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'Smart' Inverter System for Power Generation Transient Damping

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Executive Summary

The Spring 2015 Graduating Class of Mechatronics Engineering Students at the University of North Carolina Asheville have designed a system that may serve to correct the problems associated with the rise of distributed solar power. The Smart Inverter enhances power system reliability by damping the transition rate of a generator subjected to adverse loading conditions and provides for load shifting to better balance the intermittencies of supply and demand.

Abstract

The United States of America is faced with a challenging issue, particularly in states with increasing percentages of electrical power generation due to solar photovoltaic (PV) power. Distributed solar power usage is spreading. The demand for electricity during the daylight hours in many western states may soon be nearly met by PV generation alone. This will necessitate idling or shutting down conventional steam turbine generators on a daily basis, which has a deleterious effect on such equipment. The steep ramp rate (over 4000MW per hour) in the power demand curve in the evening when solar power is waning but overall electrical demand is rising will soon require the frequent cycling of expensive to operate rapid-response power plants [1]. These scenarios would result in an increase in the cost of operation, and therefore an increase in the cost of conventional electricity at the consumer level [5]. For this reason, solar energy has become a technical problem for electrical utilities. To address this issue, a small scale control system was designed and implemented that stores energy during times of potential overproduction and automatically resupplies that energy back to the power grid during times of high demand. This flattens the demand curve at the generator output. On a larger scale, this could allow conventional power generation equipment to be operated within design parameters more consistently, which keeps the operating costs of the electric company low. Additionally, the Smart Inverter system assists the turbine generators by inherently providing stable frequency control. The Smart Inverter is able to effectively meter supplementary power to and from a miniature power grid in order to damp the power demand curve as seen by the generator. This is important to ensure that the increasing use of solar energy does not drive up the cost of conventional generation. The Smart Inverter can help to ensure system reliability under changing grid conditions as the nation begins to rely more heavily on renewable sources of energy.

1. Background

The traditional method of electrical generation in the United States has been to utilize a steam or gas turbine as the prime mover of a generator. It is estimated that approximately 88% of the electricity produced in the United States is generated by steam turbines [2]. Both fossil fueled and nuclear power plants use steam turbines as the prime mover for electrical generators; the difference lies only in the method used to convert water into superheated steam.

Conventional power plants (both fossil fuel and nuclear powered) are designed to operate constantly to avoid the mechanical problems associated with 'heat cycling' the precision balanced turbine blading, casings, and other expensive components [5]. Many mechanical problems such as bowed or warped rotors, damaged bearing surfaces, etc. are most likely to occur during plant startups. Idling a turbine generator (running with the generator unloaded) for several hours per day does not induce a heat cycle, but reduces the efficiency of the plant and adds to operating costs.

Each year, the use of photovoltaic cells to generate electricity (solar power) increases [4]. The result is that less of the power demanded by consumers must come from conventional sources. It is estimated that during the next 5 years in California there will be a need to shut down or idle steam turbine generators during the day, as much of the demand for electricity during the daytime will be supplied by solar power. Idling or shutting down a generator due to lack of demand is generally detrimental to the equipment. Additionally, as solar energy usage becomes more prominent, the ramp up rate in the late afternoon steepens as the starting point lowers. Management of this ramp rate presents a challenge for system operators. As the electrical grid and sources of power begin to change, so do the techniques for managing these resources.

2. Introduction

When energy augmentation by PV generation is present, the net demand on conventional electric utilities is lowest when the sunlight is at its peak intensity. The net demand on conventional power plants is predicted to drop to as low as 12000MW during the day in the year 2020 [4]. During the afternoon, when solar generation peaks, turbines that are spinning but are not being loaded to capacity may need to be shut down or idled. This is known as 'overproduction'. This poses a problem due to the nature of mechanical equipment.

