Photovoltaics and Its Role in Power Quality

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Abstract— **A descriptive overview of photovoltaic systems and basic support equipment is offered, along with a short discussion of applications and technical/economic feasibility of photovoltaic systems. The use and electrical characteristics and power behavior in terms of power quality is discussed for off-grid and on-grid inverters. Specific issues of power quality applicable to inverters are stated along with typical solutions.**

I. INTRODUCTION

THE rising cost of fossil fuels, diminishing supply of these fuels, and increasing environmental concern have promoted renewable energy development. For solar energy, specifically photovoltaics, most applications go directly to the end user instead thorough utilities. This happens due to the intrinsic nature of this technology, which does not require centralization, combined with high capital costs that impede profitable energy sales. Solar energy is used by consumers in order to reduce operational costs, take advantage of government incentives, increase power reliability and quality, decrease vulnerability to fuel cost changes, and contribute to environmental protection on a voluntary basis or due to regulatory pressure.

II. PHOTOVOLTAIC SYSTEMS OVERVIEW

Photovoltaic technology implies direct energy conversion from light to electricity. This conversion occurs in a solid-state medium of electronic grade silicon as the most common commercially available material. A typical silicon photovoltaic cell is shown in figure 1. This cell is composed

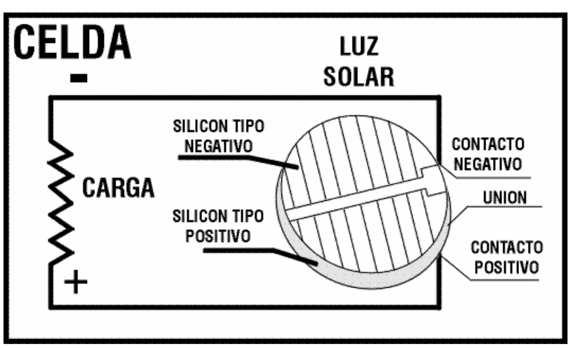

Fig. 1. Diagram of a typical photovoltaic cell.

of two thin silicon wafers sandwiched together. The upper cell wafer is carefully doped or "polluted" with phosphorous to make the wafer negatively charged; it is denominated type N. The bottom wafer is then doped with boron to make it positively charged; this wafer is denominated type P [1]. Visible light spectrum photons hit the photovoltaic cell surface and are absorbed at the union region, freeing electrons at the cell. Finally these electrons run through an external circuit producing electricity. Therefore a photovoltaic cell is essentially a diode.

Photovoltaic cells are generally interconnected in series or parallel combinations in order to obtain any current or voltage values or levels required. A group of interconnected and framed photovoltaic cells is called a photovoltaic module. Interconnection of two or more photovoltaic modules is called a photovoltaic panel. Groups of interconnected panels are called photovoltaic arrays. Photovoltaic modules, panels, or arrays are integrated with other components such as batteries, static converters, regulators, controls, and support structures in order to have an operational photovoltaic system as shown in Figure 2.

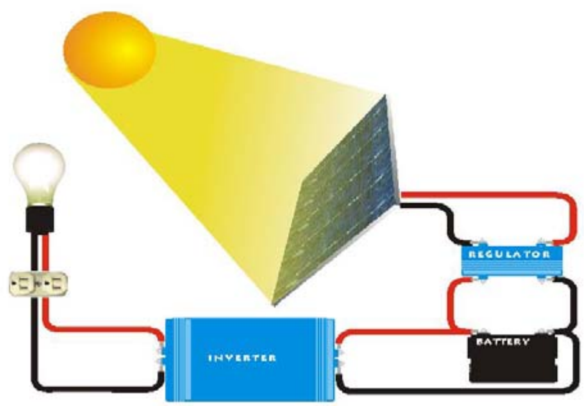

Fig. 2. Diagram of an operational photovoltaic system.

