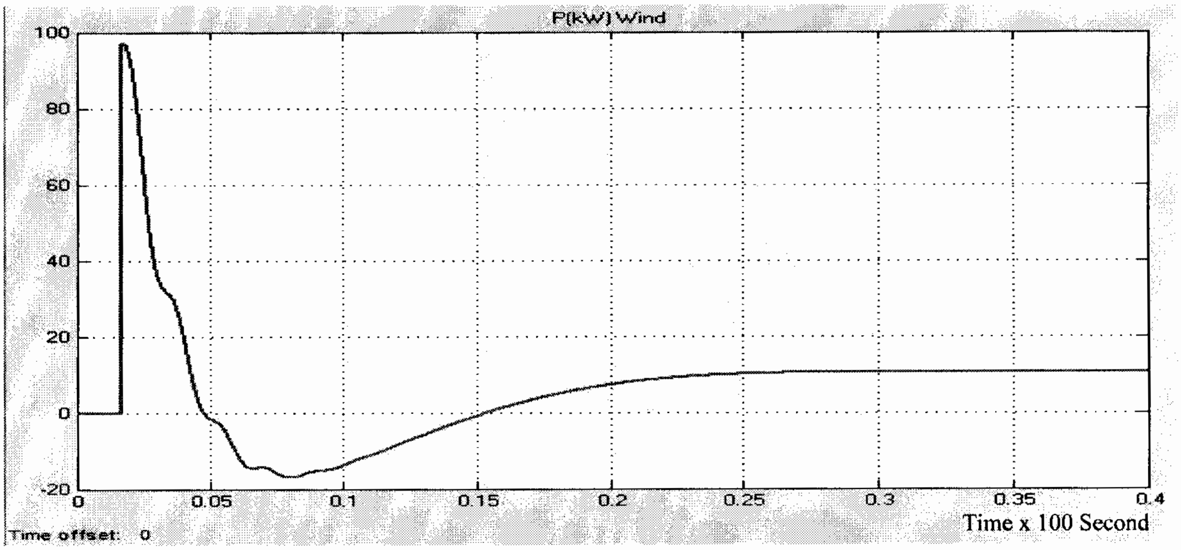


Figure 26. SimPowerSystem wind power output

The other 2-2.8 kW comes from the solar system of the power station as shown in Figure 27 when the solar arrays are exposed to irradiance of 1000 W/m^2.

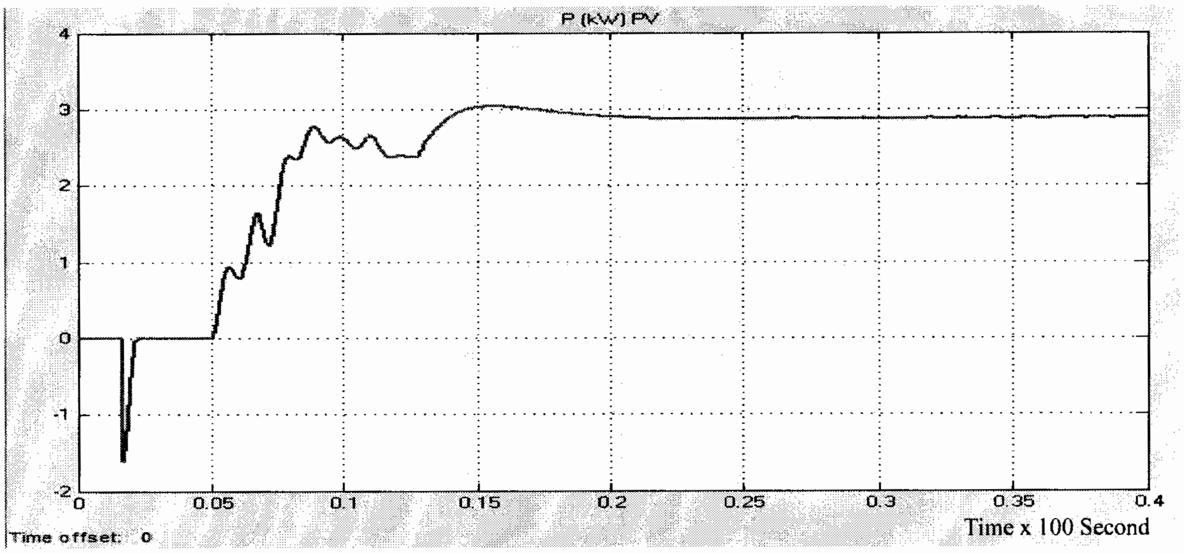


Figure 27. SimPowerSystem Solar power output

The inverter of the solar system takes DC voltage and inverts it to AC voltage, thus it can be fed into the UNI electric power grid. This grid tie inverter must synchronize its frequency with the grid (which is in this case 60 Hz). The inverter takes about 5 seconds to sense the UNI grid then start synchronizing as shown in Figure 28. The graph shows a three-phase voltage and current for solar photovoltaic side before the filter circuit and Figure 29 shows the three-phase after the filter circuit.

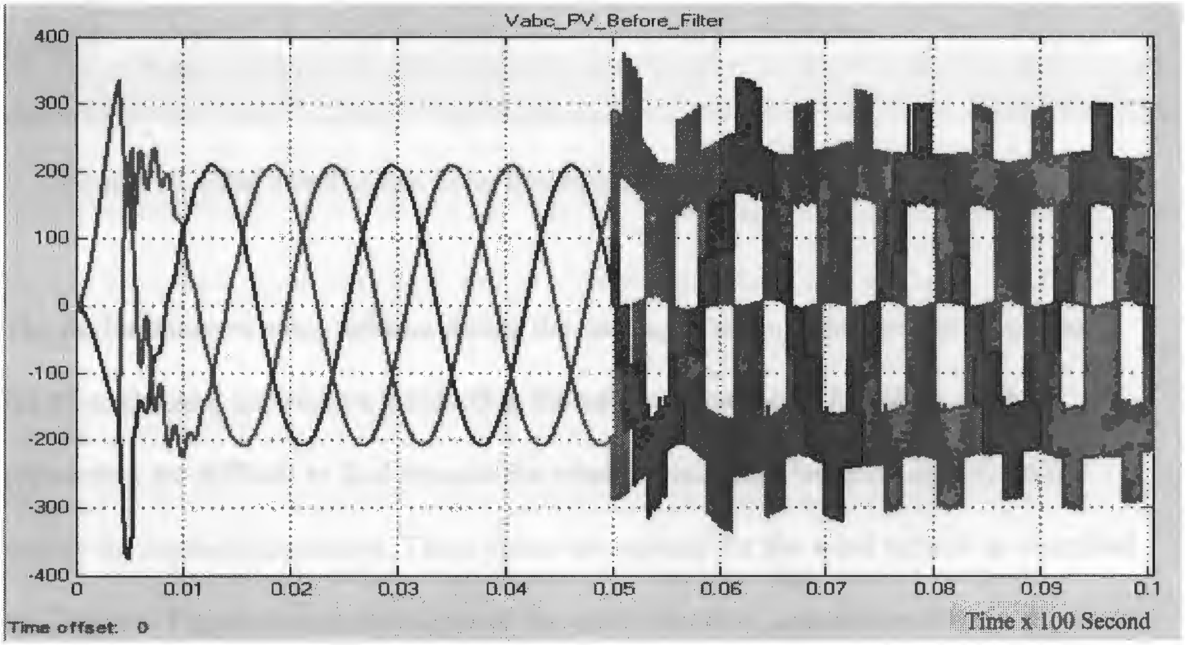


Figure 28. SimPowerSystem Solar three-phase voltage and current before the filter

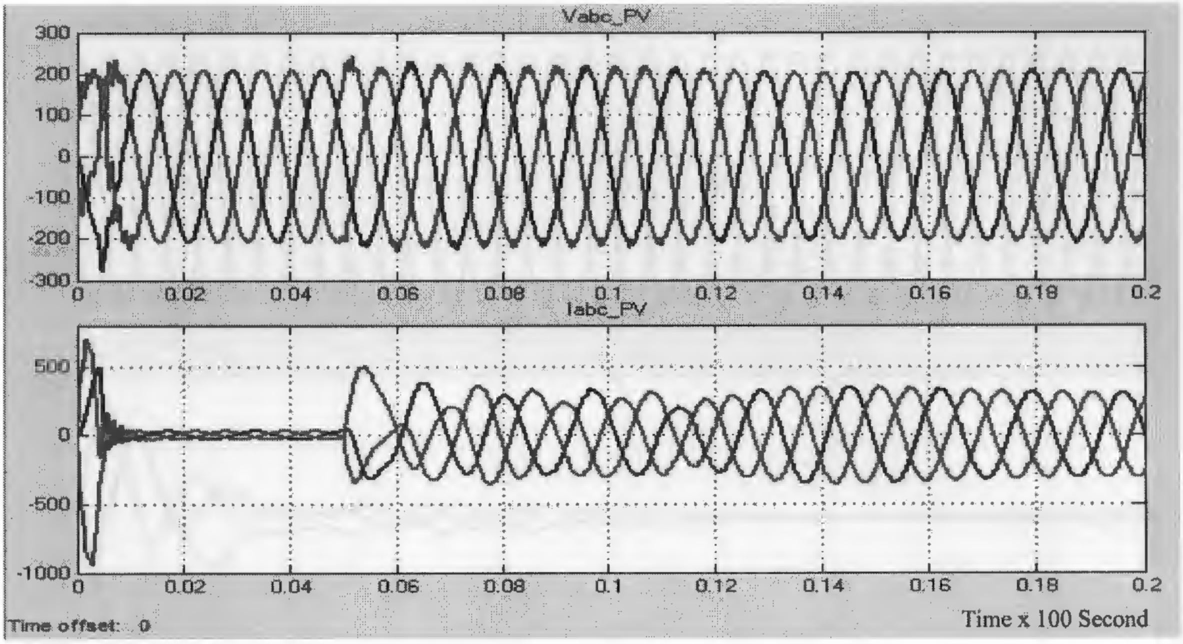


Figure 29. SimPowerSystem Solar three-phase voltage and current after the filter

The performance of wind turbines during the start-up is strongly influenced by a broad set of mechanical parameters involved in the turbine dynamics. The values of these parameters are difficult to find because the wind turbine manufacturers usually do not supply the related information. These values are entered for the wind turbine as described in Chapter 3 Figure 24 and the output of the wind turbine at normal operation is shown in Figure 30.

