AC 2007-3: INTEGRATING WIND AND SOLAR ELECTRIC ENERGY INTO POWER SYSTEM TEACHING

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Integrating Wind and Solar Electric Energy into Power System Teaching

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Abstract

The global community as well as the USA is encouraging renewable electric energy production to reduce pollution from the burning of fossil fuels. The main renewable resources for electricity generation are conventional hydro, biomass, geothermal, wind, and solar systems. Wind and solar power are two available renewable resources worldwide and many power plants based on photovoltaic and wind turbine technology have already been connected to the grid. More photovoltaic (PV) and wind turbine (WT) facilities are coming on-line every year. Incorporating wind and solar electrical energy into power system teaching will enhance the student's learning about renewable resources. This paper describes the modeling and the simulation of grid-connected PV and WT systems. The PowerWorld simulator and MATLAB/SIMULINK (registered trademark of the MathWorks Inc.) are used to conduct simulation, respectively. The PowerWorld simulator is mainly used for load flow analysis, and SIMULINK® is able to model, simulate, and analyze the dynamic and the non-linear systems. Two different scenarios are simulated in this paper: 1) PV with grid connection, 2) WT with grid connection. For the first scenario, grid-connected experimental PV analysis is compared using the PowerWorld simulation, and for the second scenario, the steady state and transient (transmission line faults) behaviors of WT are simulated and effects are analyzed using MATLAB/SIMULINK. This paper also presents a financial evaluation for the grid-connected PV and WT systems. This integrated simulation and economic study will help to enrich power system teaching, and the student will have a better understanding of the distributed power generation.

Introduction

Each kilowatt-hour (kWh) generated from renewable resources saves the environment from the burning of fossil fuels. The coal-fired and the natural-gas-fired power plants produce 2.11 lbs and 1.17 lbs carbon dioxide, respectively, to generate 1 kWh electricity[1]. Electricity generation from the renewable resources is completely pollution free, but many renewable power generation processes cost more than the fossil fuels processes except conventional hydro power. All possible hydro resources have already been developed and electricity generation from the conventional hydro is decreasing every year in the USA; for example, net generation from the hydroelectric conventional in 1995 and in 2004 were 310,833 and 268,417 thousand megawatt-hours, respectively, a decrease of 15.8%[2]. On the other hand, wind and solar are abundant renewable resources, and could be used to generate electricity to meet the future demand. Figure 1 shows the net electricity generation from wind and solar sources during 2000-2004. It can be seen from Figure 1 that between 2000 and 2004, net electricity generation from wind and solar increased by 153% and 17.36%, respectively[3,4]. The USA has an estimated wind electric energy potential of 10,777 billion kWh annually, but the total installed wind energy generating capacity is only 11,078 MW as of

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September 30, 2006. The generating capacity is expected to be 24.8 billion kWh of wind electricity in 2006. However, this is still less than 1% of total USA electricity generation[5]. The USA also has remarkable solar electric energy potential. More than 70% of the USA lands have an insolation (incident solar radiation power) rating of 5-6 kWh/m^2/day or higher, which is suitable for developing solar electric facilities[6]. To save the environment and reduce the dependency on fossil fuels, more electricity generation from renewable resources such as wind and solar should be added to the national grid.

The future generations of power engineers and designers should be exposed to the basic concept of wind and solar electric power and their interconnection with the power grid. One possible way is to integrate wind and solar electric power generation into a power system course using laboratory demonstration and simulation software such as MATLAB/SIMULINK[7] from MathWorks Inc., and the PowerWorld simulator. To introduce wind and solar electric energy into the power system teaching, two simple scenarios are studied: A simulation study of a 9.0 megawatts (MW) wind farm with grid connection using SIMULINK,® and a 5 kW experimental solar electric facility with grid connection compared to a simulation study using the PowerWorld simulator.