Cell efficiencies are in the range of 6 to 32% for amorphous silicon cell material and concentrator cells respectively. This efficiency is determined by the absorbed solar energy percentage in a one m^2 collecting area at a standard condition solar radiation of 1,000 watts per square meter, known as "one sun". The capacity factor of photovoltaic systems is around 11 to 40%, depending on location, while the availability factor is typically 95%[2]. Electric Power generated by photovoltaics is DC and depends mostly on solar radiation, although cell temperature also affects efficiency, as shown in figure 3. As temperature increases, cell efficiency decreases slightly under typical terrestrial temperature ranges.

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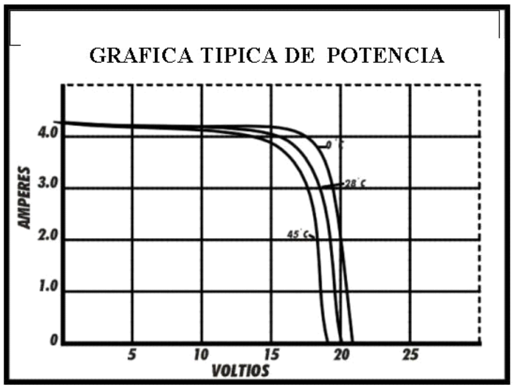

Fig. 3. Typical power curves for photovoltaic modules

Technical and economic feasibility of photovoltaics generally depends on geographic location and type of application. For example, although concentrator photovoltaic modules are more efficient than flat plate modules, they are not feasible in Puerto Rico, and similar tropical climates were diffuse radiation is dominant. A water pumping system for livestock will more likely be feasible than a outdoor public lighting application because the energy demand for the water pumping application matches energy resource availability time. For the lighting application, the load time does not match the energy availability time; therefore a more complex and less efficient system is needed. However, feasibility could dramatically change if, for example, the public lighting system is located two miles from the nearest power line, and the water pumping system is located at a farm with readily available power lines. In short, we can conclude that more work is needed in the early stage of project design than at detailed design and implementation stage. This is one of the biggest barriers for photovoltaic systems, because it is not common to find clients with the patience and resources to allow research for alternatives. Photovoltaic system costs for Puerto Rico range between 8 to 18 dollars per Watt installed with payback periods that can be immediate or up to more than 30 years depending on the specific application or project variables. Typical uses of photovoltaic systems are water pumping, communications, lighting, security equipment, measuring equipment, and providing electricity to common electric appliances that use electricity efficiently. The following list shows electrical equipment that is typically powered with photovoltaics:

LISTING OF TYPICAL ELECTRIC APPLIANCES POWERED BY PHOTOVOLTAICS

-radios	-fans
-TV sets	-respiratory therapy machines
-VCRs	-garage doors
-stereos	-electric gates
-cellular phones	-security systems
-telephone systems	-high efficiency refrigeration
-fax machines	-battery chargers
-computers	-calculators
-printers	-cash registers
-photocopiers	-power tools
-cameras	-water pumps
-lights	-water purifiers

Photovoltaic system design and installation must comply with the NEC, Section 690 and other local applicable codes and regulations. For the specific case of grid connected photovoltaic systems, the IEEE P929, "Recommended Practice for Utility Interface of Photovoltaic (PV) Systems," must be followed. All photovoltaic components should be UL listed, when available, including inverters that have passed UL 1741 tests.