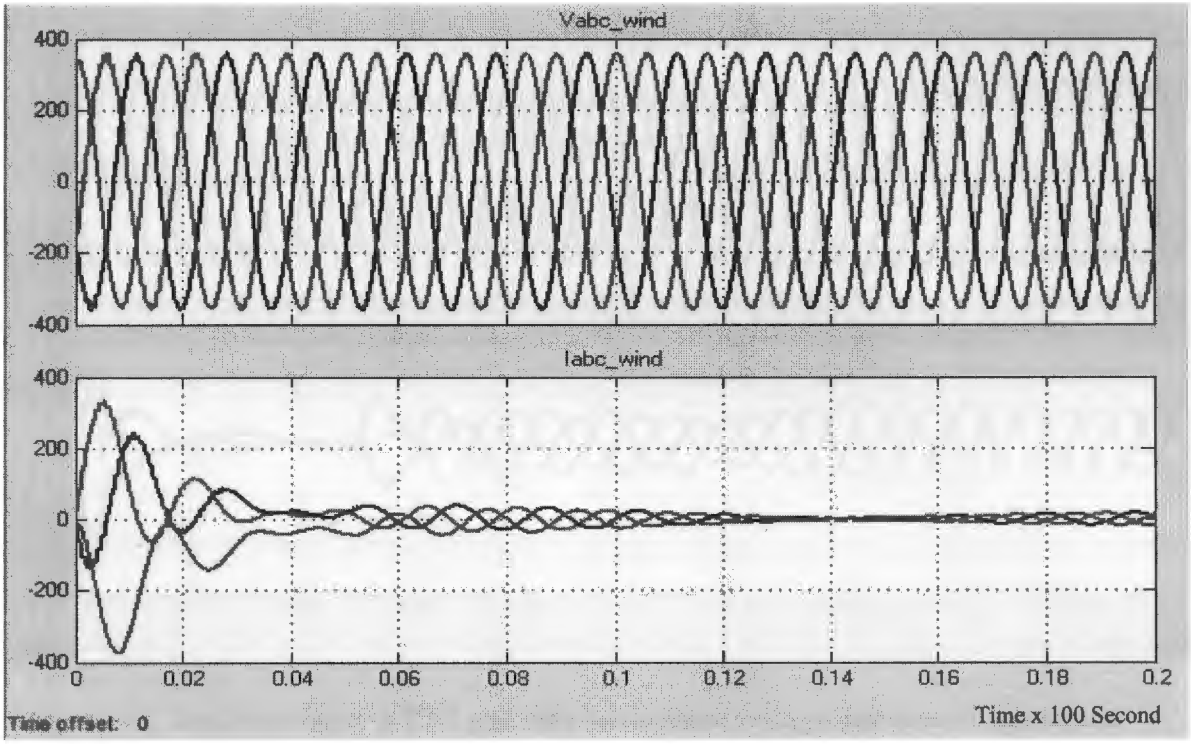


Figure 30. SimPowerSystem wind turbine three-phase voltage and current

At the UNI electric grid where the solar and wind systems are connected, voltage is not affected during start-up. However the current and frequency fluctuate for about 6 seconds, as shown in Figure 31 and 32 respectively.

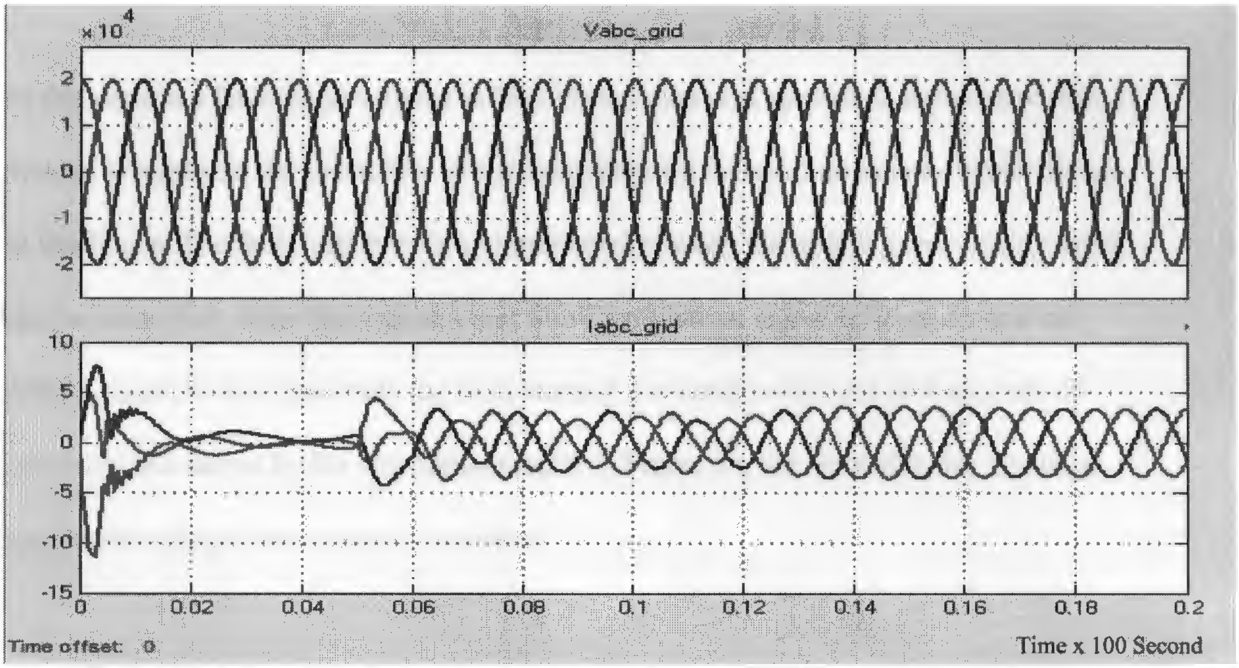


Figure 31. SimPowerSystem UNI grid side three-phase voltage and current waveform

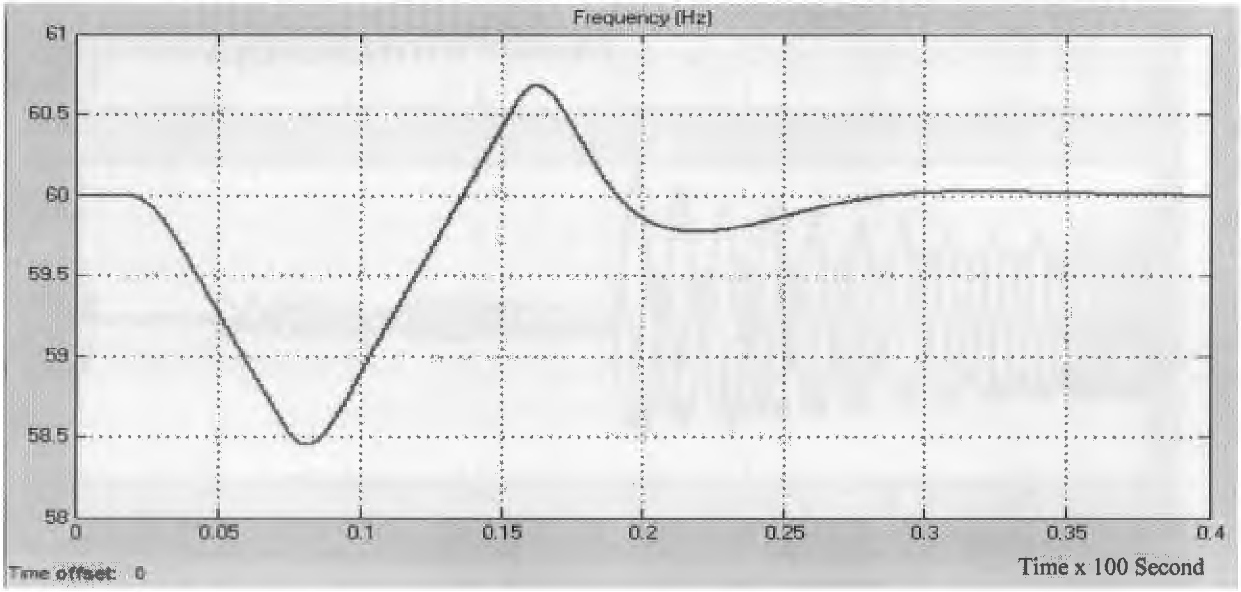


Figure 32 . SimPowerSystem UNI grid side frequency waveform

Case Study I: Analysis of PV Terminal

In this section a fault (short-circuit) in SimPowerSystems is applied to the solar power system to represent the possibility of lightning striking the solar arrays or a rapid change in irradiance. The fault implements a circuit breaker when the opening and closing times can be controlled either from an external SimPwerSystems signal or from an internal control timer. In this case study the fault starts at 2 seconds with total of 4 seconds of operation. As shown by the simulation results in Figure 33, the solar side has a voltage sag (under-voltage) and current fluctuation.

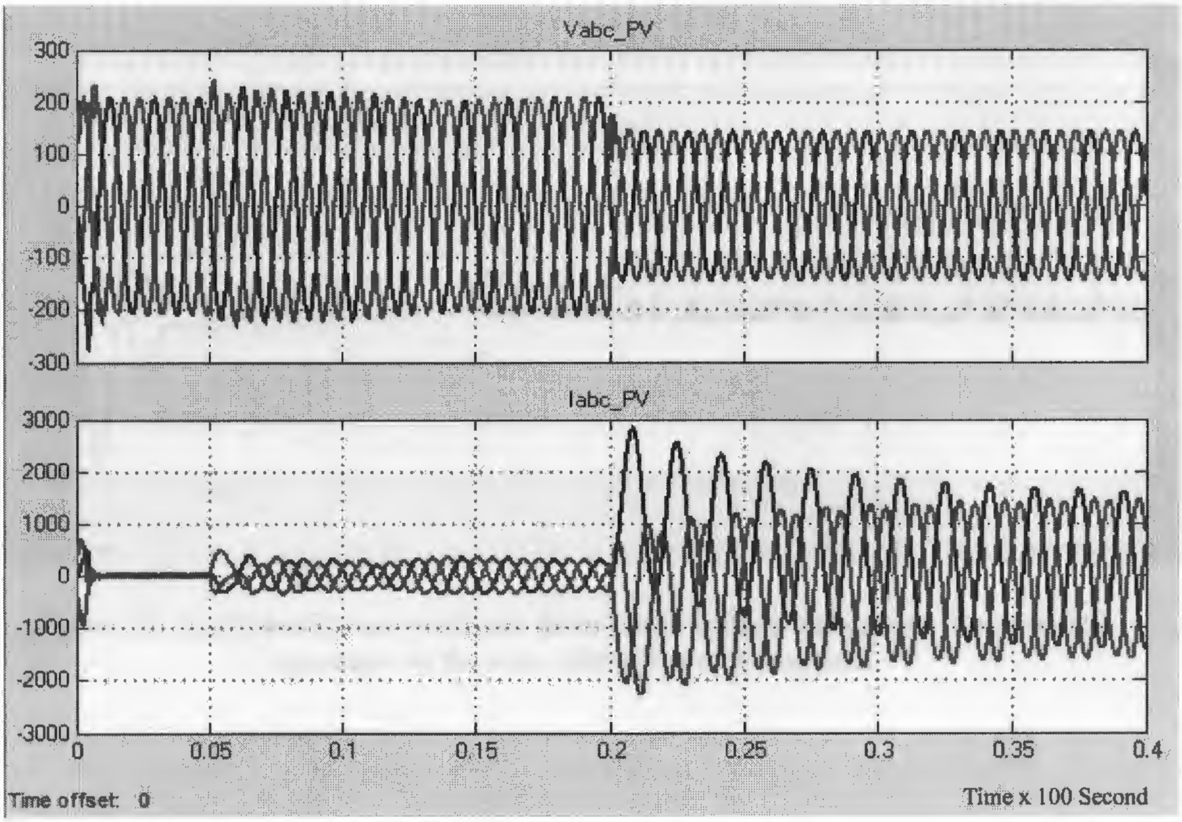


Figure 33. SimPowerSystem solar PV side three-phase voltage and current during a fault operation on the solar side of the power system