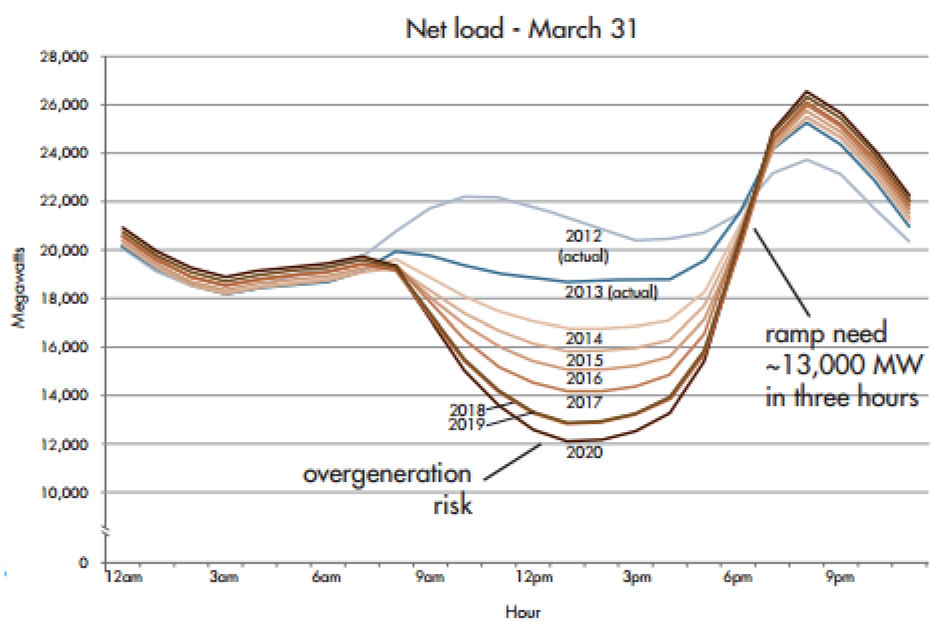

Figure 1. California's hourly power demand

Figure 1 The duck curve shows steep ramping needs as the sun sets and overgeneration risk during mid-day [4].

The function of the Smart Inverter is to sense a decrease in load demand (by sensing a rise in frequency) at a conventional generator output and respond by using the remaining capability of the generator to charge an energy storage device. This increases the load on the generator and thus assists in maintaining output frequency by keeping the power output constant and at the parameters for which the generator is designed. During periods of increased electrical demand, the output frequency of the generator tends to drop. The frequency drop signals the Smart Inverter system to discharge the energy storage device and augment the power grid with the energy that was previously stored. In this manner, the 'belly' of the demand curve (commonly known as the 'duck curve' due to its shape) is shifted upwards, and the 'overproduction' situation is avoided. Inherent to its functionality, the Smart Inverter provides the ancillary benefit of generator frequency control.

As the sun's intensity diminishes in the evening, the power generated from solar cells falls to zero, and the net load is shifted back to the conventional utilities. Simultaneously, the demand for electricity climbs in the evening hours. Within a few years as the use of PV energy increases, the result will be a sharp ramp rate in the power demand that must be met by conventional steam turbine generators.

Steam turbine casings and components must be heated up slowly and evenly while being brought into operation. The startup procedure for some larger turbines may exceed 10 hours [3]. A large operating cost could result when expensive capital equipment such as turbines are excessively cycled or idled in preparation to meet the electrical demand. These operating costs would be passed on to the consumer.

The Smart Inverter system is designed to address these issues, which are detrimental to the mechanical equipment that composes the bulk of the existing electric power infrastructure. With the Smart Inverter system installed, power is stored when demand is low and automatically released when the demand for electrical power increases.

3. Methodology

The general intent of the Smart Inverter project is to create a small scale demonstration of a much larger situation.

The daily peak power usage by the state of California, where the use of photovoltaic solar panels is widespread, is approximately 25,000 MW. This figure readily scales down to 25 resistive loads, where each load represents 1000 MW.

At 3W each, the 25 resistive loads (light bulbs) demand a total of 75W, which is within the capability of a small, single phase tabletop motor generator set. The 25 bulbs are grouped into twelve separate banks of one, two, or three bulbs each. A programmable logic controller (PLC, AC in / relay out) is used to cycle the loads in a sequence that replicates California's demand curve [4] to scale.

