Power Factor Control for Grid-Tied Photovoltaic Solar Farms

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***Abstract*—To maintain the power quality of solar farms, the common-point power factor of multiple photovoltaic (PV) inverters needs to be maintained inside of the utility requirement range. One solution is to utilize the communications capabilities of protective relays, meters, and PV inverters to integrate an active control system. This system compares the common-point power factor to the utility requirements and calculates a control signal to adjust the inverter outputs. The scheme can be implemented in a real-time automation processor or an industrial computing platform that is integrated with the inverters, allowing the control system to meet a wide variety of needs in a simple manner.**

This paper describes how using a closed-loop feedback control scheme and a proportional and integral controller can maintain the power factor in the required range. Further, the effects of various controller parameters on steady-state performance are studied. This paper also demonstrates that only one controller is sufficient for multiple inverters, making the active control scheme simple and cost-effective. Finally, it examines the communications and data collection limitations while analyzing the benefits of using multiple controllers instead of a single controller when the number of inverters increases.

I. Introduction

Photovoltaic (PV) solar farms are one of the renewable energy sources that have recently gained widespread popularity because of their environmentally friendly nature (green or clean energy) and the cost reduction of solar PV panels [1] [2]. The main components of these systems are solar PV panels and PV inverters that convert dc power generated from the panels to ac power tied to the electric grid. This energy conversion mechanism can potentially deteriorate the power quality of the grid, especially as the number of grid-tied solar farms increases [3].

The common-point power factor at the point of common coupling (PCC) of multiple PV inverters can fluctuate unpredictably outside of the utility requirement range. The variation depends on the power quality and harmonic distortions injected by the inverters [4] [5]. Therefore, maintaining the power factor at the PCC is critical for maintaining the power quality and stability of the overall system. A power factor adjustment can improve the efficiency of the overall utility network [6]. The power factor adjustment gives the utility greater flexibility to supply the power quality required by the loads.

This paper proposes a closed-loop feedback control scheme that uses a proportional and integral (PI) controller to maintain the power factor in the required range. This control process is accomplished by utilizing the communications capabilities of protective relays, meters, and PV inverters to form an integrated active control system.

A revenue meter or protective relay is commonly installed at the PCC by the utility to monitor the energy and power quality produced by the generation facility. The protective relay also provides protection functions for the interface to the grid. The proposed controller ensures that the measured power quality given by the meter or relay meets the utility requirements by sending control signals to adjust the inverter outputs. The solution models the power factor control problem as a closed-loop feedback system utilizing existing components of PV generation sites. It demonstrates how a PI controller can be useful in maintaining the desired reference power factor for multiple inverters in a simple and cost-effective manner.

II. System Architecture

An active power factor control system, as shown in Fig. 1, can be easily implemented by using the typical components of a PV generation site.

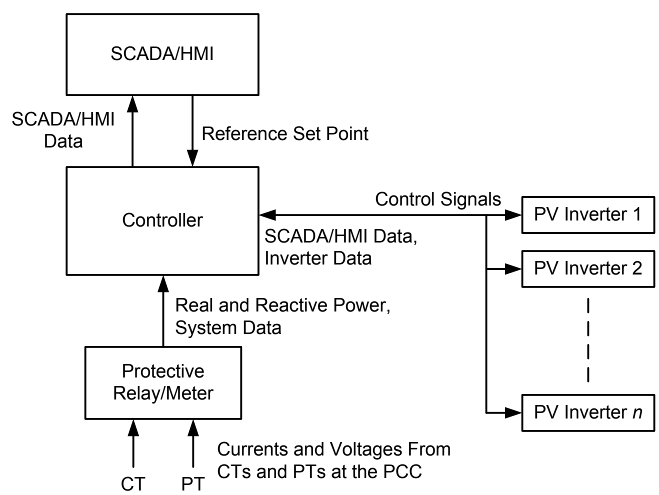

Fig. 1. Power factor control system architecture

The supervisory control and data acquisition/human-machine interface (SCADA/HMI) is responsible for displaying collected data, identifying system alarm conditions, and sending control commands to the inverters through the controller. The control commands can be to start and stop inverters and set points. One of the set points is the power factor reference set point. The power factor reference set point can be changed by sending a valid operator-entered value to the controller via the communications channel(s).