The fault operation at the solar side of the grid-connected solar-wind power system does not affect the wind side of the power system, as shown in Figure 34. However, the UNI electric grid has current fluctuation during the fault operation, as shown in figure 35 and the three-phase voltage at the UNI electric grid is not affected during the fault operation.

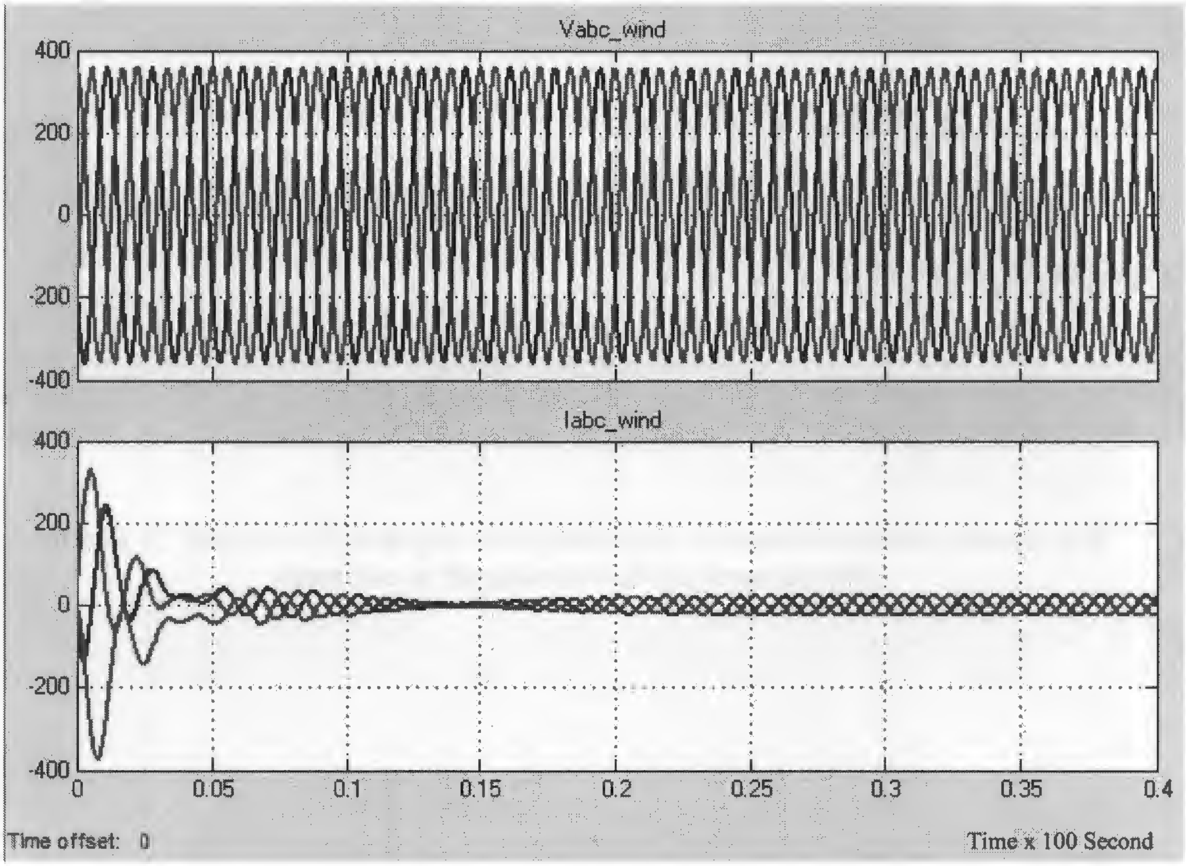


Figure 34. SimPowerSystem wind side three-phase voltage and current during a fault operation on the solar side of the power system

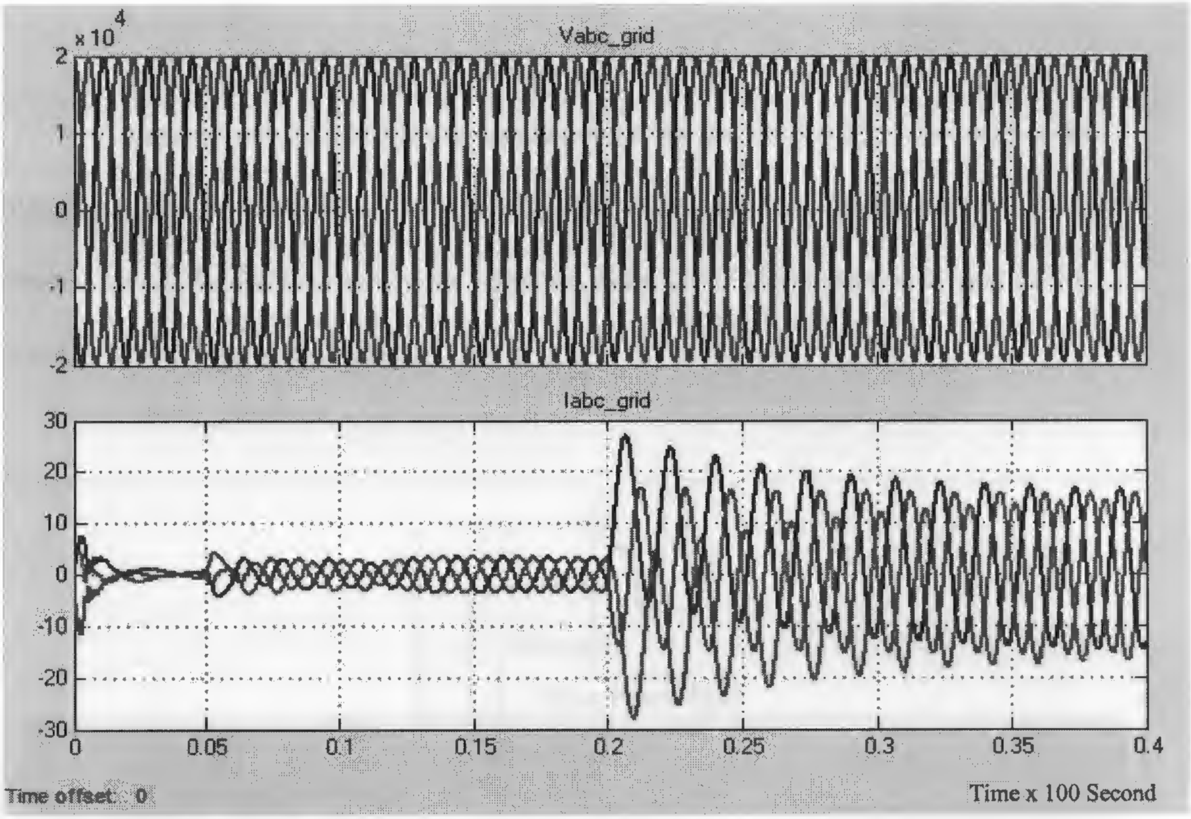


Figure 35. SimPowerSystem grid side three-phase voltage and current during a fault operation on the solar side of the power system

Case Study II: Analysis of Wind Turbine Terminal

A three-phase fault block was implemented for the wind side of the solar-wind hybrid power system as shown in Figure 36. The three-face fault block is set in internal control mode; the fault runs only for 1 second, from 20 to 21 seconds with total of 40 seconds of the system operation.