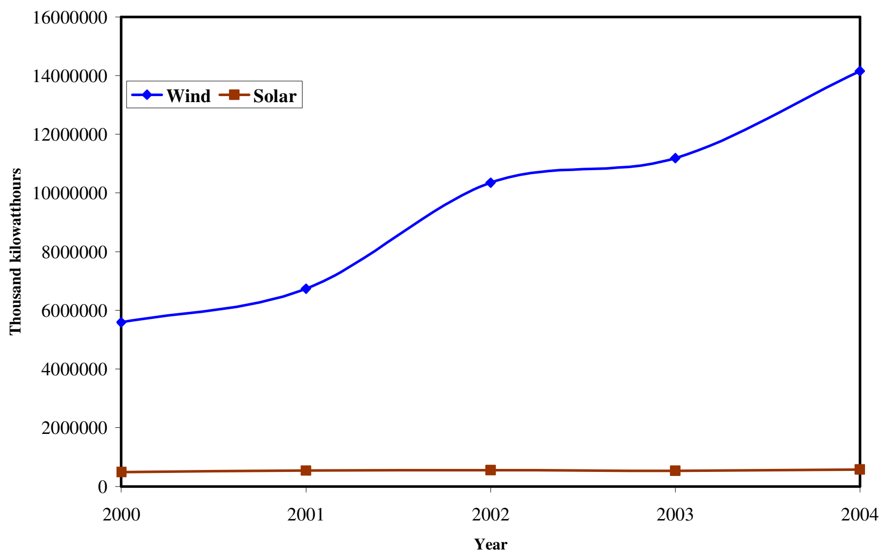

Figure 1: Net electricity generation from wind and solar during 2000-2004

The objective of this paper is to provide an introduction to wind and solar electric energy to the junior and the senior level students who are interested in electric power. Three assignments and a laboratory demonstration of the distributed generation (DG) could be useful to introduce wind and solar electric energy into the power system teaching.

Assignment 1: A brief description about wind and solar electric energy. What are the commercial uses of wind and solar electric systems? What are the selection criteria? What are the historical data for the electric energy generation from wind and solar in the USA?

Assignment 2: Simulation study of a grid-connected wind farm using MATLAB/SIMULINK:

- Three-bus to five-bus AC system
- Steady state analysis (power generation with respect to wind speed)
- Transient analysis (line-to-ground fault, line-to-line fault, and three-phase-to-ground fault)

Assignment 3: Feasibility study of wind and solar electric power generations. Both the projects are 5-15 kilometers away from the distribution line. The Study assumes that the distribution line has the capacity to carry the extra power generated by the wind firm and the photovoltaic power plant.

- Photovoltaic power plant (1 MW to 5 MW)
- Wind electric firm (5 MW to 30 MW)

Laboratory demonstration: A demonstration of the DG can be built in the laboratory using the simplified model presented in this paper. The benefits of the DG can be demonstrated using the experimental data and the simulation data.

This compact introduction to wind and solar electric energy is designed to be taught in the last four class meetings of the power system course. The first class is the introduction to wind and solar electric energy, different categories of wind and solar electric energy, selection criteria, distributed generation, and the past, present and future trends of renewable resources. The second class is to introduce the grid-connected wind turbine using MATLAB/SIMULINK (assuming that students already know MATLAB/SIMULINK; otherwise they can have extra help from the instructor). The steady state and the transient behavior would be analyzed. This class should use PowerPoint and/or animation software for the presentation. The third class is to discuss the feasibility study of wind and solar electric generation. The fourth and last class is to demonstrate the DG using the PV system in the laboratory and to compare the laboratory data with the PowerWorld simulation data. The students could conduct the simulation beforehand and compare it with the laboratory results.

Wind Electric Energy

Wind power is converted to electricity by a wind turbine (WT). In a large scaled WT, the kinetic energy in the wind (the energy of moving air molecules) is converted to rotational motion by the rotor – typically a three-bladed assembly at the front of the wind turbine. The rotor turns a shaft which transfers the motion into the nacelle (the large housing at the top of a wind turbine tower). Inside the nacelle, the slowly rotating shaft enters a gearbox that greatly increases the rotational shaft speed. The output shaft is connected to a generator that converts the rotational speed (mechanical power) into electricity. Figure 2 shows a schematic diagram of wind electricity generation[8]. The available power density calculation, in W/m^2, is given by $p = 1/2\rho v^3$, where ρ is the air density in kg/m^3 and v is the wind velocity in m/sec. The air density is computed from the ideal gas law, and thus is influenced by the ambient temperature and the pressure. Because of this pressure dependence, high altitude site locations reduce the available power density.

There are four types of wind turbines available[9]:

- *Type A:* Fixed speed wind turbine with an asynchronous squirrel-cage induction generator directly connected to the grid via a transformer. Since the squirrel-cage induction generator always draws reactive power from the grid, this configuration uses a capacitor bank for reactive power compensation.
- *Type B:* Limited variable speed wind turbine. This one uses a wound rotor generator with variable generator rotor resistance and pitch control, which allows for a speed range of up to 10% above the synchronous speed.
- *Type C:* Variable speed wind turbine with a doubly fed induction generator (DFIG) and pitch control. This concept allows a wider range of dynamic speed control compared to Type B, depending on the size of the frequency converter.
- *Type D:* Variable speed and pitch controlled wind turbine using a generator that is connected to the grid through a full-scale frequency converter. The frequency converter performs the reactive power

compensation and smoother grid connection.

Now, the first two types of wind turbines are being phased out of the market because the reactive power consumption of the squirrel-cage induction generator is nearly always partly or fully compensated for by capacitors in order to achieve a power factor close to one. The last two types of wind turbines are dominant in the international market. In this paper, the DFIG is used to discuss the performance of a wind firm connected to the grid.