At a PV generation site, the PI controller has two main functions: it is a controller and a data concentrator. As a controller, it polls data from the protective relay or meter and the inverters and utilizes the collected data along with the SCADA/HMI set point reference to calculate control signals. It then sends the signals to the PV inverters via the communications channels to adjust the output power of each inverter. One way to adjust the output power of each inverter is by using the power factor set point. Therefore, the utilized control signal for the power factor control can be the power factor set point of each inverter. As a data concentrator, the controller polls each inverter and protective relay or meter for the required system data and then forwards the data to the SCADA/HMI. The data include inverter status, currents, voltages, power and energy values, and the power factor.

The protective relay or meter provides the controller with three-phase instantaneous real and reactive power quantities. This is accomplished by using current transformers (CTs) and potential transformers (PTs) to monitor the circuit voltages and currents that are used to calculate real and reactive power. The relay or meter updates the controller with the calculated values periodically. Besides these data, the controller polls system data periodically and sends the data to the SCADA/HMI.

A. Communications Channels and Topology

The type of communication between the components of a PV generation site is dictated by the distance and communications capability supported by each of the connected devices. Microprocessor-based relays, meters, controllers, PV inverters, and the SCADA/HMI typically support traditional EIA-232 and/or EIA-485 serial communications and/or Ethernet connections. In most cases, the controller, protective relays, and meters are located inside a switchgear cabinet or switchgear room at the PCC or the PV generation site. Copper cables are widely used in short-distance configurations because of their easy installation and low cost. Ethernet connections require an Ethernet switch for multiple devices. The devices, along with the switch, form a local network, and each device uses a Cat 5 (copper) cable to connect to the switch.

The inverters are located at the PV generation site, and their distances to the controller can be hundreds or thousands of feet. Typical communications channels include fiber-optic cables, wireless radios, or copper cables for shorter distances. Communication can be via either serial or Ethernet. Fiber-optic cables require electric-to-fiber-optic converters at both ends (for serial and Ethernet communications). For radios, converters and transceivers are required for bidirectional communication.

The SCADA/HMI can be located at the same PV generation site or at a remote site. Communications between the controller and the SCADA/HMI can be via leased T1 lines, the Internet, or a multiplexed microwave or fiber-optic backbone. In all cases, the transmitted data should be encrypted to ensure proper security.

Communication between the controller and protective relays typically utilizes point-to-point connections. Communication between the controller and the PV inverters can be via a shared channel using a bus topology or ring topology. It is also possible to have point-to-point connections to each inverter. Point-to-point connections are more efficient but can become expensive as the number of components and the distance between them increase. Shared channels, on the other hand, can be more economical but may have more limited throughput.

B. Communications Protocols

The communications protocols supported by the different devices can be proprietary or standardized and open. Open communications protocols have the advantage of interoperability among device manufacturers. Most protective relays, meters, and PV inverters support the traditional standard communications protocols Modbus® and DNP3. Other protocols supported by these devices include IEC 61850 and IEEE C37.118. Due to the nature of this application, the selected communications protocol is required to support a deterministic periodic data update.

III. Control Strategy Model

The solution described in this paper models the power factor control problem as a closed-loop control system, as shown in Fig. 2. In this closed-loop control system, the desired power factor set point reference is provided by the SCADA/HMI. The process variable is the system power factor at the PCC and is given by the protective relay or meter. The process (the plant) is the inverter, and the control signals are the set points of the inverters. These set points depend on manufacturers and can be the power factor set point or both real power and reactive power set points.

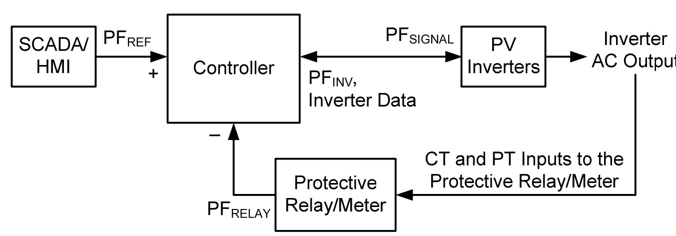

Fig. 2. Power factor closed-loop system

To implement this closed-loop control system, the controller sets up a control cycle and starts the process by polling the protective relay or meter for the instantaneous real and reactive power to calculate the system power factor at the PCC. It then polls the inverters for a set of inverter data (see Section III, Subsection D). The calculated power factor and the present SCADA/HMI power factor set point reference are used to calculate the error between the reference and the inverter outputs. Using the error and the collected inverter data, a control signal is calculated and sent to the inverters to adjust their output power. This completes the control cycle. In this dynamic system, the adjustment continues until the

SCADA/HMI reference set point is achieved. The controller continues to monitor the set point value and makes any necessary adjustments in order to maintain the set point at the reference level.