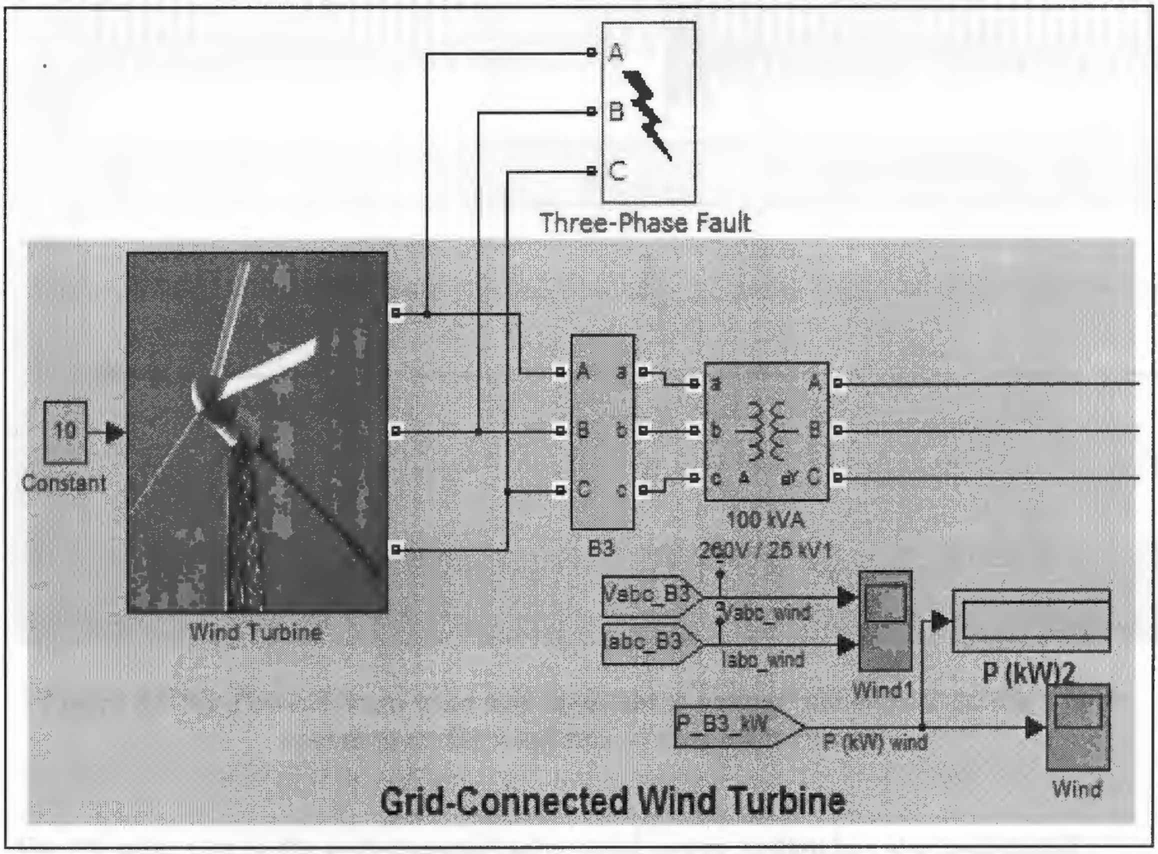


*Figure 36.*Three-phase fault connected to wind side of the power system

A transient appears on the wind side of the solar-wind power system in both the voltage and current during the three-phase fault operation. Transient voltage ranges from 100 volts to 200 volts and occurs only during the fault operation time, as shown in Figure 37. Voltage and current reaches the normal level right after the fault operation ends.

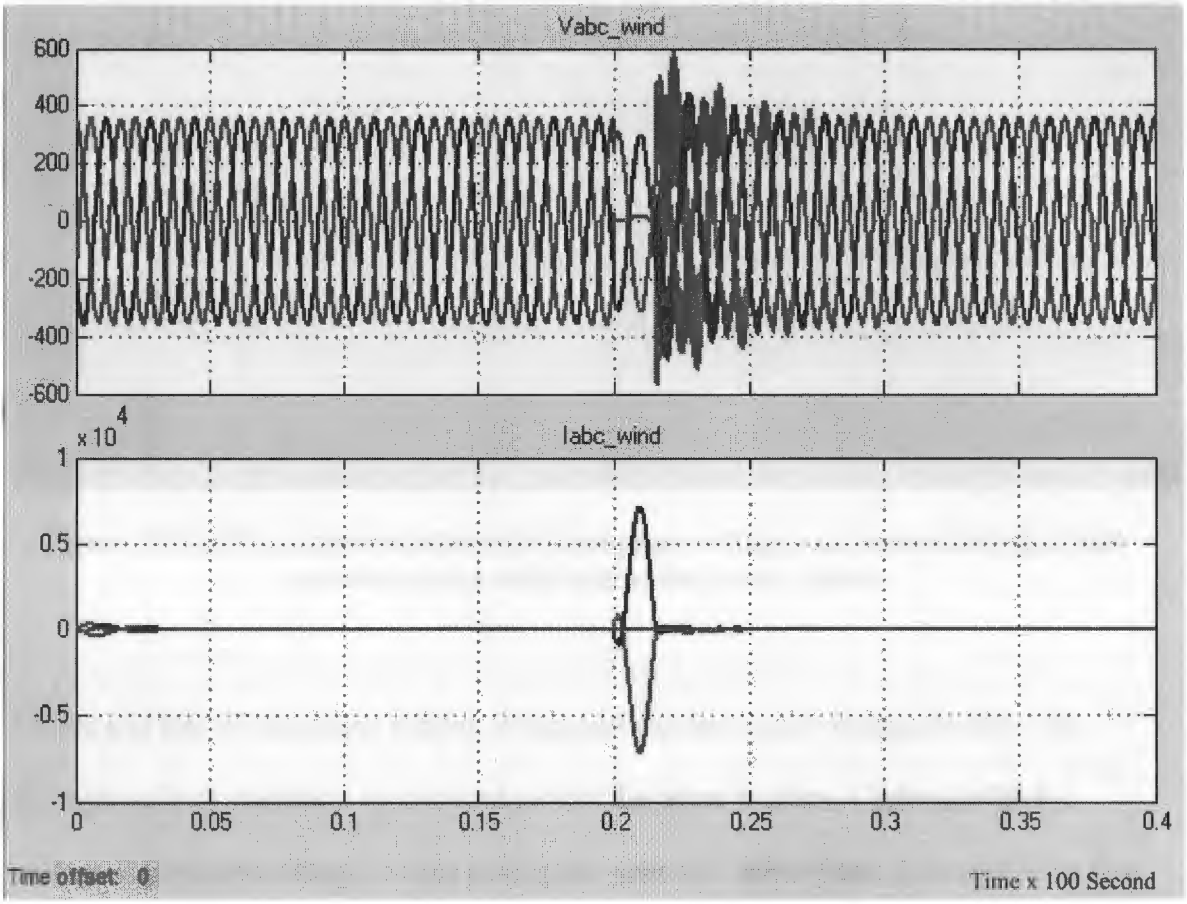


Figure 37. SimPowerSystem wind side three-phase voltage and current during a fault operation on the wind side of the power system

The PV solar side of the grid-conncted solar-wind power system has also moderated transient voltage and current during the fault operation on the wind side of the power system. The transient occurs only during the period of fault operation time and has no impact after that, as shown in Figure 38.

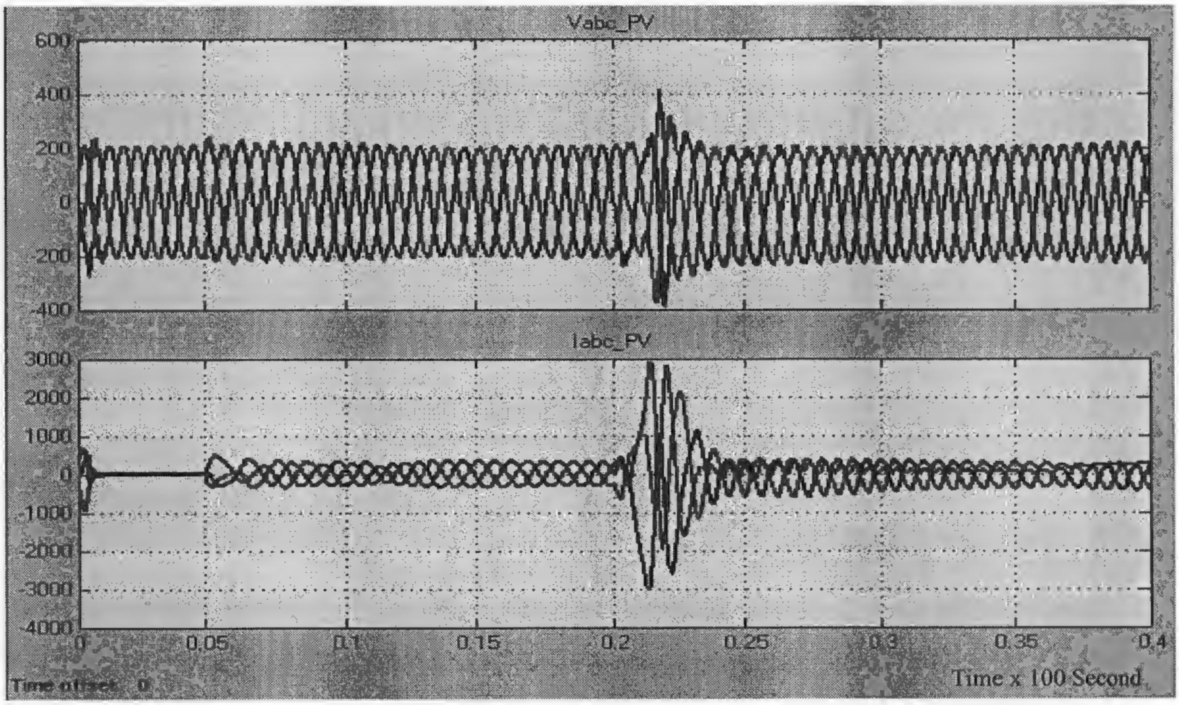


Figure 38. SimPowerSystem solar side three-phase voltage and current during a fault operation on the wind side of the power system

On the grid side of the power system, a transient current occurs during and after the three-phase fault operation on the wind side of the power system. Correspondingly, voltage sags (under-voltage) occurs during the period of three-phase fault operation time and then might cause the system to dissconnect the wind turbine conveter. Figure 39 shows the three-phase fault operation and Figures 40 and 41 show closer look to the voltage and current waveforms.

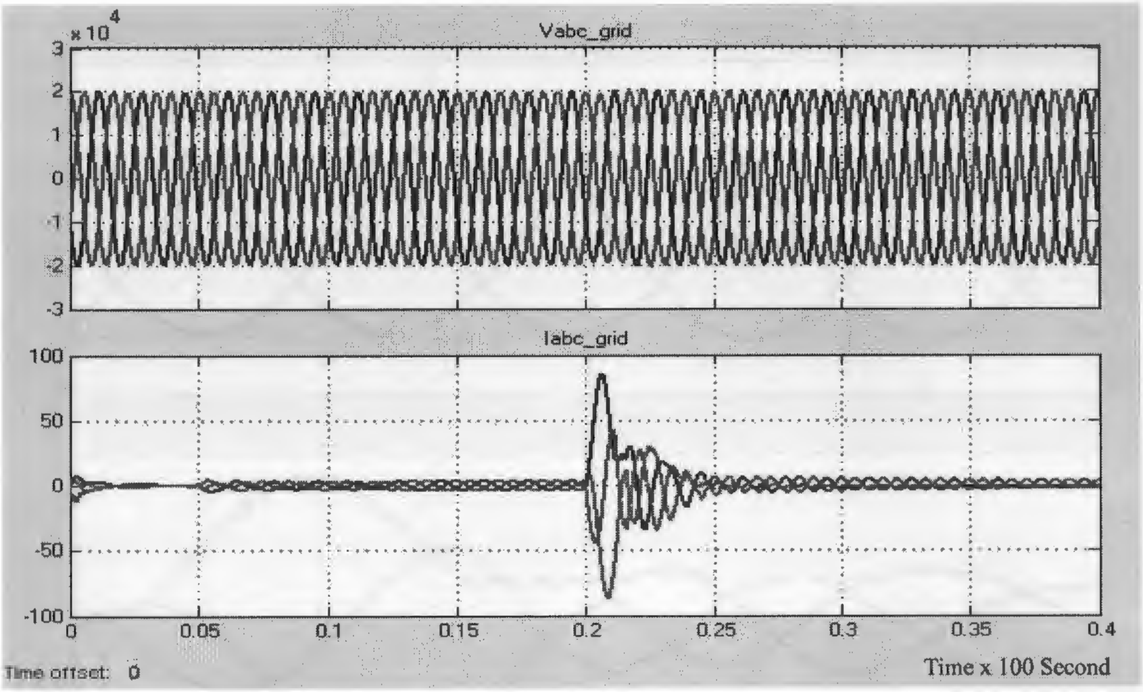


Figure 39. SimPowerSystem grid side three-phase voltage and current during a fault operation on the wind side of the power system