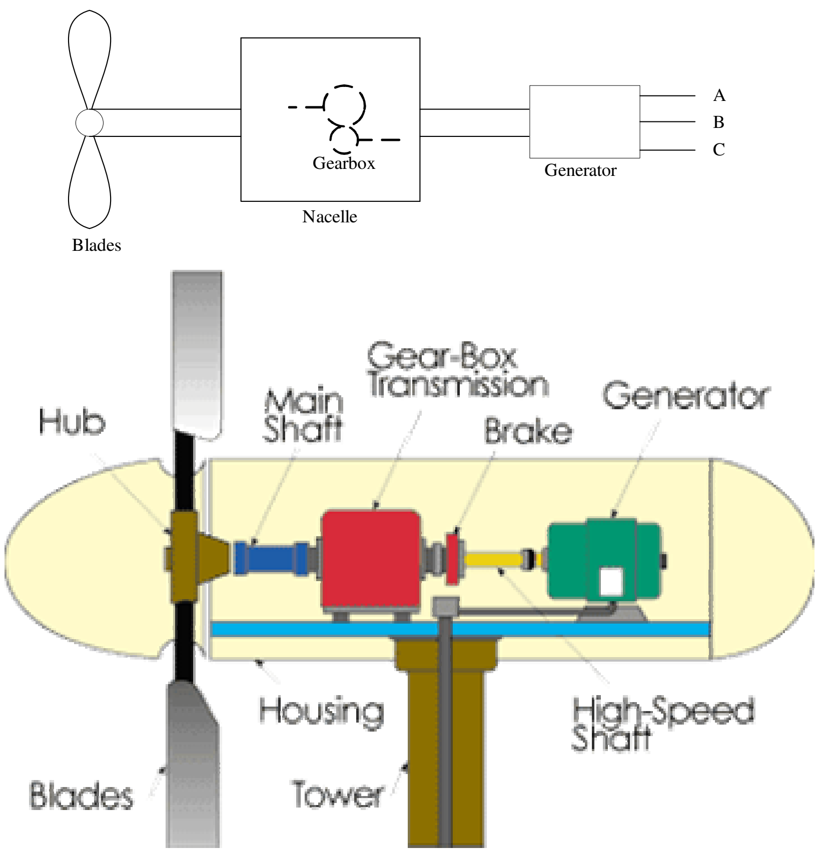

Figure 2: Schematic diagram of wind electricity generation[8]

Wind Turbine Selection and Grid Connection

The size or the generating capacity of a wind turbine for a particular installation depends on the amount of power needed and on the wind conditions at the site. A rough estimation of the wind conditions can be achieved from the United States Department of Energy[10], but to know the actual data, year round onsite wind energy measurement is needed, which could be conducted using a wind energy measurement tower. The second thing is to verify the power curve of the wind turbine. The power curve of a wind turbine is a graph that indicates how large the electrical power output will be for the turbine at different wind speeds. A typical power curve for the Vestas V80-1.8 MW wind turbine[11] is shown in Figure 3. Cost, maintenance, and size could be the variable used for appropriate selection of the wind turbine.

Wind turbines may be designed with either synchronous or asynchronous generators, and with various forms of direct or indirect grid connection for the generator. Direct grid connection means that the generator is connected directly to the (usually 3-phase) alternating current (AC) grid. Indirect grid connection means that the generator produces variable frequency AC. A back-to-back converter is placed between the wind turbine generator and the grid connection to synchronize with the grid. The variable frequency AC is converted to the DC and converted back to the AC again to achieve the required frequency. Harmonics produced by the converter switching action are filtered out. With an asynchronous generator this occurs automatically. After that an appropriate transformer is needed to make a connection with the grid.

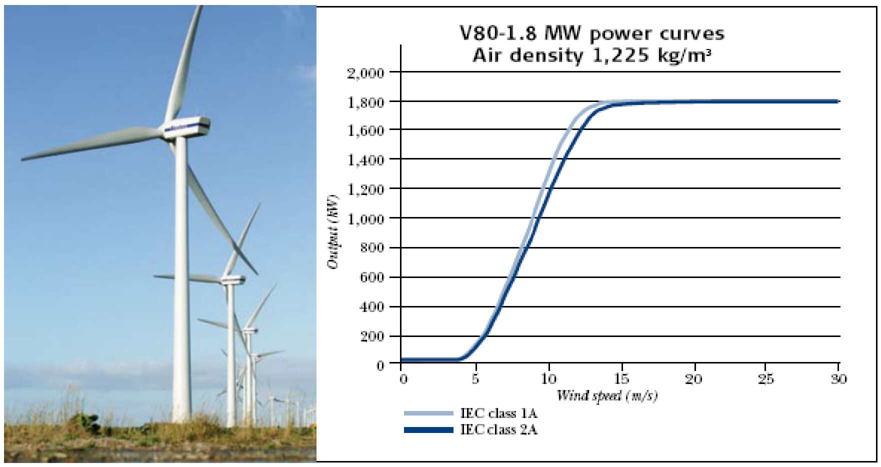

Figure 3: V80-1.8 MW wind turbine and its power curve[11]