The control strategy discussed is further illustrated as follows:

- Power factor is the ratio of real power to apparent power, $Power_{Real}/Power_{App}$. Consider the following conventions:
  - Positive power factor is when current lags voltage (inductive loads).
  - Negative power factor is when current leads voltage (capacitive loads).
- The power factor reference from the SCADA/HMI is PF_{REF}.
- The inverter output power factor is PF_{INV}.
- The power factor from the protective relay is PF_{RELAY}.
- The difference between PF_{REF} and PF_{RELAY} is $PF_{ERROR} = PF_{REF} - PF_{RELAY}$.
- The output control signal from the controller is PF_{SIGNAL}.

The controller processes input values PF_{REF}, PF_{RELAY}, and PF_{INV} and inverter data and computes the PF_{SIGNAL} output, which is transmitted to the PV inverters.

In addition to the closed-loop system, which is essentially the heart of the controller, numerous limiting factors need to be considered when implementing this solution. These factors are discussed in Section III, Subsections A and B.

A. PV Inverter Limitations

The limitations of a PV inverter depend on the inverter manufacturer and the supported functions. By no means are the following limitations meant to cover all manufacturers; they are only the main limitations that need to be considered in implementing the controller.

The main limiting factors are the output power ramp rate and the maximum power limit. The output power of a PV inverter is limited by its ramp rate and maximum output limit. A ramp rate is usually defined as a percentage of the apparent power or rated power per second. To enforce this, the controller performs a sanity check and ensures that the signal sent to the inverters is always in the valid range.

B. Controller Considerations and SCADA/HMI Control

In practice, the controller can be disabled if the error between the reference and the inverter outputs is less than ΔE_{MIN}. If disabled, the controller skips certain steps or stops sending control signals to the PV inverters. When the power factor reaches the SCADA/HMI set point or is close enough due to the discretization of sampled values, sending the same control signals to the inverters does not affect the inverter output power.

It is critical that the controller check for communications failures. When communication is lost between the controller and the protective relay or meter, the controller is disabled. This prevents the controller from sending the same control signals to the inverters without knowing the power factor at the PCC. This occurs when the controller retains the last valid value before the communications loss. When communication is lost between the controller and some of (or a subset of) the inverters, the controller stops sending signals to the lost inverters and continues sending signals to those that remain online. When communication is lost between the controller and all of the inverters, the controller stops sending control signals entirely.

Data quality is taken into account by the controller. When it receives bad-quality control data or out-of-range values from some inverters, it stops sending control signals to those inverters. This prevents unexpected control signals from being sent to the inverters.

Another situation in which the controller can be disabled occurs when too little sunlight is present to generate power at utility voltages. At night or during dark, cloudy days, the output real power can be insignificant. Controlling the power factor in such low output power has no effect on power quality.

In many applications, the SCADA/HMI sends commands to the controller to request that the inverters start or stop. In addition to executing the start/stop commands, the controller also keeps track of the status of the affected inverters so that future signals are only sent to the inverters that remain active.

C. PI Control Algorithm Model

Under normal conditions, the PI controller is in charge of the power factor control and can be implemented as shown in Fig. 3.

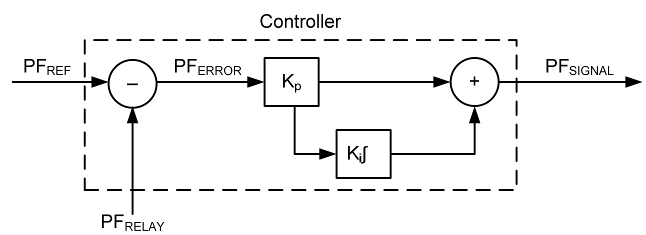

Fig. 3. PI control algorithm model

K_p and K_i are the proportional and integral constants, respectively, and are determined during the simulation and testing phase (tuning). The integral constant can be written as $K_i = K_p/T_i$, where T_i is the integration constant [7].