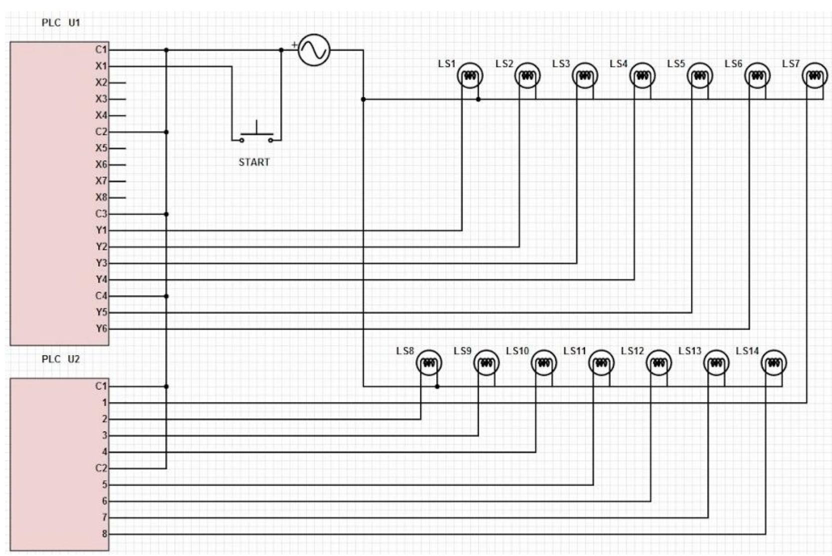

Figure 2. Basic PLC controlled load.

Figure 2 Each bulb represents a resistive load of 1-3 bulbs in parallel.

A direct current (DC) motor, which represents a prime mover or steam turbine, is coupled to a single phase 80W alternating current (AC) generator in order to supply the load bank with electricity. The shape of the generator output curve with the Smart Inverter system installed is one factor that determines the success of the project. Steep changes in generator output over time are to be avoided.

With the Smart Inverter control system disabled, the load bank was programmed to draw a power curve that is a scaled version of the California Independent Systems Operator forecast power demand curve for 2020.

TIME	# OF BULBS	POWER	MW REPRESENTATION	2020
12	21	63	21000	21
1	20	60	20000	20
2	18	54	18000	18
3	18	54	18000	18
4	18	54	18000	18
5	18	54	18000	18
6	18	54	18000	18
7	18	54	18000	18
8	17	51	17000	17
9	16	48	16000	16
10	16	48	16000	14
11	16	48	16000	13
12	16	48	16000	12
1	15	45	15000	12
2	15	45	15000	11
3	15	45	15000	11
4	15	45	15000	11
5	16	48	16000	13
6	18	54	18000	15
7	22	66	22000	22
8	25	75	25000	25
9	24	72	24000	24
10	23	69	23000	23
11	21	63	21000	21

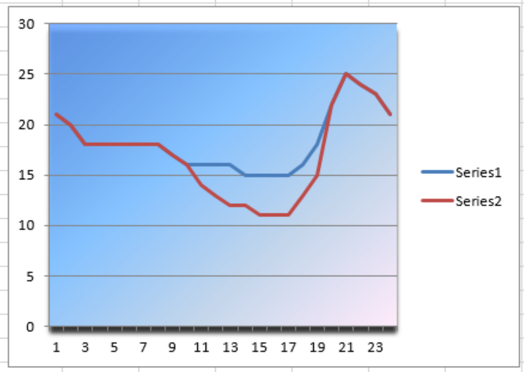

Figure 3. Load design power demand versus time

Figure 3 The power demand curves of the load bank matches the CAISO duck curves for 2015 and 2020 to scale.

The control system consists of two separately programmed Arduino UNO microcontrollers, a single 12 volt 33 amp hour battery, a commercially available 250W grid-tie power inverter, a custom built switching circuit that controls power output from the microcontroller, and a custom pulse width modulation (PWM) control circuit that charges the battery. The frequency of the grid is measured by stepping down, then half-rectifying the system voltage to a pulse which is then input to an opto-isolator. The opto-isolator serves as a frequency controlled switch which cycles a 5V source to produce a square wave at the system frequency. The first microcontroller measures system frequency by counting the rising edge of this signal. This microcontroller then outputs two simultaneous binary signals. These signals are inputs to the second microcontroller. The second microcontroller performs one of four actions based on input; 1) increase PWM to charge the battery faster, 2) decrease PWM to charge slower, 3) turn the inverter on or off, or 4) do nothing.