Wind Electric Energy Simulation with Grid Connection

A simplified power system model with the wind turbine connection is shown in Figure 4. The SimPowerSystems toolbox in MATLAB/SIMULINK is used to conduct the simulation. The Power System Blockset (PSB) in the SimPowerSystem toolbox is developed in the graphical SIMULINK® environment of the general purpose MATLAB software. The PSB is suitable for the simulation of electric circuits, power systems, power electronic devices, and electric drives. It contains a block library with common components and devices available in electrical power systems based on electromagnetic and electromechanical equations. The PSB/SIMULINK can be used for modeling and simulation of the power systems. The SIMULINK solves the system equations based on state-variable analysis using either a fixed or a variable time step. The converter is included in the wind turbine module to synchronize with the gird.

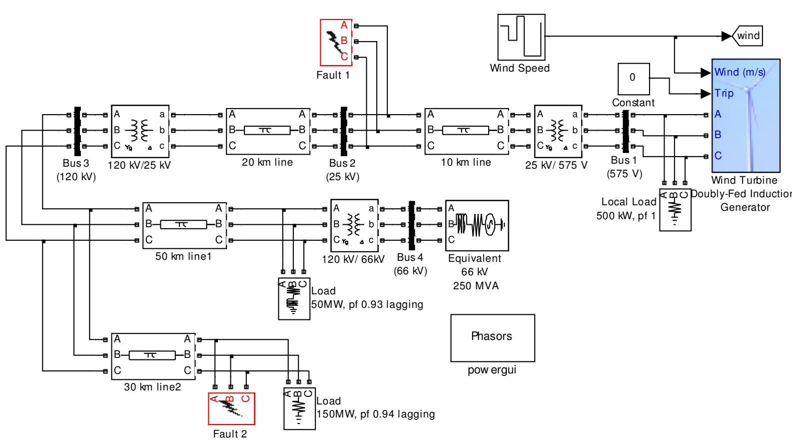

Figure 4: SIMULINK model of wind turbine grid connection

The wind speed is considered as a variable function with time; as a result, generated power from the wind turbine is also a variable function with time. Figure 5 shows the steady state voltage (p.u.) at bus 1, bus 2, and bus 3. Figure 6 shows the power generated from the wind turbine and the power at bus 1. The power at bus 1 is lower than the power generated because of the local load. Figure 6 also shows the variation of the power generation due to the wind speed variation.

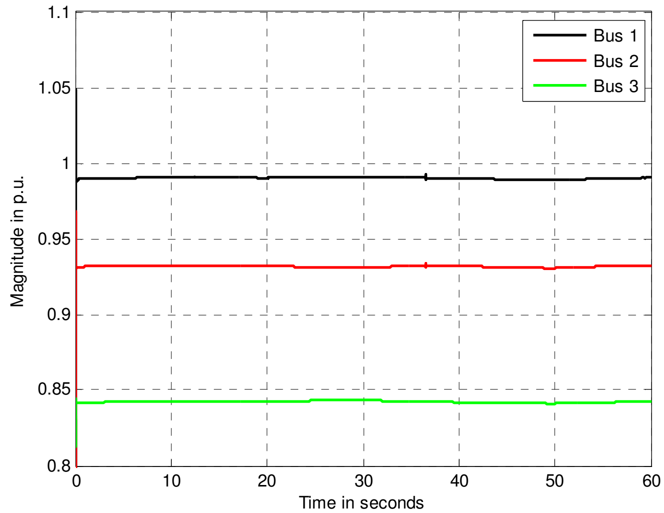

Figure 5: Steady state bus voltage in p.u.

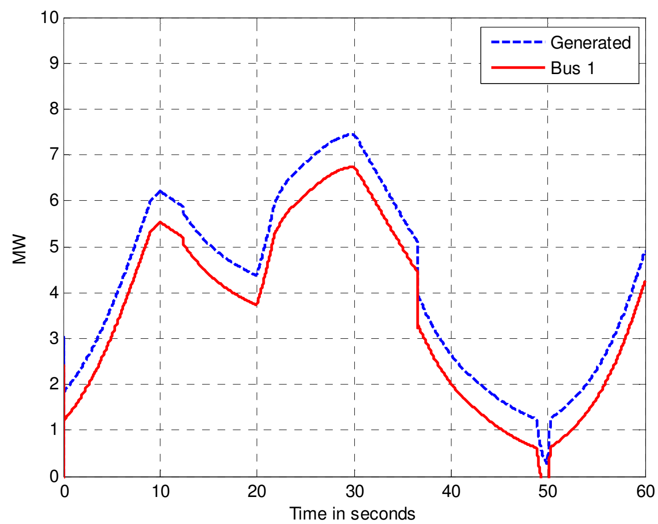

Figure 6: Wind turbine power generation and power at bus 1

The dynamic compatibility of the grid-connected wind turbine is studied using a short duration single-line to ground fault at bus 2. The voltage and the power at bus 1 are observed for the fault and shown in Figures 7 and 8. The voltages magnitudes of phase I and II are reduced to 0.6 p.u., and phase III experienced a 9% overshoot. But, all phase voltages came back to the steady state after the fault was cleared. During the fault, the power generation from the wind turbine went down with the generator acting as a motor, but came back to the normal operation as soon as the fault was cleared with a few transient oscillations.