The power factor error is:

$$PF_{ERROR} = PF_{REF} - PF_{RELAY} \tag{1}$$

To implement the integral term in the controller, the integral term is approximated by a difference equation. This leads to the following recursive equation for the integral term:

$$PF_{INTEGRAL\_NEW} = PF_{INTEGRAL\_OLD} + \frac{K_p}{T_i} CRTL_{CYCLE} PF_{ERROR\_NEW} \tag{2}$$

where:

$PF_{INTEGRAL\_OLD}$ is the integral term up to the previous sampling instant.

$PF_{INTEGRAL\_NEW}$ is the new sampling instant.

$CRTL_{CYCLE}$ is the sampling period.

The signal at the new sampling instant can be written as:

$$PF_{SIGNAL\_NEW} = K_p PF_{ERROR\_NEW} + PF_{INTEGRAL\_NEW} \quad (3)$$

Expanding (3), the signal can be expressed in recursive form [7]:

$$\begin{aligned} PF_{SIGNAL\_NEW} &= PF_{SIGNAL\_OLD} \\ &+ K_p (PF_{ERROR\_NEW} - PF_{ERROR\_OLD}) \\ &+ \frac{K_p}{T_i} CRTL_{CYCLE} PF_{ERROR\_NEW} \end{aligned} \quad (4)$$

The controller utilizes (4) to update its output control signals.

D. Control Cycle Loop

Fig. 4 shows a simplified control cycle loop. In this loop, the controller collects the control data, checks the limiting factors, utilizes the PI control algorithm to compute the output signals, and sends the signals to the inverters. The process repeats until the SCADA/HMI reference set point is achieved.

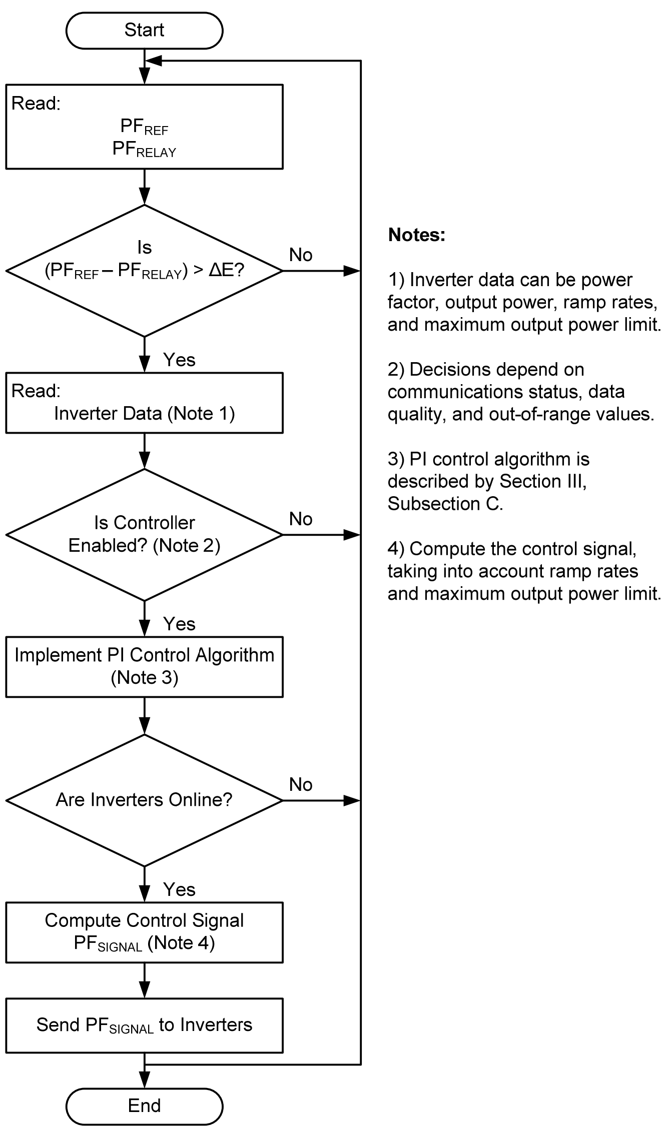

Fig. 4. Simplified control cycle loop

IV. Analysis of the Controller

Simulations are used to help understand and fine-tune the parameters of the controller in order to achieve better and more accurate performance.

One controller is sufficient for multiple PV inverters at a PV generation site. Assume that the inverters have different initial power factors and that they are turned on at the same time. The controller runs when any of the inverters are turned on. The simulation shows that the inverters first converge to a power factor and then all of the inverters with the same power factor converge to the reference set point. Fig. 5 illustrates this effect.

