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Designing an Innovative Laboratory to Teach Concepts in Grid-Tied Renewable and Other Dispersed Resources

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Abstract

An undergraduate laboratory is designed for use as part of the energy conversion and power engineering areas of the curriculum. The proposed lab includes experimentation with dispersed resources (DR) in a utility-integrated mode. The most suitable DR types for the lab are photovoltaic and wind power sources, although other sources could also be used with some changes. Some of the issues that are becoming important in recent years, such as power quality, and renewable energy impact can be studied easily in the lab. At the same time, the lab allows conventional experimenting with machines. For situations where actual DR installations are not available, opportunities exist for simulating their characteristics.

1. Introduction

Dispersed resources (DR) are considered by many experts as promising and environmentally friendly solutions in the electric energy market of the future. Photovoltaic (PV) power, wind power and fuel cells are viable dispersed resources that are already gaining momentum. This paper describes the development of a laboratory for use in a typical undergraduate Electrical Engineering curriculum. The laboratory is a part of the energy conversion and power engineering areas of the curriculum. Most conventional laboratories that serve this area consist of ac and dc motors and generators. Lab experiments are usually limited to determining motor and generator characteristics. The lab described in this paper is a departure from the typical power lab. It is a multi-function laboratory that allows:

- testing of the varying nature of the intermittent generation from renewable sources
- the power quality performance of power conditioning units such as inverters
- the performance analysis of PV/inverter-driven dc or ac motors
- the performance analysis of inverters in the presence of electronic loads, which require some form of switching devices, and loads which are sensitive to voltage waveform distortions, sags and swells.
- monitoring of harmonic losses under different kinds of loads and feeder impedance (varying X/R ratios) characteristics.
- determining the impact of reactive compensation on the distribution feeder.

The laboratory is targeted for the areas of power systems, power electronics, electromechanics, and power quality. It is not meant to be the only lab for all these areas, but one that can prove certain concepts in all these areas with the added dimension of dispersed resources and also helps students to understand that many of the problems in power are multi-disciplinary in nature. The laboratory gives the flexibility to experiment with different feeder, load and dispersed resource characteristics. The driving force behind the lab is the development of a common technology that will provide the ability to experiment DR interconnection issues irrespective of the type of the system, the differences in the utility distribution network and the differences in the types of load. The differences in utility networks are manifested in the nature of transmission, such as rural systems exhibiting mostly radial feeders, and urban systems with inherent reduced power flow margins on feeders; summer or winter peaking operation; voltage-weak versus voltage-strong systems; presence of voltage control devices, etc. The variations in loads is brought about because of the possible combination of residential (mostly lighting and thermostatic), industrial/agricultural (mostly motor and electronic loads represented by adjustable speed drives), and commercial/institutional (lighting, thermostatic and electronic loads represented by computers, fluorescent lighting, and other specialty devices).

Classes of DR

Among the renewable resources for electric power generation, solar PV, solar thermal and wind can be classified under DR technology. Geothermal, biomass, and hydroelectric power generation technologies are not technically considered as dispersed resources because these resources are not available everywhere. Among other technologies that qualify for dispersed resources, the most promising is the fuel cell. The fuel cell works in a reverse electrolysis process producing dc electricity from a combination of Hydrogen and Oxygen. Unlike PV and wind power generations, electricity from fuel cells are very much similar to that from a conventional power plant except that it needs to be inverted to ac before synchronizing with the utility grid.

The experiments created for this lab only deal with PV at this time. The main reason is that a PV array exists on campus. Some of the technical issues with wind will be similar to PV because both produce intermittent power. Hence the discussion in this paper is equally applicable to other DR types, which produce dc electricity and need to have a dc/ac inverter for interconnection with the power grid.

2. Lab setup

A schematic of the laboratory setup for performing the experiments is shown in Fig. 1. The power from DR feeds into the distribution line represented by the variable resistance and reactance. The flexibility of placement of the DR system on any part of the feeder is indicated by repeated drawings of the same at different locations on the diagram. The ac generation side is represented by the motor-generator set connected to a utility feed. The distributed nature of the feeder impedance is represented by having several R (resistive) and X (inductive reactance) along the line. Shunt compensation is also represented along the feeder line.

A physical representation of the lab set up is shown in Fig. 2. The next section deals with some of the individual components of the setup.