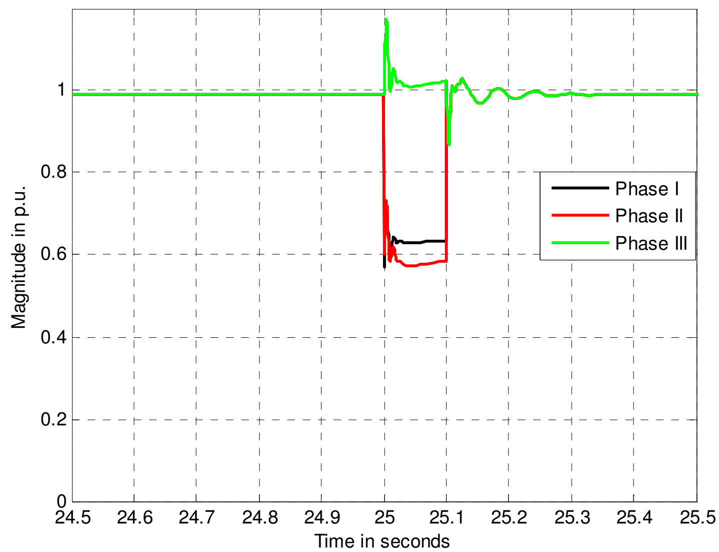

Figure 7: Voltage at bus 1 during fault

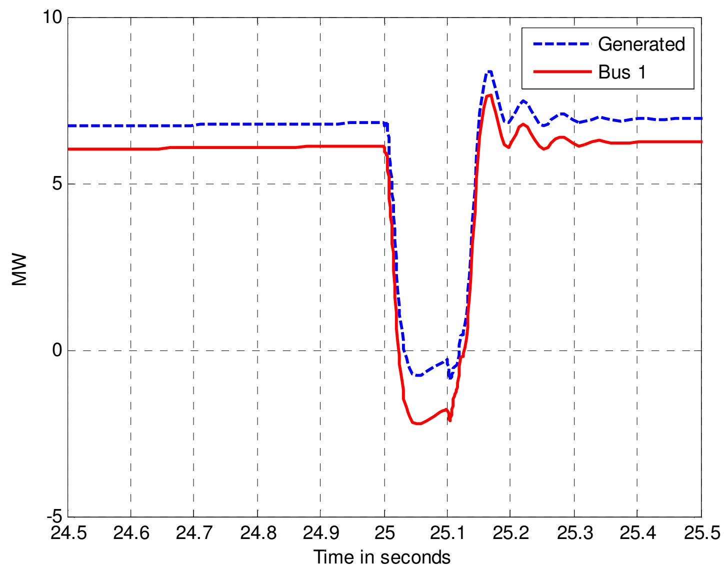

Figure 8: Wind turbine power during fault

Photovoltaic Electric Energy

The heart of photovoltaic (PV) electrical energy is the solar cell, which is a semiconductor device such as silicon that converts sun light into electricity. When photons in sunlight impinge on the solar cell and are absorbed by the semiconductor material, electrons are knocked loose from their atoms. This allows them to flow through the circuit to produce electricity. The complementary positively charged holes flow in the opposite direction of the electrons in a silicon solar cell. Solar cells produce the DC electricity, and an inverter is needed to convert the DC to the AC. Sometimes, the power generated by a single solar cell is not enough for a useful application. A group of solar cells are electrically configured into modules and arrays to produce a usable power level. Figure 9 shows a schematic diagram of the photovoltaic electric energy generation with an inverter. Some common applications of the PV are: distributed generation (grid-connected PV), water pumping at remote locations, powering remote/vacation homes, space stations, remote traffic signals, vaccine refrigeration in remote areas, rural communications, remote community recreation, etc. Figure 10 shows the photovoltaic water pumping application at a remote ranch in Wyoming, USA.