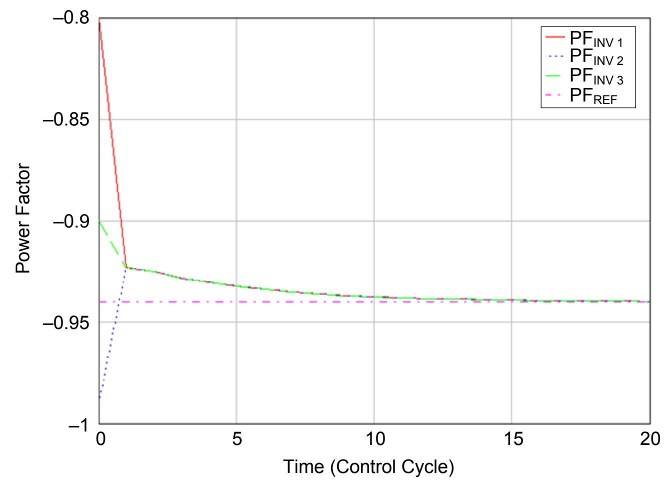

Fig. 5. Three inverter power factors converge

In this example, suppose that a PV site has three PV inverters and their initial power factors are –0.8, –0.99, and –0.9. In ideal cases, the ramp rate does not limit either power factor or output power. The inverters first converge to a synchronized point in the first control cycle, and then all three inverters with the same power factor converge to the reference set point. In cases where the ramp rate limits the inverter power factor or output power, the inverters can take a few cycles to converge to the synchronized point.

Now examine the expression of the system power factor at the PCC, and determine how each inverter affects the system power factor in different scenarios, such as when an inverter starts and stops and when system disturbances occur. Although the following analysis is theoretical, it gives some insight into such effects in practice.

Power factor is defined as the ratio of real power to apparent power (i.e., PF = P/S), where P is real power and S is apparent power. Power factor can be written as PF = P/S = cosφ, where φ is the angle between P and S. The relation between real and reactive power is Q = Ptanφ. Using these identities, power factor as a function of real and reactive power can be written as:

$$PF = \cos\left[\tan^{-1}\left(\frac{Q}{P}\right)\right] \quad (5)$$

Equation (5) can be rearranged to express reactive power as a function of real power and power factor:

$$Q = P\tan\left[\cos^{-1}(PF)\right] \tag{6}$$

Suppose that the real and reactive power at the PCC are Q_T and P_T and:

$$\begin{aligned} Q_T &= Q_1 + Q_2 + \cdots + Q_n \\ P_T &= P_1 + P_2 + \cdots + P_n \end{aligned} \tag{7}$$

where:

Q_1, Q_2, · · · Q_n is the reactive power.

P_1, P_2, · · · P_n is the active power generated by Inverters 1, 2, and *n*.

The power factor at the PCC can be calculated by (8), (9), and (10).

$$PF = \cos\left[\tan^{-1}\left(\frac{Q_T}{P_T}\right)\right] \tag{8}$$

$$PF = \cos\left[\tan^{-1}\left(\frac{Q_1 + Q_2 + \cdots + Q_n}{P_1 + P_2 + \cdots + P_n}\right)\right] \tag{9}$$

Equation (10) expresses the system power factor in functions of the power factor and real power of each inverter. If all inverter power factors have converged to the synchronized point or the set point (i.e., $PF_1 = PF_2 = \cdots = PF_n = PF_{SP}$), then the power factor at the PCC is $PF = PF_{SP}$.

A. PV Inverter Start

Without loss of generality, assume that Inverter 1 is off and the remaining inverters are running and have converged to the set point. When Inverter 1 turns on, the power factor at the PCC is affected. According to (10), if Inverter 1 starts with the initial power factor equal to the set point, then the power factor at the PCC is affected minimally (or will not be affected in theory by the equation). If the initial power factor is different than the set point, the power factor at the PCC departs from the set point, the controller reacts to this change, and eventually the power factor converges to the set point.

To illustrate this, assume that a site has three inverters. Two of the inverters start at Time 0, and the third inverter starts at Time 40 with a power factor different than the set point. The two inverters converge to the set point before Inverter 3 starts. When Inverter 3 starts, it adds real and reactive power to the system. The added power causes the power factor to depart from the set point, forcing the controller to react. An example of such an effect is shown in Fig. 6 and Fig. 7. Fig. 6 shows the reaction of the control signals due to Inverter 3 start.