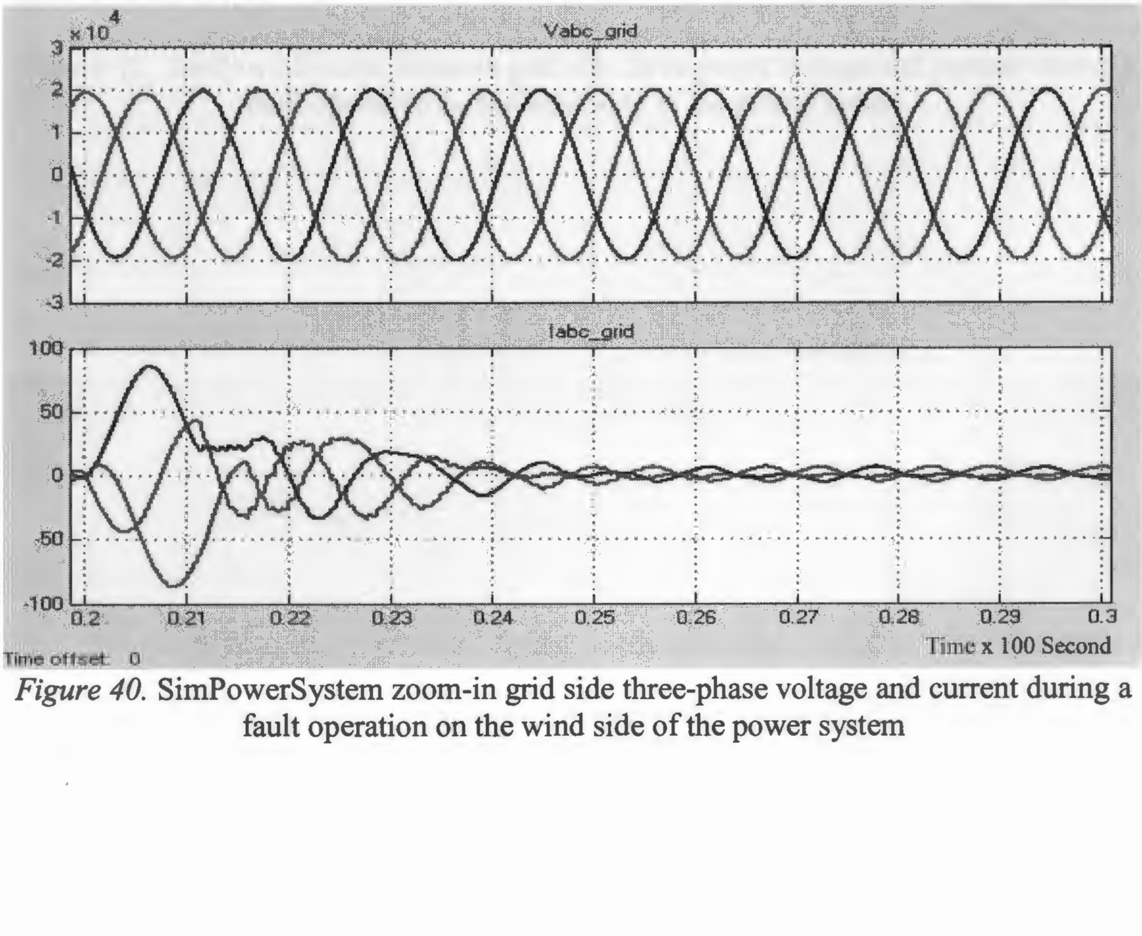


Figure 40. SimPowerSystem zoom-in grid side three-phase voltage and current during a fault operation on the wind side of the power system

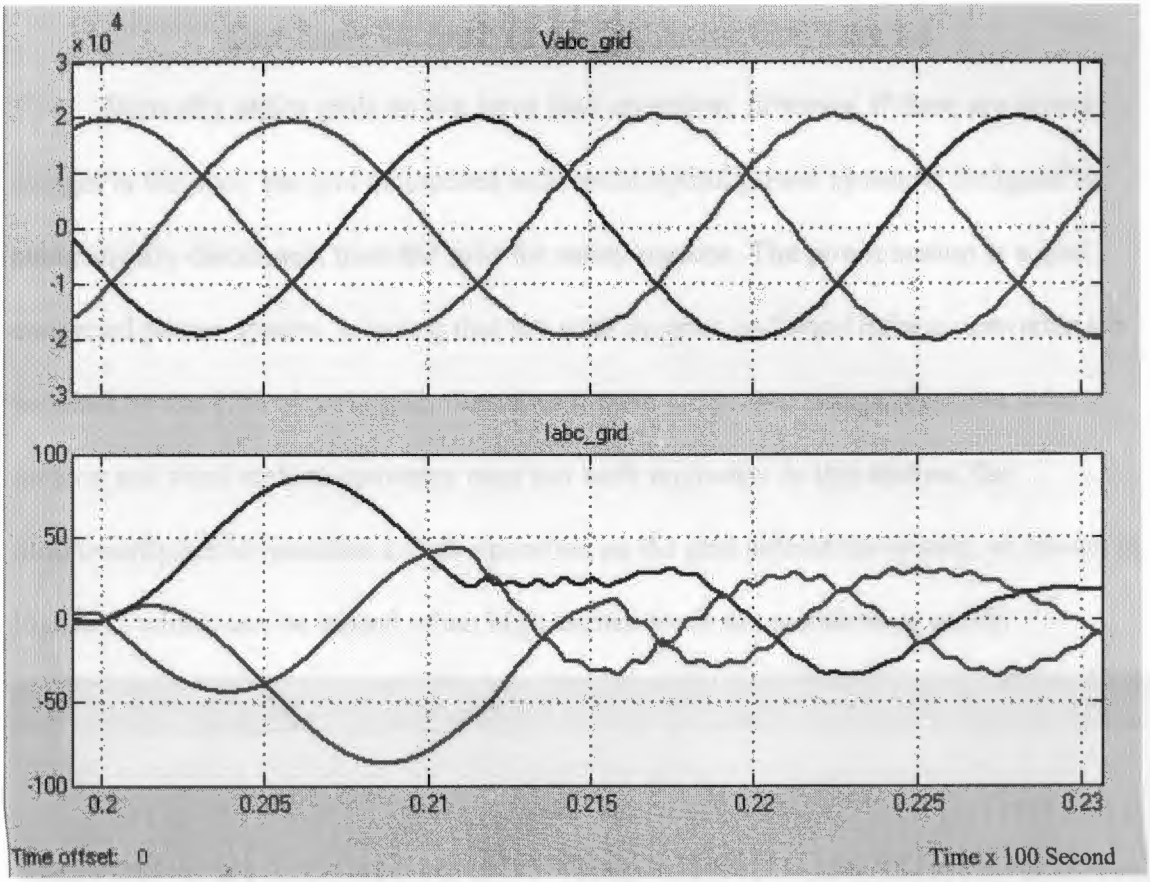


Figure 41. SimPowerSystem zoom-in grid side three-phase voltage and current during a fault operation on the wind side of the power system

Case Study III: Analysis of UNI Electric Grid Terminal

Normally utility grids do not have fault operation, however, if there are power outages in the area, the grid-connected solar-wind hybrid power system is designed to automatically disconnect from the grid for safety reasons. The power station is a grid connected power system, meaning that the solar inverter and wind turbine converter are powered by the UNI electric grid, therefore if there are power outages then the solar inverter and wind turbine converter may not work anymore. In this section, the SimPowerSystems simulates a fault operation on the grid side of the system, as shown in Figure 42 which can be caused when high current loads are switched on or off.

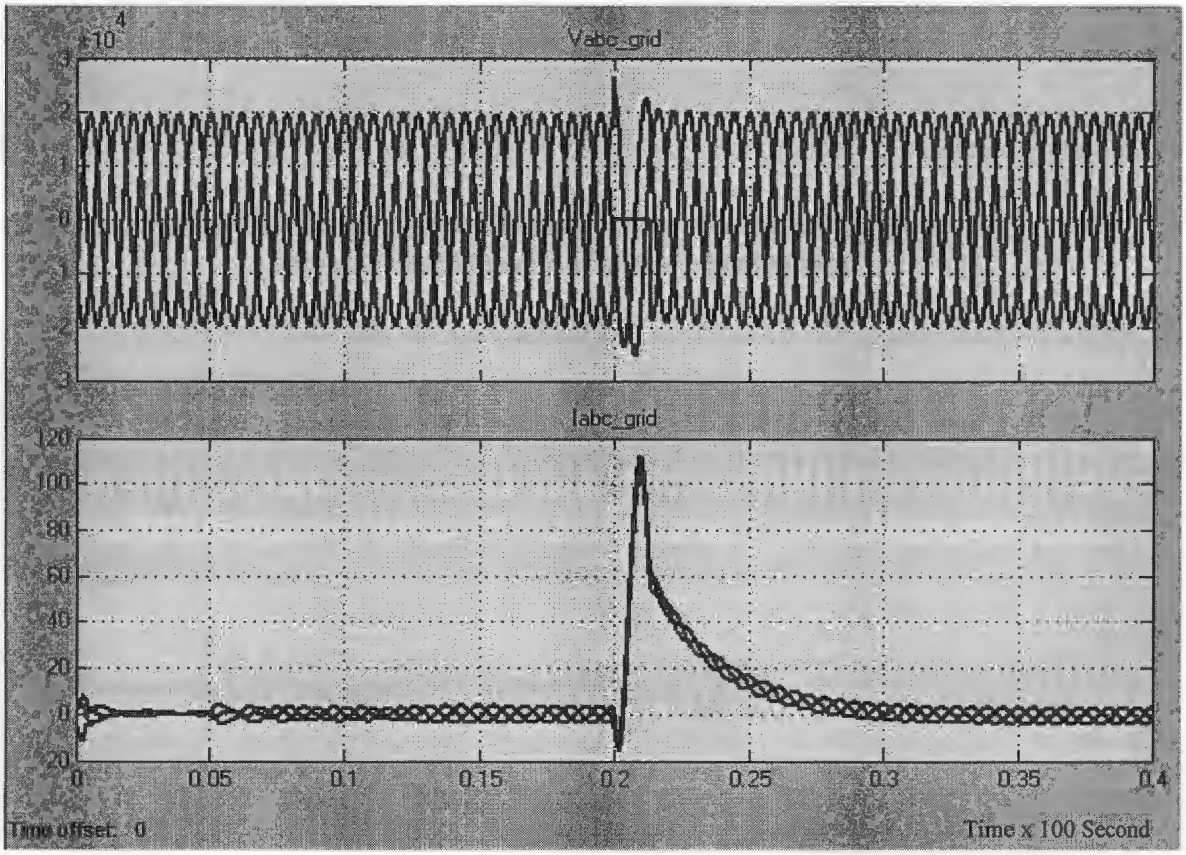


Figure 42. SimPowerSystem grid side three-phase voltage and current during a fault operation on the utility grid side of the power system

The wind and solar sides, as well as the utility power system, experience a fluctuation in both voltage and current, as shown in Figure 43 and 44 respectively due to this specific fault case. The fluctuation appears more in the current waveforms than the voltage due to the high current load simulating operations.