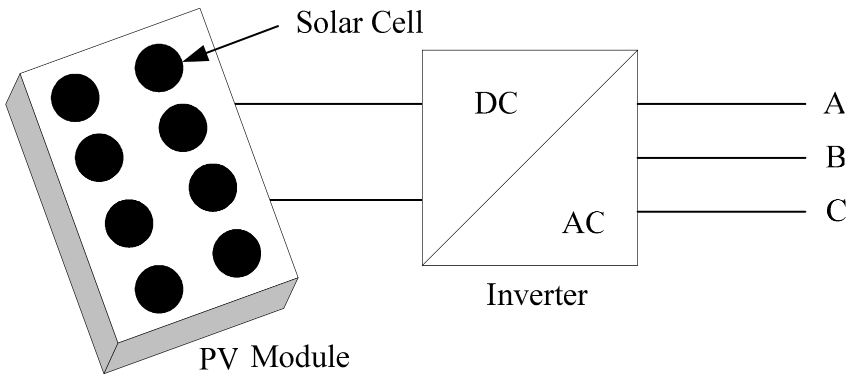

Figure 9: Photovoltaic Electric Energy Generation

Figure 10: Photovoltaic water pumping at a remote ranch in Wyoming, USA

Grid-Connected PV System – Laboratory Setup and Simulation

Four PV systems with a total capacity of 50 kW were installed on the University of Wyoming campus and three of them are located on the roof of the engineering building. Each PV system on the roof is capable of generating 5 kW and uses the Omnion 5 kW grid-tied inverter. Specially designed for interfacing with a power grid, the Omnion inverter synchronizes its output voltage with the phase and the frequency of the grid voltage. In order to push the power into the grid, the phase of the inverter current is slightly leading where the inverter is connected to the grid. There are many regulations and guidelines laid down by IEEE regarding the connection of a PV system to the grid. Among them, the system must not allow power flow into the solar array, thus, becoming a load not a source. The schematic diagram of the experimental model is shown in Figure 11. The synchronous generator allowed for a special wiring setup specially designed for a single phase output. A bank of inductors and resistive load banks are used for proper loading. Finally, the motor-generator is powered by an ABB variable speed drive. This ensured control of the output frequency meeting the tough specifications of the Omnion inverter. The PV array is connected at position 5 through an Omnion inverter and a single phase transformer. Voltage at position one is kept at 240V, or 1 pu. As previously mentioned, PowerWorld is a software package used to study power flow of a power grid. It uses the Newton-Raphson method for non-linear iterative solutions. Per unit values of 20A and 240V were used to determine the per unit impedance for the experimental model. PowerWorld bases its per unit analysis on an apparent power of 100MVA. By varying the line impedance values in a PowerWorld simulation, a close approximation to the model was found. The best calculated experimental values were Z = .333 + j.404 pu. The PowerWorld values were Z = .280 + j.360. Further, PowerWorld simulations with a distributed generation scheme would use the PowerWorld impedance number. The PowerWorld simulator model is shown in Figure 12.

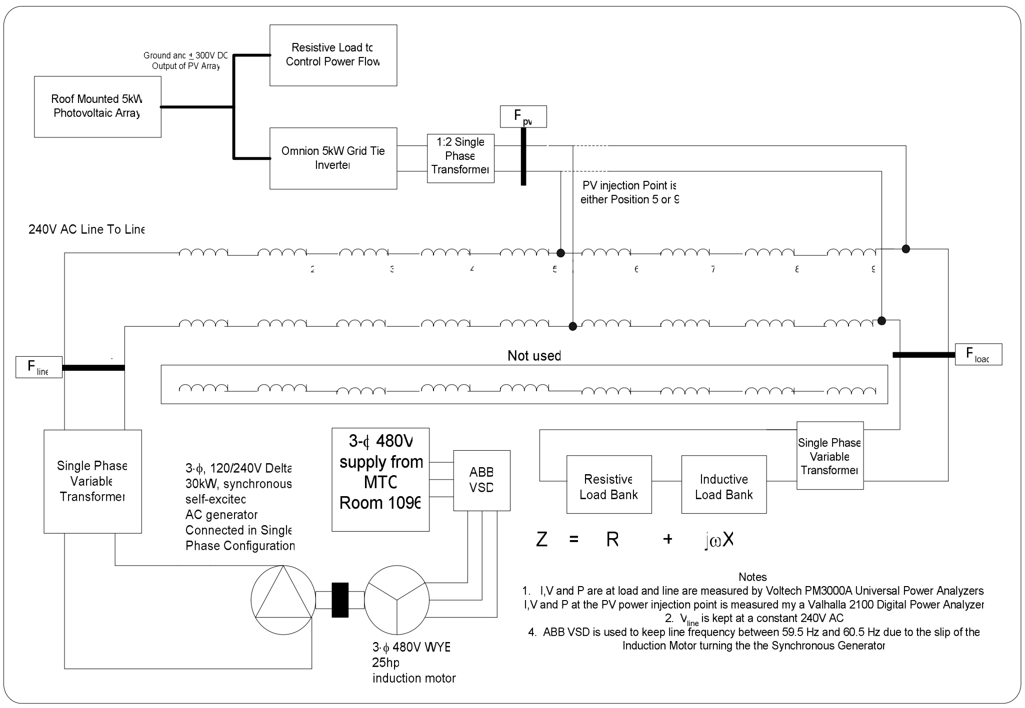

Figure 11. The schematic diagram of the experimental model

Figure 13 shows the receiving end voltage, V_R, versus the percentage of load power supplied by the photovoltaic system and the line load percentage versus the percentage of load power supplied by the photovoltaic system. In each chart, the corresponding PowerWorld simulation is shown. As the power supplied by the photovoltaic system increases, there is a corresponding rise in V_R as well. In each case, V_R increased at a linear rate from as the percentage of power supplied by the PV generation source increased.