2.1 PV system component

A 5 kW rack-mounted system was constructed on the roof of the University of Wyoming's Engineering Building [1]. The rack-mounted system did not require penetrations through the roof surface. The structurally engineered system utilized 35 pounds/sq. ft of ballast to withstand design wind loads up to 90 mph. The array features high-powered PV modules from ASE Americas. This system is shown in Fig. 2.

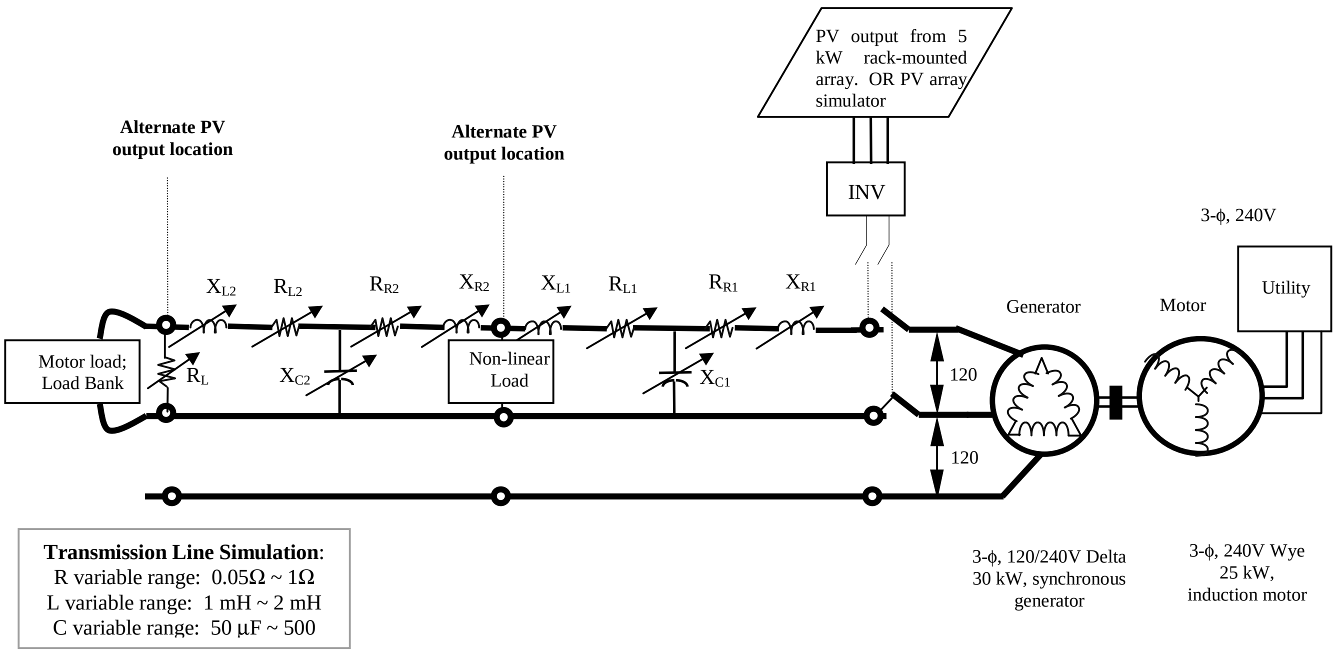

Fig. 1. A schematic of the lab setup