III. Photovoltaic Systems and Inverters

Static converters called inverters are common in photovoltaic systems where AC power is required. Inverters for photovoltaic systems are available for 120 volts, 1 ph and 120/240 volts 1 ph, and other common grid configurations worldwide including 3 ph systems. Small photovoltaic systems are considered to be those less than 10 kW, medium size as no more than 500 kW, and large size as any above that range [3]. There are two principal configurations of photovoltaic system; stand-alone systems and grid connected systems. The inverters are the main component that differentiates these two possible configurations. Stand-alone inverters are used for off-grid applications that typically use batteries for energy storage and for DC voltage regulation. The grid connected only inverters are for systems that do not use batteries. Stand alone/grid connected inverters can operate either on or off the grid. Most modern inverters are self-commutating machines, which means that they supply their own switching signal. Older inverters, especially for grid-connected applications, were line-commutated machines, which means that they used the original grid line voltage to produce their own switching signal. Power electronics progress in switching speed and increased power handling capabilities has made line commutated inverters somewhat obsolete. This is due to higher cost of line-commutated inverters and lesser ability to respond to sudden changes of grid parameters. Inverters for stand-alone systems can be either modified wave type or true sine wave. Modified wave inverters have a quasi-sine wave shape output with some harmonic content, which produces some slight interference with some appliances, such as making electric clocks run slower or faster; making inductive loads such as magnetic florescent ballasts and motors to hum; and causing noise interference on AM radios, TV sets and sometimes cordless phones. These problems were typically resolved by installing the inverter further from loads, by trying different appliances, or with the use of filtering. Since the power electronics of modified type inverters is simpler than true sine type inverters (which produce a clean sine wave, have less harmonic content, and are more energy efficient), it was at one time an economic choice to compromise efficiency and power quality. At the present, however, modified sine wave inverters are being phased out and replaced by true sine inverters. This is mainly because less expensive true sine inverters are coming onto the market, making it unnecessary to compromise efficiency and power quality. Stand alone/grid connected type inverters are true sine generators in order to accomplish grid interaction. Grid connected only inverters are of course, true sine generators for the same reason as stand-alone/grid connected inverters. New grid connected only inverters are more efficient due to the application of maximum power tracking capabilities to maximize solar energy harvest. A typical installation of a multifunction inverter for off-grid and on-grid photovoltaic applications with its support components is shown in figure 4 below.

Fig. 4. Multifunction inverter with support components.

IV. Uninterrupted Power Service (UPS) Inverters

Inverters, either modified or true sine wave type, used for UPS are basically the same used for photovoltaic stand alone application. Some of these inverters are connected to a manual transfer switch in order to perform this task. Other inverters are equipped with an automatic transfer switch that operates in the absence of grid power and is disconnected from loads after grid power is reestablished and enough time has elapsed. Some of this kind of inverters is equipped with battery chargers to perform battery charging from utility power.

V. Inverters and Power Quality Issues

Inverters are typically a current source type that works near the unity power factor, although voltage source type inverters are available for special applications where reactive power is required. Due to their modern power electronic architectural design, inverters have the advantage over rotational machines that they do not have inertia, and corrective response to electrical disturbance can be achieved as low as half a cycle. Inverters incorporate safety protection features at the load side for stand-alone and grid connected types as well to their interconnection with the grid, specifically for grid connected only inverters. For the load side, inverters are protected or designed to be turned off as a result from overloads, under voltage, over voltage, and over temperature events. For grid-connected inverters, protection schemes from and to the grid are incorporated also. Typically these inverters are protected from under/over frequency and under/over voltage from the grid. Acceptable harmonic levels of photovoltaic systems with inverters connected to a utility are defined in IEEE Standard 519-1992 "Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems," Chapter 10 which is titled "Recommended Practices for Individual Customers". Generally, and based on my own experience, photovoltaic systems with acceptable harmonic levels are successfully installed if correct wire sizes are used and one point grounding is achieved with same size wire as the larger AC current carrying conductor. However, this experience is based on the customer side. There are very few photovoltaic systems installed in Puerto Rico, of which a negligible number are connected to the island utility grid. There is not enough practical experience in Puerto Rico, compared with the other parts of the world to offer confidence to the local utility fair grid operation in a potentially high proliferation scenario of photovoltaic systems interconnected with the utility grid; therefore, further research and demonstration projects must be done on this topic. Photovoltaics as a renewable energy technology has a high potential worldwide to play an important role in the emerging distributed generation scheme. This is even more feasible in places like Puerto Rico, where the residential and commercial electric energy market sectors are larger than the high demand centralized industrial sector. An example of support for the fundamental research effort and demonstrate feasibility is the photovoltaic laboratory recently installed in the Center for Research and Development of the University of Puerto Rico, Mayagüez Campus. The lab equipment consists of two complete photovoltaic systems, one equipped with a multifunction inverter capable of performing off and on grid operation with 100 Ah of battery storage at 48 vdc. The other photovoltaic system consists of a grid connected only inverter with maximum power point tracking capability. The photovoltaic array size for these photovoltaic systems totals one kW and is capable of different selectable configurations. A line diagram for the photovoltaic lab is shown in figure 5.