Line load is another way of evaluating the performance of the grid-connected PV system. As the power from the PV system increases, there is a substantial drop in the overall distribution line load, which is shown in Figure 14. Interestingly, the line load does not drop at the same rate as the increasing PV power. In the 0.7 pf lagging case, when the PV is supplying 59.6% of the load power, the line load is at 82.93%. Without the PV, the line load would have been ~96%. While this is a ~13% improvement, the total power supplied by the PV is almost 60%. Benefits of a distributed generation scheme, including voltage support and the lowering of line load are very real and represent compelling evidence to support the argument of implementation of a widespread distributed generation system.

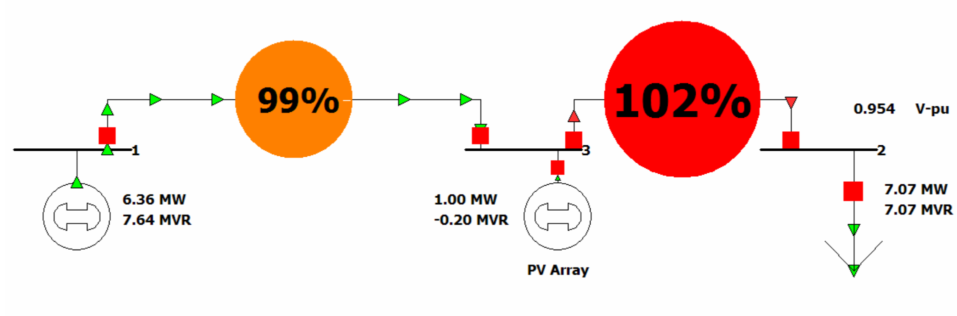

Figure 12: Simplified PowerWorld simulator model

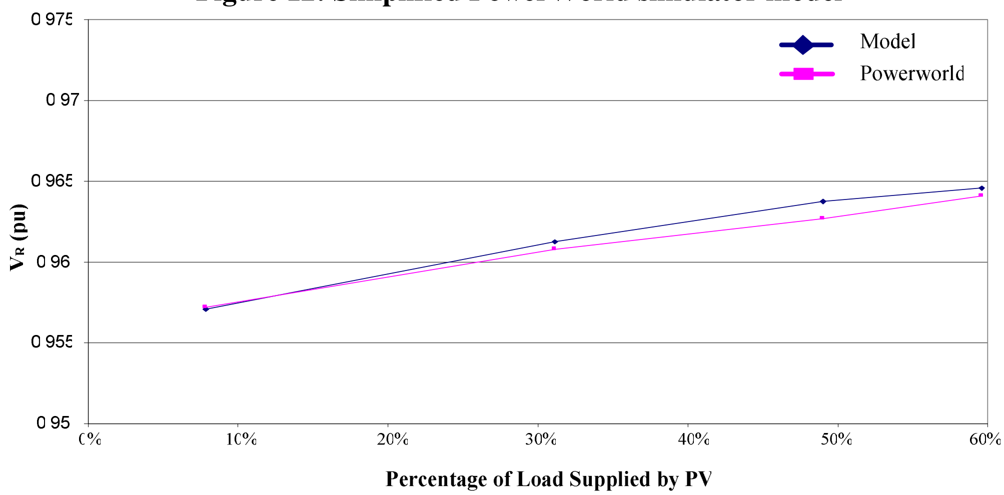

Figure 13: Receiving end voltage vs load supplied by PV

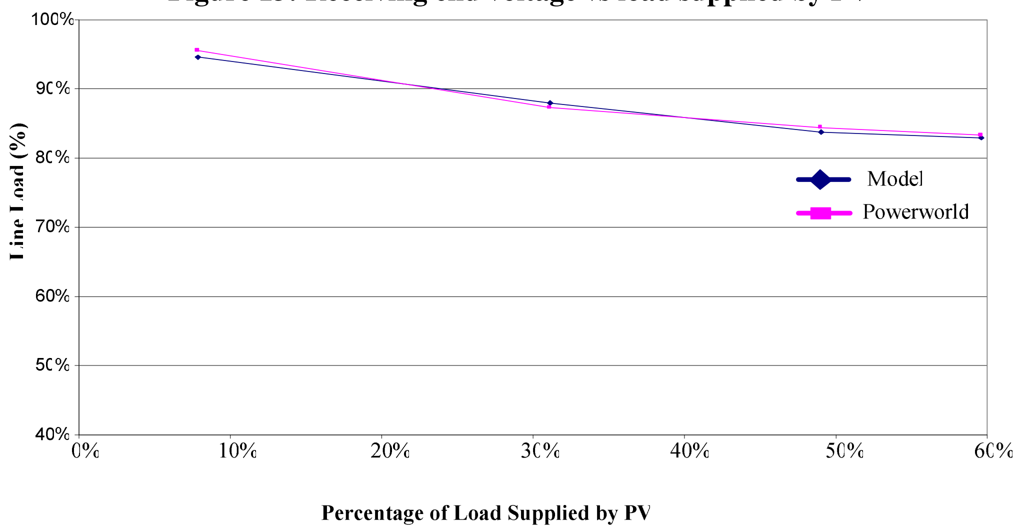

Figure 14: Percentage of Line load vs load supplied by PV

Feasibility Study

Feasibility studies are conducted for a 9 MW wind farm and for a 1 MW photovoltaic electric energy generation (PVEG) facilities, and both of them are considered 10 kilometers away from the grid. The capacity factor is considered as 30% for the both facilities. No taxes are considered for the calculation, because the USA is promoting non-hydro renewable energy with a 30% tax credit.[12] Table I shows the capital cost and the revenue for the 9 MW wind farm and for the 1 MW PVEG. All values in Table I are calculated using the following assumptions:

❖ *Wind Farm:*
- Plant cost $1000/kW
- Line Cost $0.05million/kilometer
- Electricity price 7¢/kWh
- O & M cost is 3% of the gross revenue

❖ *Photovoltaic Electric Generation:*
- Plant cost $3000/kW
- Line Cost $0.05million/kilometer
- Electricity price 7¢/kWh
- O & M cost is 1% of the gross revenue

Table I. Capital Cost and Revenue for the 9 MW Wind Farm and for the 1 MW PVEG

	Plant Cost ($ million)		Line Cost ($ million)		Total ($ million)	
	Wind	Solar	Wind	Solar	Wind	Solar
Capital Cost	9.0	3.0	0.50	0.50	9.50	3.50
Gross revenue/year	-	-	-	-	1.66	0.184
O & M/year	-	-	-	-	0.05	0.0018
Net revenue/year	-	-	-	-	1.61	0.1822

There are six key methods to rank the projects and to decide whether or not they are accepted: 1) payback, 2) discounted payback, 3) net present value (NPV), 4) internal rate of return (IRR), 5) modified internal rate of return (MIRR), and 6) profitability index (PI). To evaluate both the projects described above, the NPV and the IRR methods are used in this paper. The NPV can be calculated as,