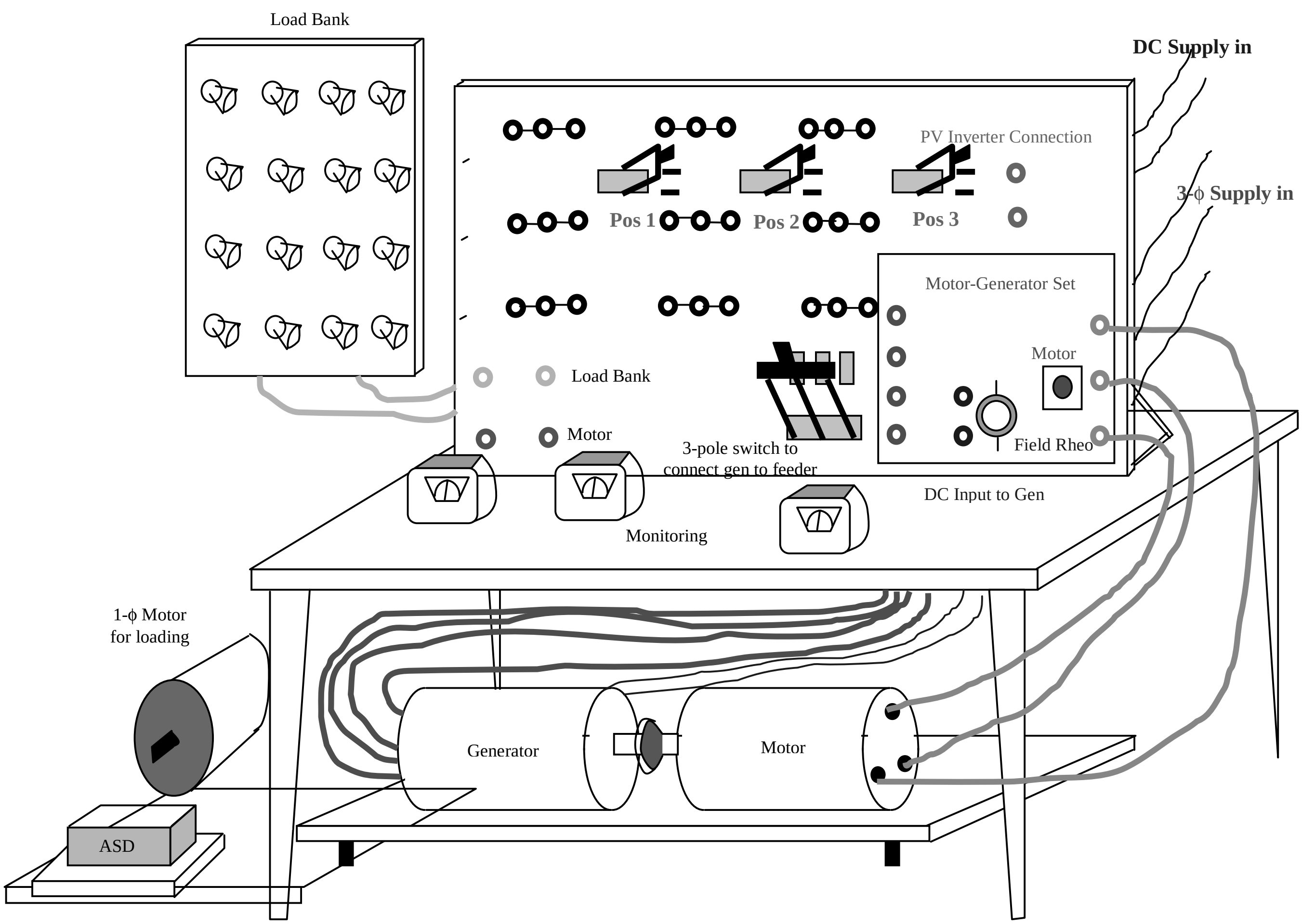

Fig. 2 Physical representation of the setup

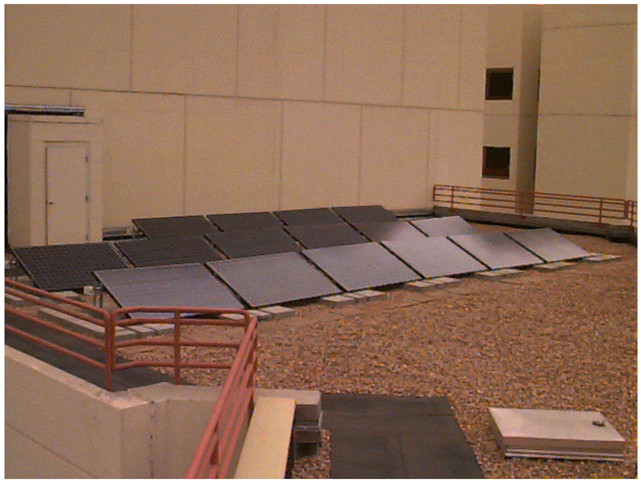

Fig. 2. The 5 kW Rack-mounted PV array

Figure 3a show the ac power output on June 25, 1997 – a very clear day - from the 5 kW rack-mounted PV system. Fig. 3b shows a plot of the total harmonic distortion (THD) present in the ac power output of Fig. 3a. As seen from this figure, the THD is at or below the acceptable limit as recommended by IEEE 519-1993 [2].