This facility will be used to address power quality issues of distributed generation sources with respect load and utility side.

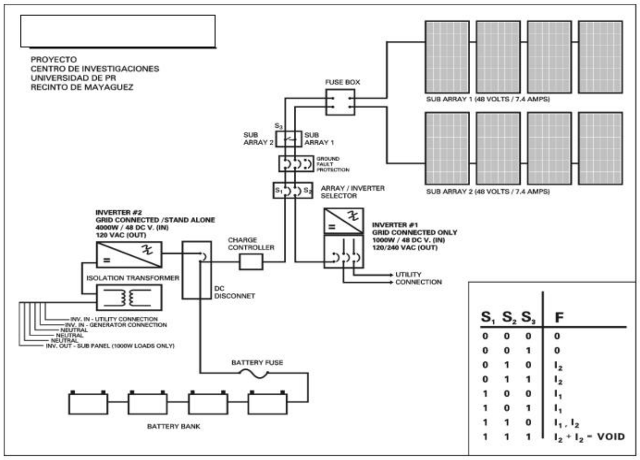

Fig. 5. Line diagram of the University of Puerto Rico Photovoltaics Lab.

One central specific power quality issue for photovoltaics regard utilities standpoint, is that photovoltaic system and servicing loads shall be protected from islanding occurrence. Islanding is defined in IEEE 929 as a condition in which a portion of the utility system, which contains both load and generation, is isolated from the remainder of the utility system probability. Modern inverters avoid islanding occurrence by using the utility voltage and frequency as a reference. If utility voltage and frequency are within acceptable levels, the inverter will provide to the utility or loads the current available from the photovoltaic array. If the utility signal is not there for comparison, the inverter will not deliver current and will shut down. Possible DC current injection to the utility grid, which is also an issue, can be prevented by two methods. One method is the use of an isolation transformer and the other method is the use of microprocessor based controlled digital filtering.

VI. CONCLUSION

Photovoltaics as a renewable energy technology has a high potential to play an important role as a distributed generation option in Puerto Rico, especially for the dispersed residential and commercial electric energy sector, compared with the smaller high demand and centralized industrial sector. Sufficient research, development, and commercialization of photovoltaic equipment has been done worldwide to bring reliable photovoltaic equipment onto the market for grid connected applications for which power quality issues for both load and utilities have been addressed. Individual customers in Puerto Rico have practical experience for off-grid and on-grid applications; however, more experience with photovoltaic systems performance from the utility perspective has to be gained to increase the confidence of the local utility as well the local government. With this experience, it will be easier to implement an incentive package for residential and commercial customers in order to reduce Puerto Rico's dependence on fossil fuels and increase the reliability of utility service.

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VIII. BIOGRAPHIES

Gerardo Cosme Nunez, P.E. graduated from Kansas State University in Electrical Engineering and Physical Sciences in the area of environment. He is founder of Solartek in Puerto Rico, and works a consultant and contractor in energy efficiency, renewable energy and related environmental and new product development matters for government, private, and academic sectors. He has practical experience in the utility sector in generation, planning processes, distribution maintenance and upgrade, power quality, and reliability assessments. His special fields of interest include the development of power management controllers for distributed energy sources and new energy related product development. He is a member of the IEEE, an active member of the Institute of Electrical Engineers of the Puerto Rico Association of Engineers and Surveyors, and a member of the Puerto Rico Chamber of Commerce where he has served as President of their Energy Committee.