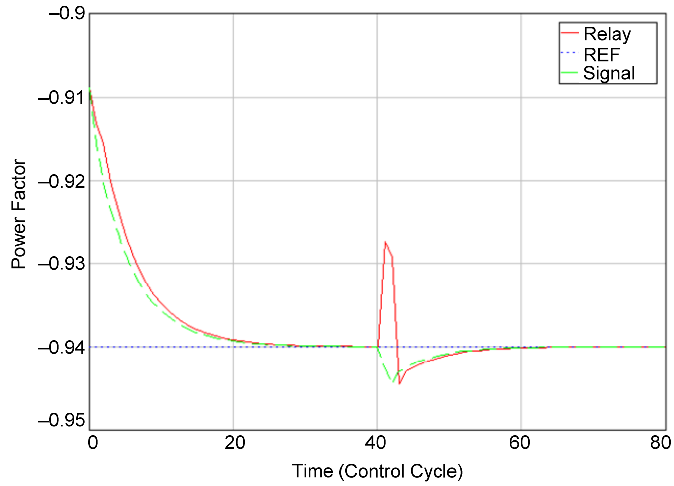

Fig. 6. System (relay) power factor and control signal reaction due to Inverter 3 start

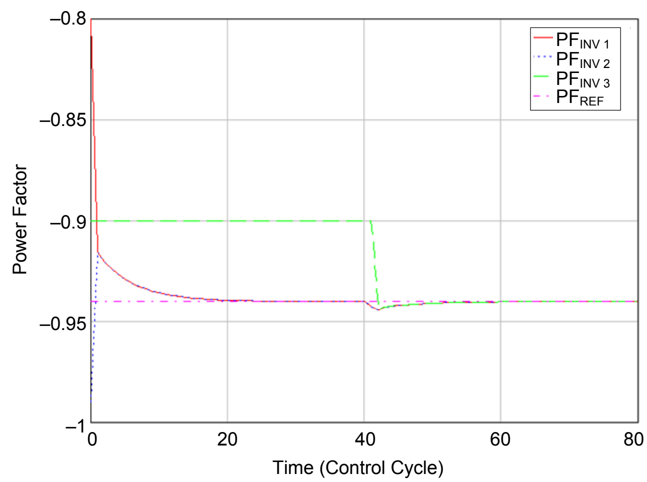

Fig. 7. Power factors of the inverters due to Inverter 3 start

B. PV Inverter Stop

Again, without loss of generality, examine the case where Inverter 1 stops contributing power to the system after all of the inverters have converged to the set point. When Inverter 1 stops, assuming its real power becomes zero immediately (i.e., $P_1 = 0$), the power factor at the PCC is not affected, according to (10). In practice, if the real power does not become zero immediately and the power factor becomes different than the set point when Inverter 1 turns off, the power factor at the PCC departs from the set point and the controller reacts to this, changes, and tries to adjust the inverter outputs.

$$PF = \cos\left[\tan^{-1}\left(\frac{P_1\tan\left[\cos^{-1}(PF_1)\right] + P_2\tan\left[\cos^{-1}(PF_2)\right] + \cdots + P_n\tan\left[\cos^{-1}(PF_n)\right]}{P_1 + P_2 + \cdots + P_n}\right)\right] \tag{10}$$

C. System Disturbances

To simulate this, an exponential decreasing disturbance is added to change the power factor at the PCC. First, assume that the power factor at the PCC has converged to the set point. The decreasing disturbance is then added to the system power factor. Fig. 8 shows the controller reactions to these changes and the corresponding inverter output adjustments that drive the system power factor back to the set point.

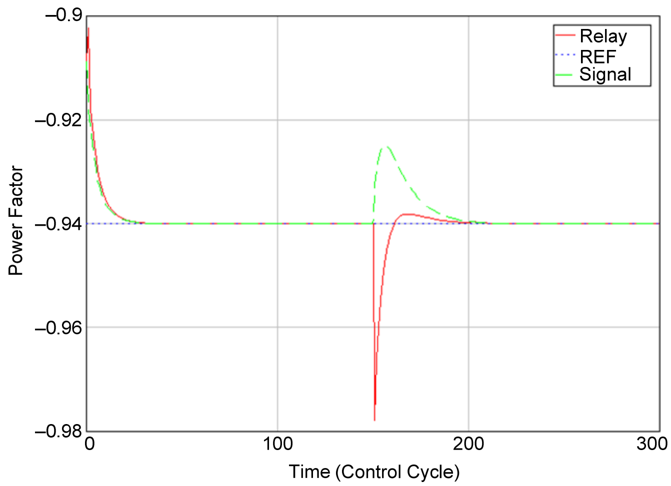

Fig. 8. System power factor and control signal reaction to the system disturbances