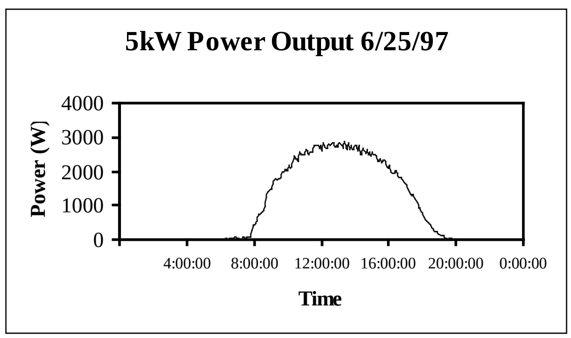

Fig. 3a. AC power output from a 5 kW PV system.

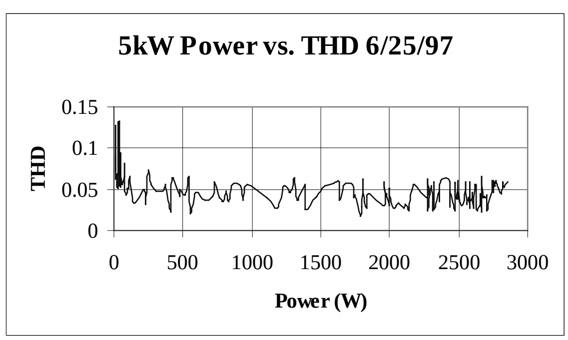

Fig. 3b. Total harmonic distortion from PV inverter connected to utility.

As an alternative, one can also use a simulator for PV power output. An example is Hewlett Packard's HP E4350A solar array simulator [3]. The E4350A duplicates the output of solar cells using an internal DSP to generate the requisite I-V curves of a cell.

2.2 Equipment Description

- Baldor Series 15H ASD: 1-phase 5 kVA or 3-phase 15 kVA, Constant torque PWM inverter control
- 1-phase, 15 HP, 120V induction motor
- 3-phase, 240 V, 25 HP, 60 Hz induction motor (for driving synchronous generator)
- 1 Marathon Lima 3-phase synchronous generator, 30 kW 1800 RPM, 12 lead, 240V delta connected stator; double bearing, SAE-3
- Resistive and inductive load bank
- Motor starter
- Resistors, inductors, capacitor of variable values; rheostat
- DC and AC load break switches
- DC power supply

2.3 Feeder design

The distribution feeder is represented by two cascaded T-model transmission line [4] as shown in Fig. 1. The right T side of the feeder model has subscript 1 and the left side has subscript 2. Both sides of the T model have equal values of resistance and inductance. By varying the values of R, X_L and X_C, one can achieve the characteristics of short, medium or long feeder lines. The diagram of Fig. 1 shows a 1-phase setup. However, capability exists to upgrade the setup to a full 3-phase system.

3. Experimentation

The power and energy topics that can be studied in the lab and the rationale are described below.

- PV and wind power systems can potentially decrease the need for conventional shunt capacitor compensation. This requires inverters that are capable of reactive power production. This lab allows experimentation with new power electronic system design for inverters.
- Different configurations of generation and demand on the system can be simulated. Various load mix scenarios: non-linear and electronic loads, leading and lagging power factors can be created.
- In radial distribution circuits, certain feeders can become over-stressed and distribution companies look for cost-effective solutions to relieve the stress by installing PV or wind power systems at remote ends of the feeder lines. This strategy also can reduce losses in the feeders. This lab setup provides the capability of feeders with variable resistance and reactance capability to simulate long feeder lines.
- Harmonic generation from inverters can be monitored. Conversely, the impact of utility distribution system power quality on inverter operation can also be monitored. Many distribution feeders are now having to deal with non-linear electronic loads, such as adjustable speed drive systems. This setup allows the monitoring of the performance of an inverter in the presence of such non-linear loads.
- Potential operation of dc motor directly from PV/wind power systems.
- Determination of the amount of energy savings by substitution of conventional energy.