Benefits of Storing Electric Energy from Wind in Puerto Rico

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Abstract – Use of an Energy Storage System (ESS) only to convert a wind park from an energy source to a power source could have an excessive cost. On the other hand, electric energy storage could provide solutions to already identified needs in Puerto Rico's electric power network tilting the economic analysis balance in favor of eolic generation. Rapid response spinning reserve, frequency control and reactive support are three of the potential benefits of using electric energy storage in Puerto Rico.

Keywords – electric energy storage, wind generation, spinning reserve, frequency control, reactive support.

1. Introduction

Several studies have been conducted in Puerto Rico to determine wind energy potential [1], wind resources estimates [2], the viability of wind energy conversion systems [3], wind farm assessment [4], wind power capacity value [5], and wind resource maps [6]. Despite these efforts a continuous argument against eolic electric generation is the random nature of the prime energy source, the wind. The use of energy storage resolves this problem at a considerable cost since usually storing significant amounts of electricity is expensive. If the Energy Storage System (ESS) is used only to convert the wind park from an energy source to a power source the cost of the ESS could be excessive. In the other hand, using the stored energy to alleviate other problems could make the ESS economically feasible.

Rapid response spinning reserve, frequency control and reactive support are three of the potential benefits of electric energy storage in Puerto Rico. Previous studies [7,8,9] have shown that a Battery Energy Storage System (BESS) is an economic alternative to provide rapid response spinning reserve as well as frequency control [10]. Conversations with the Puerto Rico Electric Power Authority (PREPA) personnel as well as a recent study [11] indicate the need for additional reactive support on Puerto Rico system under specific circumstances. One or more properly located ESS may provide the needed reactive support.

The combination of current developments in electric generation from wind, relatively high cost of electricity and inclusion of the benefits derived from energy storage could tilt the economic analysis balance in favor of eolic generation projects in Puerto Rico. This article intent is to spur this discussion.

2. Wind Resource in Puerto Rico

All studies to determine wind energy potential in Puerto Rico indicate that the best wind resource is located in the North and East coasts of the Island as shown in Figure 1.

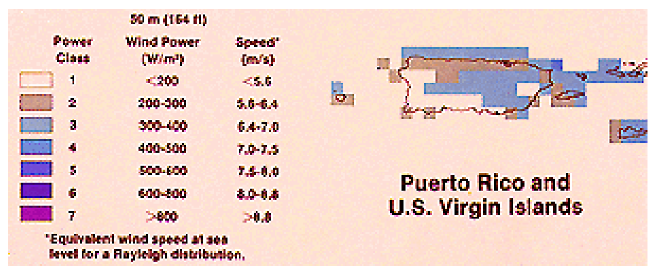

Figure 1. Annual average wind resource for Puerto Rico and the U.S. Virgin Islands (from US Wind Resource Atlas).

Most of the studies already mentioned have estimated wind energy potential using the arithmetic mean wind speed. It has been shown that a more accurate estimate of available energy can be obtained using cubic mean wind speed [12]. Equation 1.1 shows how to calculate both.

$$\bar{v} = \left[\frac{\sum_{i=1}^{N} f_i v_i^n}{\sum_{i=1}^{N} f_i} \right]^{1/n} \qquad (1.1)$$

where $\bar{v}$ is the mean wind velocity, v is the actual wind speed in m/s, f is the frequency of wind speed, n =1 for arithmetic mean, n =2 for root mean and n = 3 for cubic mean.

There is an on going effort at UPRM to use available data [1,4] to better estimate wind energy potential using cubic mean wind speed for the East coast of Puerto Rico. Preliminary results show that a single 110 kW commercially available turbine could generate from 7.4 MWh per month (May) to 28 MWh per month (November).[1] Thirty of these turbines could generate a similar amount of energy in just one day for any given month. These turbines, with 30 m rotor diameters, could be generously spaced 10 diameters apart in the prevailing wind direction and 5 diameters apart in the direction perpendicular to the prevailing wind occupying between 1 km^2 and 2 km^2.