D. Sensitivity to Sun Radiation

Based on (10), if all of the inverters can maintain the set point power factor (i.e., all inverters keep the real and reactive power ratio constant), then the power factor at the PCC is less sensitive to the changes of the real (and reactive) power of the inverters. This suggests that as long as a set point is maintained by every inverter (i.e., $PF_1 = PF_2 = \cdots = PF_n = PF_{SP}$), the output power affects the system power factor minimally.

PV inverter output power is quite sensitive to sun radiation. The output power variation can change significantly in a very short period of time based on the amount of radiation. If every inverter can maintain a set point power factor that ensures the system power factor is maintained at the reference set point, then the system power factor is less sensitive to the amount of sun radiation.

E. Controller Parameters

In control theory, it is well known that a proportional control cannot reduce the steady-state error to zero. The error decreases with increasing gain, but the system will likely oscillate and become unstable [8]. Adding the integral, the steady-state error can be reduced to zero. A small constant time integration, T_i, causes the system to oscillate, and a large time integration reduces the strength of integral action [8].

Simulations show that large K_p and/or K_i cause the system power factor to oscillate, become unstable, and be unable to converge to the set point. Looking at (4), the third parameter is the control cycle. A large control cycle increases the integral constant, K_i. Once the proportional constant, K_p, and integration constant, T_i, are chosen, a large control cycle can cause the system to become unstable and unable to converge to the set point. A small control cycle may load the controller and restrict its ability to perform other tasks. When the controller acts as a data concentrator (its other role being a power factor controller), the control cycle can be chosen accordingly to handle both the control data and SCADA/HMI data.

F. Controller Parameter Tuning

Parameter tuning involves the selection of controller parameters K_p and T_i that are suitable for the application. Numerous tuning techniques or methods are described in literature. A simple way to tune the parameters is to assume the dynamic of the power factor at the PCC is similar to well-known processes that have tabulated values for the parameters. Although the tabulated values may not be the best choices, they can be fine-tuned during the testing phase. For instance, the well-known values for flow are $K_p = 0.3$ and $T_i = 1$ second. These values can be used as a starting point for further tuning.

One of the classic tuning methods is the closed-loop Ziegler and Nichols method [7] [8]. The procedure is as follows:

1. Set K_p as a very small value and T_i as a large value.
2. Slowly increase K_p until the process starts to oscillate.
3. Adjust K_p to make the oscillation continue with a constant amplitude.
4. Record this value of K_p as K_u and the period of oscillation as T_u.
5. The method suggests $K_p = 0.45\ K_u$ and $T_i = T_u/1.2$.

Simulations that use this method find a set of values for the parameters that can be used as the initial values during field testing and tuning. For example, K_p is set to 0.05 and T_i is set to 1,000. After adjusting the constant K_p, simulations show that $K_u = 1$ and $T_u = 2$ seconds. Therefore, $K_p = 0.45$ and $T_i = 1.67$ seconds. These values can be used as the initial values in the testing phase. In addition, simulations show that these values allow a control cycle of about 4 seconds to keep the system converging to the set point with decaying oscillations.

V. Implementation Example

The example PV generation site has three 1 MW inverters and utilizes about 40,000 solar panels. The controller and a protective relay are located inside a switchgear cabinet at the PCC. The inverters are about 600, 1,200, and 1,800 feet away from the controller. The SCADA/HMI is located in another state of the country.

The controller has numerous serial ports, one of which is connected directly to the protective relay that provides the system power factor. A second port communicates with the three inverters. The relay interface is EIA-232, and the inverters communicate via four-wire multidrop EIA-485 full-duplex communications networks. Communication between the SCADA/HMI and the controller utilizes a DSL modem connected to a local Internet provider. The communications protocol between the controller and the protective relay is a proprietary communications protocol. The protocol between the controller and the SCADA/HMI is Ethernet Modbus/TCP, and the protocol between the controller and the inverters is serial Modbus RTU.