- Possible power factor correction mechanisms can be studied.
- Conventional synchronous and induction machine operating characteristics can also be studied.

3.1 Experimentation to study feeder voltage profile, system losses, voltage regulation, etc.

The important steps in this experiment are provided below:

- Place PV power after inversion successively at position 1 (Pos 1 in Fig. 2), position 2 (Pos 2 in Fig. 2), and position 3 (Pos 3 in Fig. 2).
- For each position, load the remote end of the feeder with the induction motor and the load bank. Combination of reactive and inductive loads can be used at this remote end to create varying power factor loads.
- Then, determine the voltage profile along the feeder (that is, at the three positions). Calculate input power both from utility side and PV side, output power, voltage regulation and feeder losses.
- Design an optimal compensation scheme to obtain a preferred voltage regulation.
- Repeat the experiment without any PV output.
- Compare the electrical quantities.

3.2 Other Experimental layout

Two other experiments that can be performed with the same lab setup are shown below. These include experimentation with the adjustable speed drive system to determine impact of non-linear loads on the PV inverter operation. Quantifiable parameters are total harmonic distortion on the utility input side, as well as the PV inverter side, and the inverter efficiency. Students will learn to correlate the theory on power quality analysis using with data from the experiment. The setup is shown in Fig. 4.

The other experiment is the operation of a dc motor directly from a PV array. Since an inverter is not used, a separate maximum power point tracker (MPPT) has to be used as shown in Fig. 5. Since the voltage and current of a PV cell depends on the amount of solar radiation, an MPPT is required to always detect the maximum power output of the PV array.

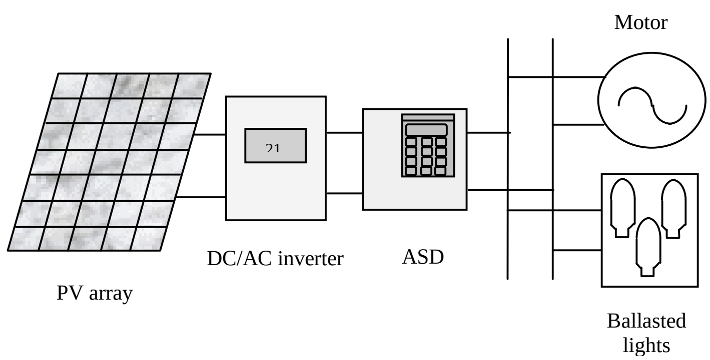

Fig. 4. PV in the presence of Non-linear loads

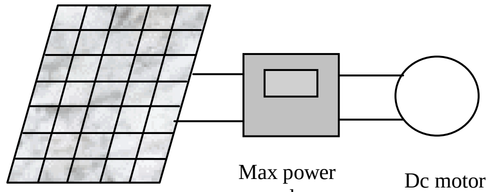

Fig. 5. Direct dc motor operation with PV

4. Discussion and Conclusions

The lab described in this paper grew out of a research project initiated under the US Department of Energy's EPSCoR [5] program. The project deals with characterizing the electrical systems aspects of a PV system. At the same time, it was felt necessary to create lab experiments for the undergraduate Electromechanics class. Many power engineering curriculums around the US are currently undergoing significant changes in the face of power industry restructuring [6, 7]. Some are overhauling their core power course to include renewable resources, environmental impact, distributed resources, and power electronics. The lab described in this paper introduces a concept for studying the impact of dispersed resources in electric utilities. While some new experiments are outlined, there are several others that can be created with some thought. The setup cost of the lab is somewhat high given that PV and wind power system capital cost can be rather high. An alternative is to simulate the characteristics of these resources by hardware.

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6. Acknowledgments

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Badrul H. Chowdhury obtained his B.S degree in Electrical Engineering from Bangladesh Univ. of Engr. & Tech., Dhaka, Bangladesh in 1981. He obtained his M.S. and Ph.D. degrees also in Electrical Engineering from Virginia Tech, Blacksburg, VA in 1983 and 1987 respectively. He is currently an Associate Professor in the Electrical & Computer Engineering department of the University of Missouri–Rolla. From 1987 to 1998 he was with the University of Wyoming's Electrical Engineering department where he attained the rank of Professor. He has served as the Principal Investigator in several engineering education-related projects sponsored by the US National Science Foundation.