Several small wind farms like this could be installed in the North and East coast of Puerto Rico. Wind farms could be installed inland, in the Islands of Culebra and Vieques for instance, or offshore in the North coast. The cost of using energy storage to convert these wind farms from energy producers to power producers can outweigh the benefits. Therefore it is necessary to consider other benefits of the ESS to make them economically feasible.

3. INMEDIATE BENEFITS of ENERGY STORAGE for PUERTO RICO

We have noted that rapid response spinning reserve, frequency control and reactive support are three of the potential benefits an ESS for Puerto Rico. We elaborate our argument in the following sections.

3.1. Rapid Response Spinning Reserve

In any power system, the failure of a generator unit changes the ratio of demand to on-line generation capacity instantaneously. This change causes a corresponding decline in the speed of the remaining generators and consequently in the frequency of the electricity that these generators produce. Uncorrected, the decline in frequency can damage the remaining generators and within a few seconds, cause the collapse of the entire power system [13]. Unless sufficient generation with the ability to rapidly increase output (rapid response spinning reserve) is available, the decline in frequency will be largely determined by frequency sensitive characteristics of the loads and by the magnitude of the overload. In many situations, the frequency decline may reach levels that could lead to tripping of steam turbine generating units by under frequency protective relays. To prevent extended operation at lower than normal frequency, load-shedding schemes are employed to reduce the connected load to a level that can be safely supplied by available generation [14].

The Puerto Rico Electric Power Authority (PREPA) identified its island condition and the relatively large size and slow response of its generating units as main factors leading to unacceptable system performance (blackouts) when generation deficiency occurs. The study described in [8,9] evaluated possible energy storage solutions, Battery Energy Storage Systems (BESS) vs. Superconducting Magnetic Energy Storage (SMES), to Puerto Rico's rapid response spinning reserve insufficiency under generation deficiency conditions.

The combined results of our study showed that the most economical solution to the problem was a BESS unit with stored energy requirement of 7.7 MWh. This capacity is sufficient to allow the start-up of gas turbine units to maintain the reserve power of the BESS.

A SMES plus diesels option, a combination that will keep the required power output over a five minutes period or more, will also solve the problem. The SMES plus diesels solution present value was calculated as $133 million. The 60 MW BESS present value was calculated as $104 million, $29 million less than the SMES plus diesels solution.

Note that the required 7.7 MWh of stored energy could be produced from a relatively small wind park as noted before.

3.2. Frequency control

Frequency control is a critical operating problem on any island electric utility. The lower inertia of island systems causes frequency to deviate rapidly as the load and topology of the system changes. These deviations have a negative effect on the quality of power. Therefore, means for fast acting frequency control are required.

An ESS can be very useful executing frequency control. The following example, taken from [10], will illustrate this point. Allow only the ESS to perform frequency control. All the other system governors will have a large deadband so that they will not respond to normal frequency deviations. A deadband of frequency error is defined for each ESS, which is ±0.05 Hz and maximum ESS power for frequency control is set to ± 30 MW. Figure 2 shows the frequency error function for the ESS [10].

[1] From "Study of Wind Resource for the Fajardo Zone", INEL 6025 homework by José A. García-Pérez, October 2002.

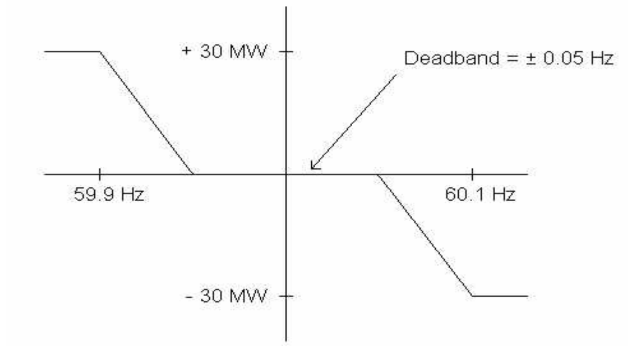

Figure 2. Frequency error function.