$$NPV = \sum_{t=0}^{n} \frac{NR}{(1+k)^t} - C \qquad (1)$$

where NR is the net revenue per year, n is the project's life time (30 years for the both projects), C is the capital costs, and k is the project's cost of capital, which is considered 7% for the calculations. The payback period and the IRR can be calculated from equation (1) by setting the NPV to zero, and then k represents the IRR when n is a constant, and n represents the payback period when k is a constant. The net revenue and the project's cost of capital are considered constant throughout the projects life time, but in reality they might vary every year. The positive NPV indicates that the project is lucrative and the IRR is defined as that discount rate which equates the present value of a project's expected cash inflows to the present value of the project's costs[13]. Economic analysis are shown in Table II. The economic analysis show that the wind farm is highly lucrative and has a shorter payback period. On the other hand, the PVEG has a negative NPV, which indicates that the project is not economically viable. This is because of the high capital costs involved in the PVEG. Government incentive could make the PVEG also viable.

Table II. Economic Analysis of the 9 MW Wind Farm and 1 MW SPVEG

	Wind Farm	Solar Photovoltaic Electric Energy Generation
NPV ($ million)	10.47	-1.24
Payback period (Year)	8	-
IRR (percent)	16.8	-

Conclusion

Electric energy generation from the renewable resources is pollution free and highly demanded in the modern civilization. Educational background in alternative energy generation such as wind and photovoltaic technology would enrich the capability of the power engineering students. The combination of the simulation and the experimental setup would help the students to understand the energy generation concepts related to renewable resources and their grid connections. The grid-connected wind turbine was simulated using MATLAB/SIMULINK to study the steady state and the dynamic behaviors. Simulation results showed that the wind turbine is compatible with the grid during the steady state and the transient conditions. An experimental setup of a grid-connected photovoltaic system along with the PowerWorld simulator model was also studied. The experimental and the simulation results showed that a grid-connected PV system improves the voltage stability and lowers the line loading. Finally, an economic analysis was conducted to give student an introduction to wind and solar electric generation and transmission costs.

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