With no other system changes, a rise or drop in generator frequency is indicative of a loading transient. The Smart Inverter stores or releases electrical energy based on the frequency trend of the generator.

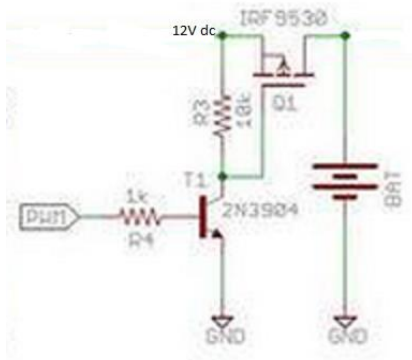

Figure 4. Smart Inverter charging control circuit

4. Data Summary

‘DMM’ brand data logging software and a data logging digital multi-meter were used to record parameters before and during system operation. A five second sample time was used to record system voltage and current at the output node of the generator. This information was manipulated to give power curves for the miniature grid by (1)

$$P = \text{work done per unit time} = \frac{VQ}{t} = VI \quad (1)$$

Where Q = electric charge in coulombs

t = time in seconds

V = electric potential in volts

I = electric current in amperes

Voltage and current samples were multiplied together, yielding the instantaneous power of the generator.

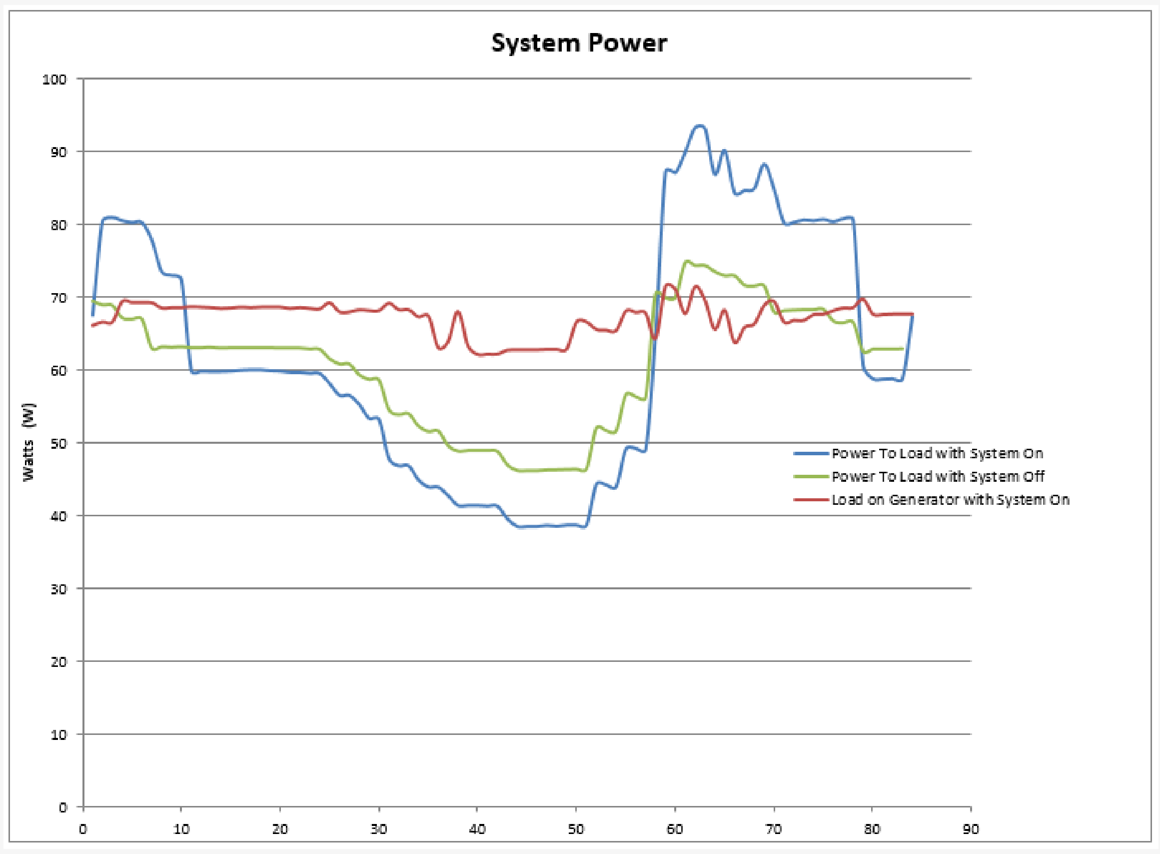

Figure 5. Power demand of the load bank with and without the Smart Inverter activated