Further assume that system redispatching will be performed every 3 minutes, with a load pick-up rate of 15 MW/min. In this example the load is increased by 20 MW two minutes after the last redispatching, frequency decreases to 59.895 Hz, after a minute the system is redispatched again through the AGC and frequency returns to 60 Hz. After two minutes of the last redispatch the load is decreased by 20 MW, frequency increases to 60.106 Hz. A minute after the change in load, the system is redispatched again and the frequency is corrected to 60 Hz.

Figure 3 shows the frequency control performed by the ESS. The frequency stays between 59.94 Hz and 60.06 Hz. Figure 4 shows the output power of the ESS.

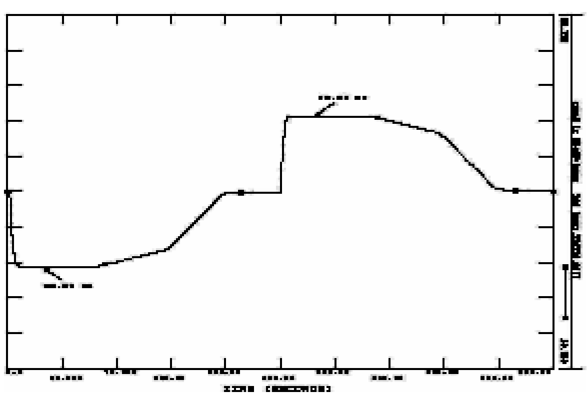

Figure 3. Frequency control

Such control action can be performed with a fraction of the 60 MW needed for rapid response spinning reserve.

3.3. Reactive support

SMES store electrical energy as a dc current, while the electrical grid is connected to operate with ac currents. BESS stores energy chemically but the electric reaction at the battery terminal is also DC. Hence, for these two ESS an intermediary must be inserted between the ESS and the electrical system — a Power Conditioning System (PCS).

The PCS acts as the power interface between the energy store and the utility system by performing a bidirectional energy transfer between the two as is schematically depicted in Figure 5. The PCS can also generate or absorb reactive power from the utility system concurrently with the real power exchanged. The ratio of real and reactive power exchanged at any instant can adjusted by an external system controller in response to system conditions. The PCS could be designed with the capability to deliver any combination of real and reactive power instantaneously within its rating envelope (and capacity of the energy store) as illustrated in Figure 6.

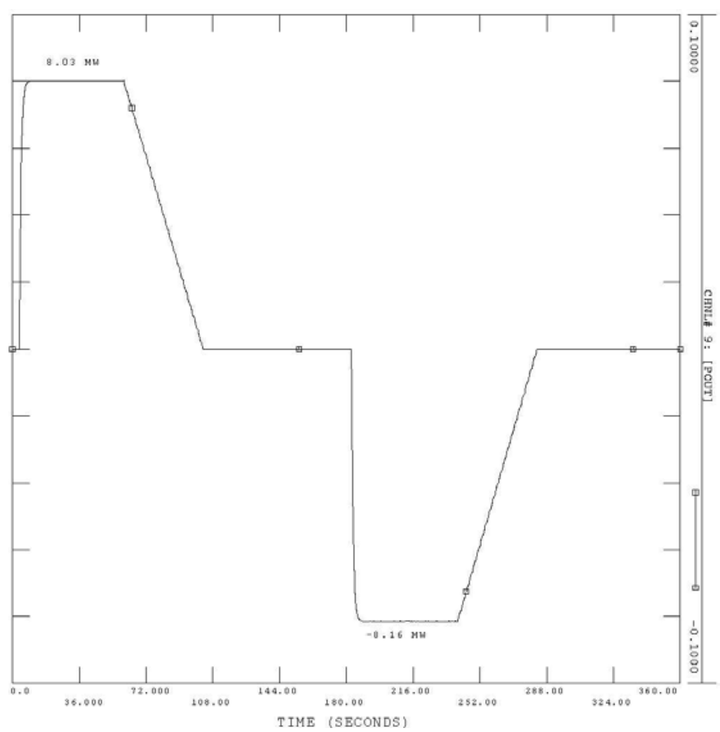

Figure 4. ESS power output.