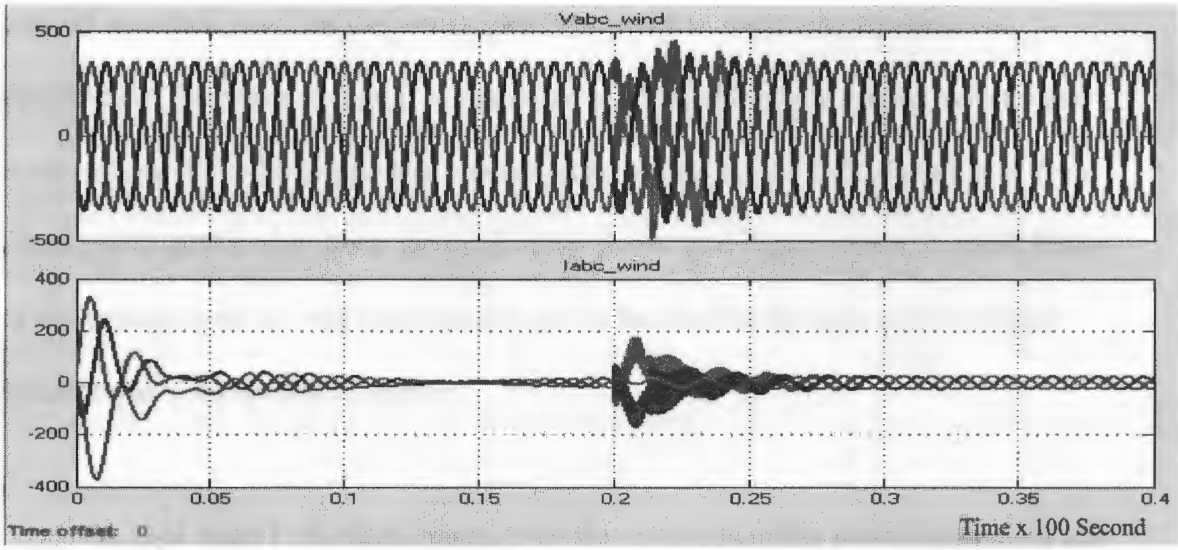


Figure 43. SimPowerSystem wind side three-phase voltage and current during a fault operation on the grid side of the power system

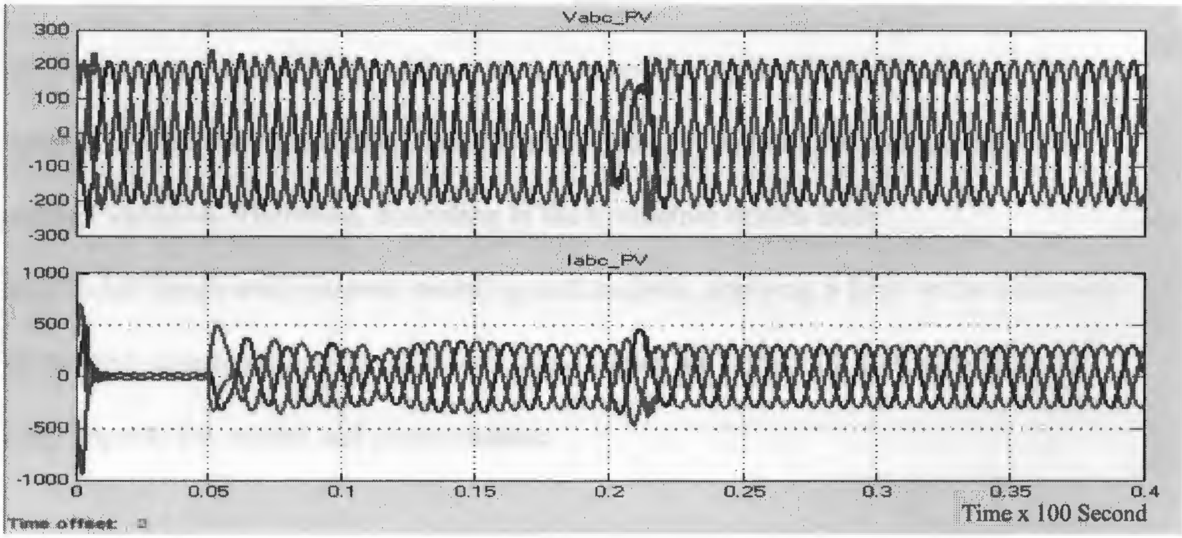


Figure 44. SimPowerSystem solar side three-phase voltage and current during a fault operation on the grid side of the power system

CHAPTER V

CONCLUSION AND RECOMMENDATION

Discussion

The performance of the grid-connected solar-wind hybrid power system during normal operation provides the power quality required to ensure the stability and reliability of the power system it is connected to. The solar power system inverter and wind turbine converter enable this power system to provide the UNI electric grid with clean power quality that meets the local utility power grid requirements. A small flicker in the voltage lines or a start-up transient can be handled by the solar power system inverter and wind turbine converter.

In case study I, the fault operation on the solar side of the power system did not impact the voltage and current at the wind side of the power system. In the same way, it did not impact the voltage at the grid side of the power system; however, it has an impact on the current at the grid side of the power system. During the fault operation on the solar system, the inverter was able to keep the voltage steady to meet the utility acceptable voltage variation. Therefore, according to the simulation results from MATLAB/SimPowerSystemsn modeling and analysis, applying a fault on the solar side of the grid-connected solar-wind power system does not impact the output voltage. It only impacts the current and power output.

Case study II presented the simulation of a three-phase fault at the wind turbine which represents a lightning strike or a very high variation of wind speed. The result showed two significant impacts at the grid side of the power system;

1. Current transient occurs during the three-phase fault operation.
2. Harminics occurs during and after three-phase fault operation clears.

These two significant effects might cause the power system to dissconnect (stop) the wind turbine conveter from injecting more current transient and harmonics. The solar side of the system had voltage and current transient and the grid side had only current transient. This current transient, which was caused by the wind side of the power system, has less impact on the grid side than the current transient that caused by the solar side of the power system.

Case study III fault operation does not truly occur in real world. The grid-connected solar-wind hybrid power system is built to assist the UNI electric grid only when there is power. In other words, the solar power system inverter and wind turbine converter only works when there's power in the grid. If there is power outage in the area, then the power station is automatically disconnected from the UNI electric grid. In the simulation, applying a fault on the grid side of the power system showed a big impact in both solar and wind power system and in the real world that might cause damages to the solar power system inverter.

Summary

The concept of a grid-connected solar-wind hybrid power system is presented and shows a new way in which distributed renewable sources can be used to provide clean power and assist the electric power grid systems. The solar power system inverter and wind turbine converter have the capability to handle fault operation with fast recovery to meet utilities acceptable voltage In this thesis, a variety of models are discussed and simulations are carried out in MATLAB/Simulink and SimPowerSystems toolboxes to demonstrate what is happening inside each part of the solar-wind hybrid power system. The results show that these kinds of power systems can assist the electric power grid system to reduce the overall cost of energy.

Recommendation and Future Work

Further studies on the design of the grid-connected solar-wind hybrid power systems can be extended for future work by improving the development of the station. The power output of the grid-connected solar-wind hybrid station was not analyzed in this study. The solar inverter and wind converter are consuming power to meet the utility acceptable voltage; therefore the power is being delivered to the utility grid individually. Another way to for the solar-wind hybrid systems to consume less power when inverting voltage, is to have both solar system and wind system in one multiple input inverter.

The ability of a grid-connected to provide power, when there is a power outage in the area, is important. Developing a solar-wind hybrid power system has the capability to alternate between a grid-connected and stand-alone is an ideal for homeowners once the system is cost affective and commercially available.

REFERENCE

Abderrazzaq, M. A. (2006). Analysis of the turbine standstill for a grid connected wind farm (case study).*Renewable Energy*, *89*(104), 89–104.

Arifujjaman, M. (2009). Reliability analysis of grid connected small wind turbine power electronics. *Applied Energy*, *86*(9), 1617–1623.

Bhave, A. (1999). Hybrid solar–wind system with battery storage operating in grid-connected and standalone mode: Control and energy management – experimental investigation. *Renewable Energy,17*(3), 355–358.

Bergey. (2011, March 1). *Technical data*. Retrieved from http://production-images.webapeel.com/bergey/assets/2011/9/7/96578/Excel.S.OM.2011.R1.pdf

Chen, H.H, Kang, H.Y., & Lee, A.H. (2009). Strategic selection of suitable projects for hybrid solar-wind power generation systems. *Renewable and Sustainable Energy Reviews, 14*, 413–421.

Chen, Y. (2007). Multi-input inverter for grid-connected hybrid pv/wind power system. *IEEE Transaction on Power Electronic, 22(3),* 1070-1077.

Dali, M. (2010). Hybrid solar–wind system with battery storage operating in grid-connected and standalone mode: Control and energy management – experimental investigation. *Energy*, *35*(6), 2587–2595.

Dugan, R., McGranaghan, M., Santoso, S., & Beaty, H. (2003). *Electric power systems quality*. (2nd ed.). Hightstown, NJ: McGraw-Hill.