Figure 5 The green line shows the steep transitions of the unassisted system and matches the CAISO duck curve to scale. This is the power demand curve of the load. Power varies over time from 46W to 75W. The red line shows the demand on the generator with the Smart Inverter activated. The 'belly' of the curve (overproduction region) is removed. There is no extended steep ramp rate. The power demand remains much flatter, between 62W and 72W for the duration of the simulated day.

5. Data Analysis and Inference

The frequency of the motor/generator tends to rise as the power demand decreases. The frequency detection circuit signals the system to charge the battery. This further loads the generator, which decreases the rate of the frequency rise.

Conversely, as power demand on the generator increases, frequency tends to drop. The frequency detection circuit signals the system to augment the grid with power from the battery that has been inverted back to AC. This reduces the load on the generator and causes the frequency to drop at a smaller rate.

In all cases, the Smart Inverter maintained generator frequency at 60(+/- .5) Hz. The system inherently provides frequency stability because it operates based on frequency. Voltage fluctuated between 111 and 132 volts with no operator action. These parameters are consistent with national operating standards [6].

There is energy loss and inefficiency associated with the Smart Inverter system, as with any system where energy is converted from one form to another (AC to DC and vice versa). Approximately 1 watt of energy leakage in the charging circuit is due to heat losses from the transistors, even when the system is not charging the battery.

6. Results and Discussion

In conclusion, the Mechatronics Senior Design Team found that automatic energy storage and reallocation is possible on a small scale. The Smart Inverter accomplishes the tasks of eliminating overproduction (by storing energy during periods of low demand) and reducing the ramp rate to maximum load (by reallocating stored electrical energy).

The results of the Smart Inverter project agreed with the initial expectations of the team, that a frequency controlled storage and metering system is feasible.

If the project were to be repeated, a consideration would be to add reactive power to the system by introducing small inductive loads and all three phases to the load bank. At this scale, the effects of inductive loading on the system are expected to be negligible, so the load was designed to simulate a local system that includes a power factor correction device. The purely resistive loads (light bulbs) mimic a PF that has been corrected to 1.

A second consideration is that conventional steam turbines are equipped with a speed governing devices that throttles steam flow in order to maintain output frequency. If output frequency were automatically regulated, a large scale Smart Inverter system would need to employ an alternate method of sensing changes in load demand, possibly simply by monitoring power trends in real time.

7. References

1. Farrell, John, 'Utilities Cry “Fowl” Over Duck Chart and Distributed Solar Power', 2014, http://cleantechnica.com/2014/07/21/utilities-cry-fowl-over-duck-chart-and-distributed-solar-powercrying-fowl-or-crying-wolf-open-season-on-the-utilitys-solar-duck-chart/

2. Thomas Publishing staff, “Steam Turbines”, 2015, http://www.thomasnet.com/articles/electrical-power-generation/steam-turbines

3. Energy and Environmental Analysis, "Technology Characterization: Steam Turbines”, 2015 (PDF). *Report prepared for U.S. Environmental Protection Agency*. http://www.epa.gov/chp/documents/catalog_chptech_4.pdf

4. California Independent System Operator, “What the Duck Curve Tells Us About Managing a Green Grid”, 2014, http://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf

5. Farshad Shamoradi, Naser Mohammadi, and Mahdi Heidari Kahkesh, Ahwaz Power Generation Management Co. “Steam Turbine Rotor Vibration Failures: Causes and Solutions”, 2013, http://www.powermag.com/steam-turbine-rotor-vibration-failures-causes-and-solutions/

6. North American Electric Reliability Corporation, “Reliability Standards”, 2011, http://www.nerc.net/standardsreports/standardssummary.aspx