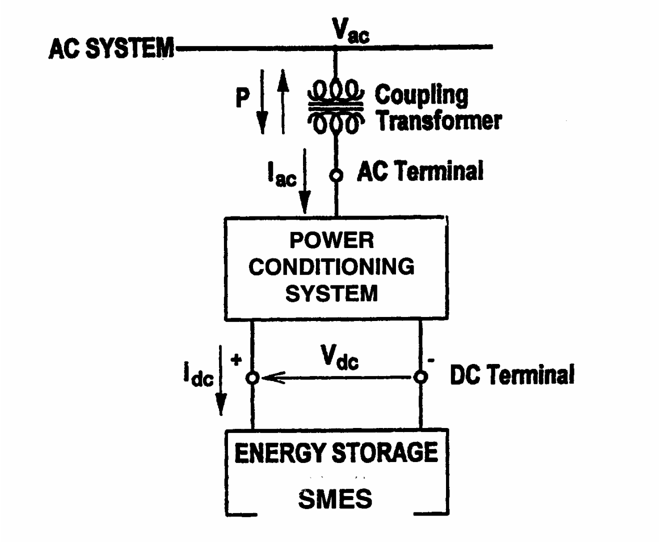

Figure 5 PCS Controls Power Flow Between Energy Storage and Utility Systems

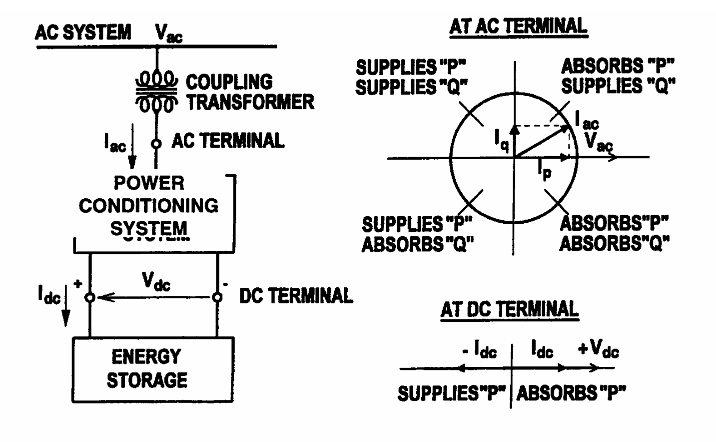

Figure 6. Four Quadrant Power Control by PCS

This capability of injecting either active or reactive power as needed makes the ESS very useful against voltage instability, a condition usually associated to reactive support inadequacy. In [11] we identified that a weak connection between the load center, in the North of Puerto Rico, and the major generation centers, in the South, combined with generation decrease could lead to insufficient reactive margin in the buses near the North load centers. The reactive power margin in a bus indicates its actual reactive power reserve. It has to be negative in order to operate without shunt compensation [14].

If shunt compensation is required a properly located ESS (near these load centers) could inject the required reactive support. The amount of reactive support required and the duration of the injection will vary with the system operating conditions. This function is compatible with the use of the ESS for rapid response spinning reserve and frequency control.

V. CONCLUSIONS

The cost of using energy storage to convert wind farms from electric energy producers to electric power producers could be too expensive. In order to justify the investment on a ESS multiple uses for it may be required. We propose the use of ESS to provide rapid response spinning reserve, frequency control and reactive support in the island of Puerto Rico as well as to promote the use of eolic generation.

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VII. Biography

Dr. Agustín A. Irizarry-Rivera obtained his B.S. from the University of Puerto Rico Mayagüez in 1988, his M.S. from the University of Michigan, Ann Arbor in 1990 and his Ph.D. from Iowa State University, Ames in 1996, all degrees in electrical engineering. Dr. Irizarry-Rivera is Associate Professor of Electrical Engineering and has been a faculty member at UPRM since 1997. He is a member of IEEE and ASEE and a registered Professional Engineer in Puerto Rico since 1991.