Fox-Penner, P. (2010). Smart power: climate change, the smart grid, and the future of electric utilities. *Island Pr*

Giraud, F., & Salameh, Z. (2007). Measurements of harmonics generated by an interactive wind/photovoltaic hybrid power system. *Electric Power Components and Systems*, *35*, 757–768. doi: 10.1080/15325000601175132

Kalogirou, S. (2009). Solar energy engineering: processes and systems. *Academic Press.*

Lorenzo, E. (1994). *Solar Electricity Engineering of Photovoltaic System.* Artes Graficas Gala, S.L., Spain. ISBN: 84-86505-55-0

Mark, S, Sissine, F, & Net, T. (2009*).* Smart grid: modernizing electric power transmission and distribution; energy independence, storage and security; energy independence and security act of 2007 (eisa); improving electrical grid efficiency, communication, reliability, and resiliency; *integrating new and renewable energy sources*. The Capitol Net Inc.

Nema, P. (2009). A current and future state of art development of hybrid energy system using wind and pv-solar: A review. *Renewable and Sustainable Energy Reviews*, *13*(8), 2096–2103.

Kyaw, M. (2011). Fault ride through and voltage regulation for grid connected wind turbine. *Renewable Energy*, *36*(1), 206–215.

Tong, W. (2010). *Wind power generation and wind turbine design*. Billerica: WIT Press.

Sharp. (Photographer). (2010). *Electrical characteristics*. [Web Photo]. Retrieved from http://www.sharpusa.com/SolarElectricity.aspx

Su Yan, Y. (2011). Real-time prediction models for output power and efficiency of grid-connected solar photovoltaic systems. *Applied Energy, 92,* 1-8. doi:10.1016/j.apenergy.2011.12.052

Rosemary, H. (1997*). Data acquisition for sensor systems*. Great Britain : Springer.

Massey, G. (2010). *Essentials of distributed generation systems*. Ontario: Jones and Bartlett

Xantrex. (Photographer). (2009). *Basic system overview*. [Web Photo]. Retrieved from http://updates.clipsal.com/ClipsalOnline/Files/Brochures/W0001361.pdf

APPENDIX A

DATASHEETS

Product data sheet
Characteristics

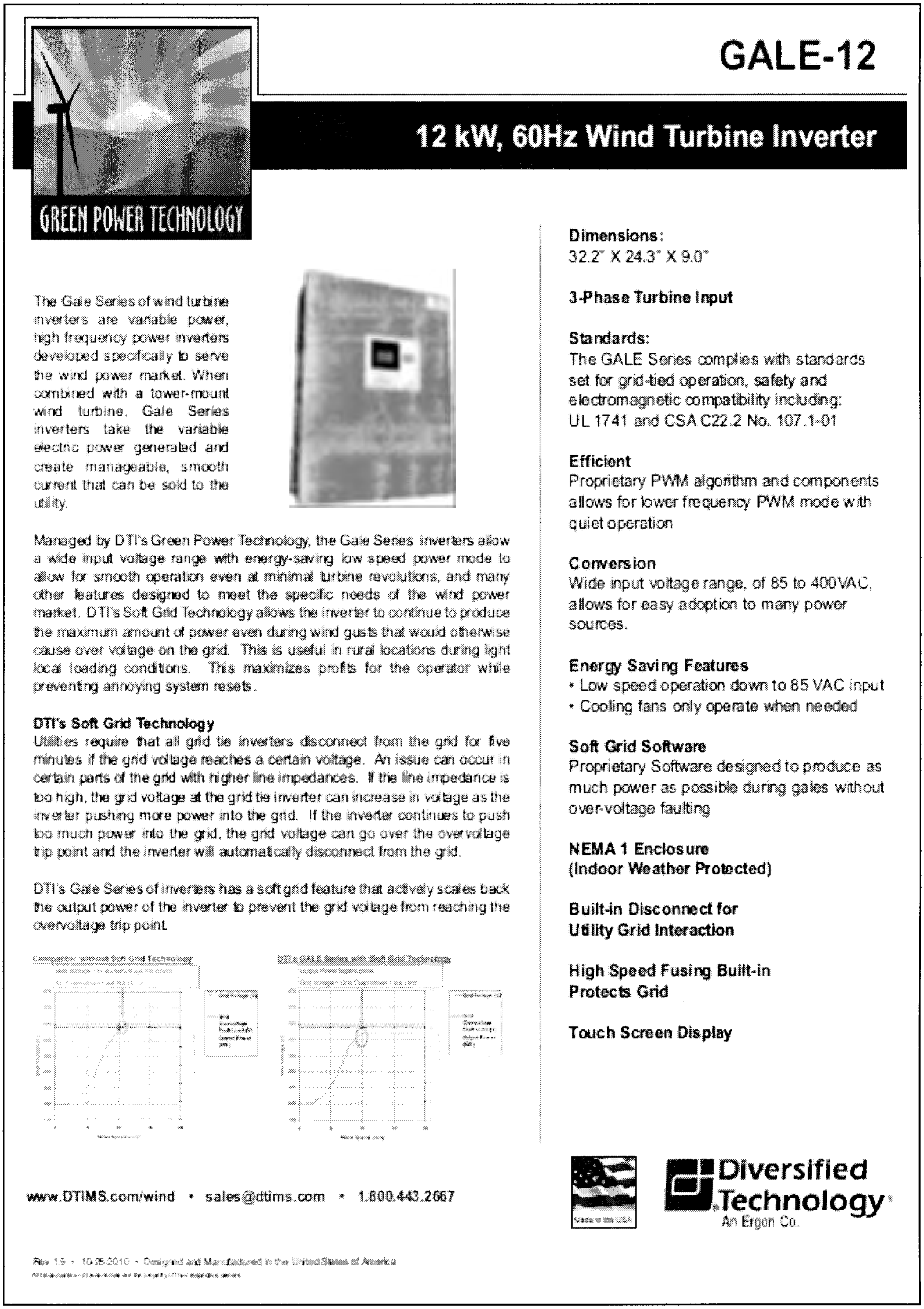
864-1006
Xantrex - grid-tie solar inverter GT 3.3N - 3.3 kW AC - 13.8A

Main

Range of product	Xantrex
Device short name	GT 3.3N
Product or component type	Grid-tie solar inverter
Network number of phases	Single phase
Type of signal	True sine wave output
Nominal output power	3.3 kW AC - 208 V 3.1 kW AC - 240 V

Complementary

Output voltage	240 V AC single phase 208 V AC single phase 211...264 V AC 183...229 V AC
Output type	Current source
Output current	13.8 A - 208 V 14.9 A - 240 V
Network frequency	60 Hz (output) 59.3...60.5 Hz (output)
Cos phi	> 0.99 at rated power (output) > 0.95 at full power range (output)
Harmonic distortion	< 3 %
Input voltage	<= 600 V DC open circuit 200...400 V MPPT - CEC & CSA 200...550 V MPPT
Input current	< 24 A DC - short circuit 16.5 A DC - 208 V 17.5 A DC - 240 V
Utility backfeed current	0 A
Overcurrent protection	20 A (output)
Reverse polarity protection	Short-circuit diode
Efficiency	95.9 % peak - 240 V 95.5 % CEC - 240 V 95 % CEC - 208 V 95.6 % peak - 208 V
Power consumption in W	1 W night time
Function available	GF detection, IDIF > 1 A
Display type	Backlit LCD
Messages display capacity	2 lines of 16 characters
Communication interface	RS232 Xanbus 1 RJ45
AWG gauge	14...6
Type of cooling	Convection
Device mounting	Wall mounted
Height	724 mm
Width	403 mm
Depth	145 mm
Product weight	22.2 kg



GALE-12

12 kW, 60Hz Wind Turbine Inverter

GREEN POWER TECHNOLOGY

The Gale Series of wind turbine inverters are variable power, high frequency power inverters developed specifically to serve the wind power market. When combined with a tower-mount wind turbine, Gale Series inverters take the variable electric power generated and create manageable, smooth current that can be sold to the utility.

Managed by DTI's Green Power Technology, the Gale Series inverters allow a wide input voltage range with energy-saving low speed power mode to allow for smooth operation even at minimal turbine revolutions, and many other features designed to meet the specific needs of the wind power market. DTI's Soft Grid Technology allows the inverter to continue to produce the maximum amount of power even during wind gusts that would otherwise cause over voltage on the grid. This is useful in rural locations during light local loading conditions. This maximizes profits for the operator while preventing annoying system resets.

DTI's Soft Grid Technology
Utilities require that all grid tie inverters disconnect from the grid for five minutes if the grid voltage reaches a certain voltage. An issue can occur in certain parts of the grid with higher line impedances. If the line impedance is too high, the grid voltage at the grid tie inverter can increase in voltage as the inverter pushing more power into the grid. If the inverter continues to push too much power into the grid, the grid voltage can go over the overvoltage trip point and the inverter will automatically disconnect from the grid.

DTI's Gale Series of inverters has a soft grid feature that actively scales back the output power of the inverter to prevent the grid voltage from reaching the overvoltage trip point.

www.DTIMS.com/wind • sales@dtims.com • 1.800.443.2667

Rev 1.5 • 10.25.2010 • Designed and Manufactured in the United States of America

Dimensions:
32.2" X 24.3" X 9.0"

3-Phase Turbine Input

Standards:
The GALE Series complies with standards set for grid-tied operation, safety and electromagnetic compatibility including:
UL 1741 and CSA C22.2 No. 107.1-01

Efficient
Proprietary PWM algorithm and components allows for lower frequency PWM mode with quiet operation

Conversion
Wide input voltage range, of 85 to 400VAC, allows for easy adoption to many power sources.

Energy Saving Features
- Low speed operation down to 85 VAC input
- Cooling fans only operate when needed

Soft Grid Software
Proprietary Software designed to produce as much power as possible during gales without over-voltage faulting

NEMA 1 Enclosure
(Indoor Weather Protected)

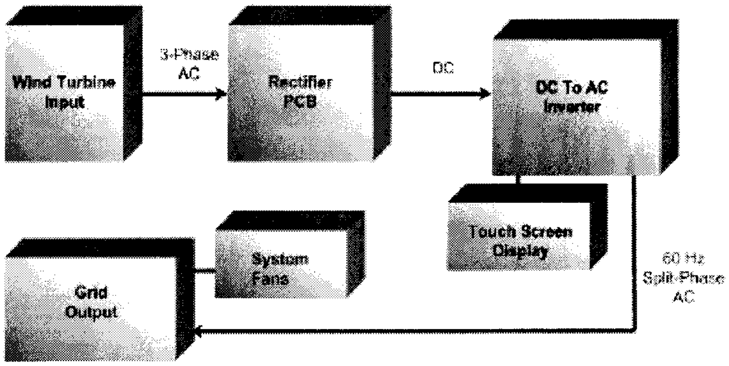
Built-in Disconnect for
Utility Grid Interaction

High Speed Fusing Built-in
Protects Grid

Touch Screen Display

Diversified Technology
An Ergon Co.

GALE-12 12kW, 60Hz Wind Turbine Inverter



Turbine Input:	
Input Voltage Maximum (3 Phase Input)	400 VAC
Input Start Voltage Maximum	85 VAC
Input Operating Voltage Range	85 to 400 VAC
Input Frequency Maximum	400 Hz
Input Current Maximum	40 Amps
Input Short Circuit Current Maximum	462 Amps
Input Wire Gauge	6 – 2 AWG 90 °C Cu
Grid Output:	
Continuous Output Power Maximum	12,000W
Continuous Output Power Tolerance	+/-10%
Continuous Output Current Maximum	50 Amps
Continuous Output Current Tolerance	+/-10%
Output Voltage Nominal (Single Phase)	240 VAC
Operating Voltage Range	212-264
Voltage Measurement Tolerance	+/-10 VAC
Operating Frequency Nominal	60 Hz
Operating Frequency Range	59.3 to 60.5 Hz
Operating Frequency Measurement Tolerance	+/- 0.5 Hz
Output Power Factor	0.95 +/- 0.05
Temperature Range Normal Operation	-20°C to 45°C
Output Over-Current Protection Maximum	80 Amps
Output Fault Current Maximum	1030 Amps
Synchronization In-Rush Current Maximum	6.3 Amps
Utility Interconnection Trip Time	100 msec
Time Measurement Tolerance	+/- 85 msec
Output Wire Gauge	6 – 1/0 AWG 90 °C Cu
Enclosure:	
Install in indoor weather protected environment.	
Mounting	Wall mount
Maximum Ambient Temperature	113°F / 45°C
Dimensions	32.2"H x 24.3"W x 9.0"D
Weight	153 lbs. / 69 Kg

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An Ergon Co.

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BUSINESS MEMBER

APPENDIX B

SIMULATION FIGURES

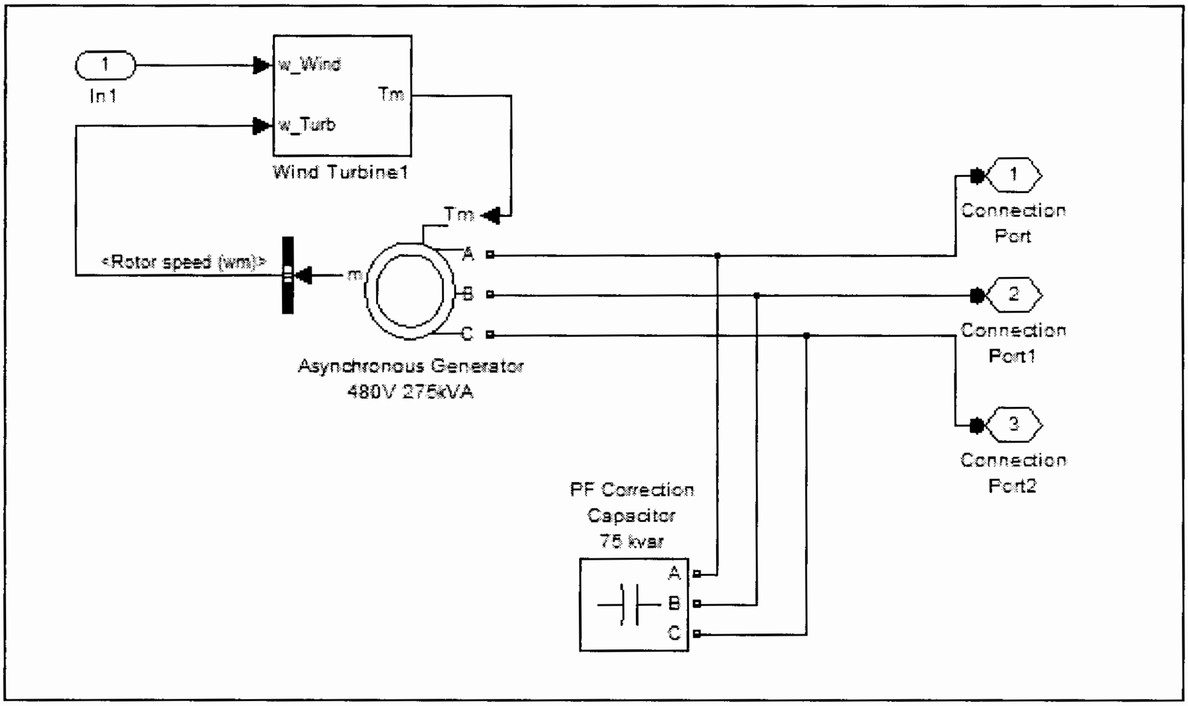

Figure 45. SimPowerSystem wind turbine

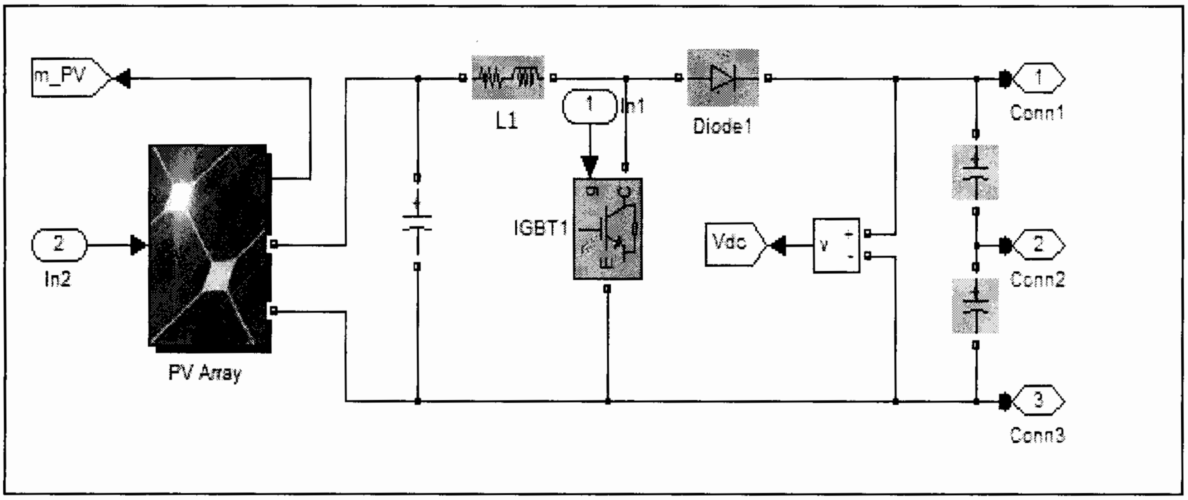

Figure 46. SimPowerSystem solar panel

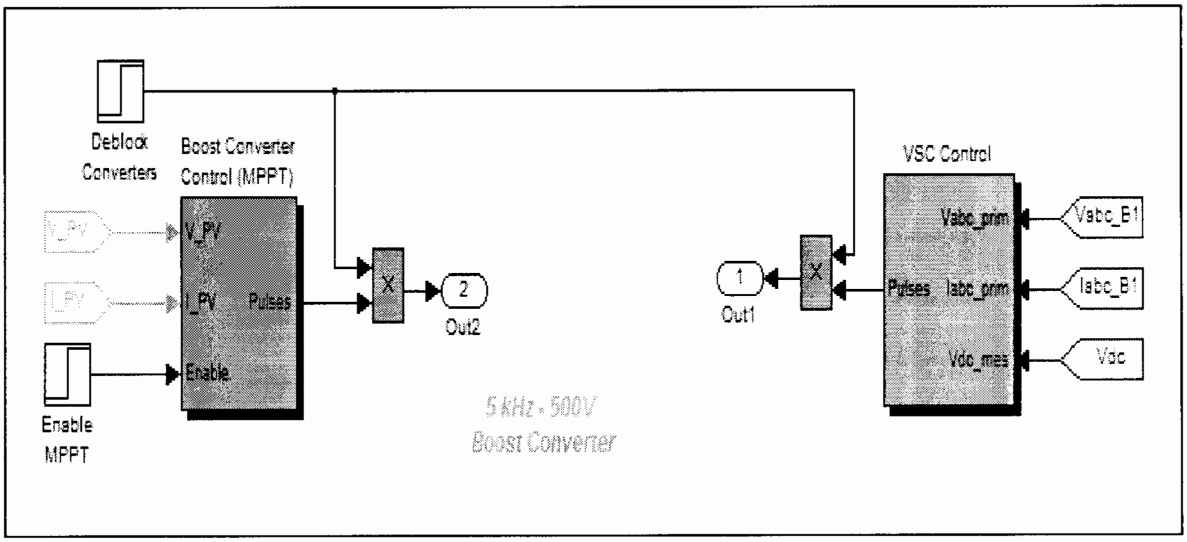

Figure 47. SimPowerSystem solar panel inverter

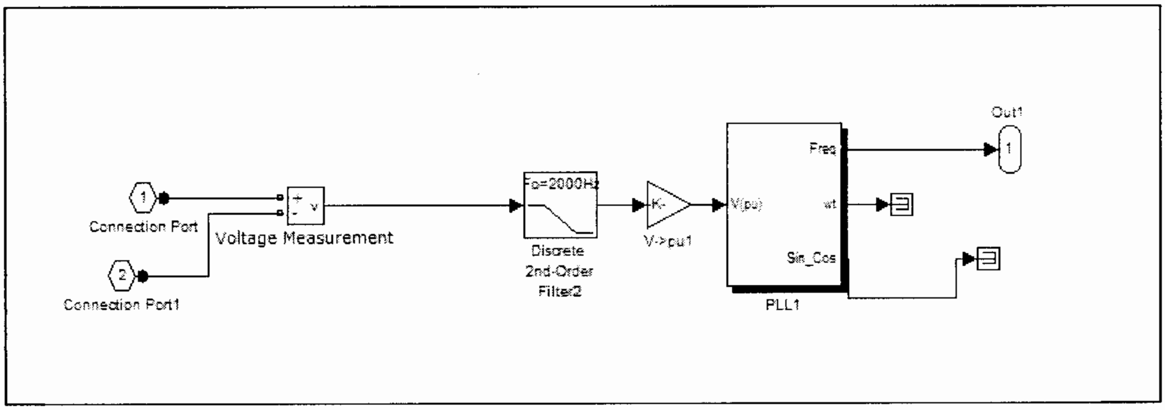

Figure 48. SimPowerSystem frequency measurement