The controller is implemented using IEC 61131 structured text. The controller includes all of the limitations discussed in Section III, Subsections A and B. The output power ramp rate is set to 10 percent, and the minimum output power to disable the controller is 50 kW. Due to the amount of the required system data from the inverters and the multidrop (shared) channel, the control cycle is selected to be 3.2 seconds.

The controller parameters are $K_p = 0.02$ and $T_i = 1.28$ seconds after field tuning and testing using a control cycle of 3.2 seconds. The system performance shows that the power factor is kept in the range of 5 percent of the reference set point under normal conditions.

VI. Single Versus Multiple Controllers

Because of the distance between the PV inverters and the controller, the inverters typically share a communications channel to the controller. The communications channel must be shared by both the control data and the SCADA/HMI data. As the number of inverters increases or the amount of data from each inverter increases, channel bandwidth becomes a critical limitation to a single automation controller.

As the number of inverters increases for a medium- to large-sized PV generation site, it may become necessary to implement multiple controllers. Each controller is then assigned to handle a unique group of inverters. The number of inverters that a controller can handle depends on the communications channel, its capacity, and the amount of data being transferred to the controller. This multiple-controller scheme is extremely scalable. Once the number of inverters is defined and tested for a single controller, the solution can be easily duplicated with the remaining inverters.

In a different system architecture configuration, two controllers can be used to separate the control data and SCADA/HMI data if the system supports two communications channels. One channel can be used for control functions and the second for SCADA/HMI data collection. As the number of inverters increases, multiple controllers may be a more practical solution.

VII. Conclusion

Utilizing the components of a typical PV generation site, an active closed-loop power factor control system can be easily implemented. This is accomplished by utilizing the communications capabilities of the components, which allow the controller to collect the required control data and make decisions to adjust the inverter outputs. The implemented solution proves to be simple and cost-effective for achieving the desired power factor reference set point.

Once the PI controller parameters are chosen appropriately after field testing and tuning, the controller can track the power factor changes at the PCC quite well. An implemented solution proves that the controller can keep the power factor within 5 percent of the reference set point.

VIII. References

[1] M. Salimi, "Low-Cost Grid Connected Photovoltaic System," proceedings of the 2nd International Conference on Environmental Science and Technology, *International Proceedings of Chemical, Biological, and Environmental Engineering*, Vol. 6, 2011.

[2] S. B. Kjaer, J. K. Pedersen, and F. Blaabjerg, "A Review of Single-Phase Grid-Connected Inverters for Photovoltaic Modules," *IEEE Transactions on Industry Applications*, Vol. 41, No. 5, September/October 2005, pp. 1292–1306.

[3] S. K. Khadem, M. Basu, and M. F. Conlon, "Power Quality in Grid Connected Renewable Energy Systems: Role of Custom Power Devices," proceedings of the International Conference on Renewable Energies and Power Quality, Granada, Spain, March 2010.

[4] J. H. R. Enslin and P. J. M. Heskes, "Harmonic Interaction Between a Large Number of Distributed Power Inverters and the Distribution Network," *IEEE Transactions on Power Electronics*, Vol. 19, No. 6, November 2004, pp. 1586–1593.

[5] B. Verhoeven, "Utility Aspects of Grid Connected Photovoltaic Power Systems," Report IEA PVPS T5-01:1998, December 1998.

[6] R. Ellenbogen, "Distributed Generation, Customer Premise Loads and the Utility Network: A Case Study," February 2008.

[7] K. T. Erickson, *Programmable Logic Controllers: An Emphasis on Design and Application*, Dogwood Valley Press, LLC, Rolla, MO, 2005.

[8] K. J. Åström and R. Murray, *Feedback Systems: An Introduction for Scientists and Engineers*, Princeton University Press, 2008.

IX. Biographies

David Taggart holds a B.S. in Metallurgical Engineering from California Polytechnic State University, San Luis Obispo, and an M.S. in Materials Engineering from Rensselaer Polytechnic Institute. He is the President/COO and cofounder of Belectric, Inc. His career spans 24 years across the aerospace, automotive, and renewable energy industries. At Lockheed's famous Skunk Works, he led teams producing industry firsts in advanced composite structures, manufacturing automation, and stealth technology. He cofounded Hypercar, Inc., with Amory Lovins of the Rocky Mountain Institute, where he built and led an international team to develop a full-sized sport utility vehicle integrating digital control, advanced composites, and hydrogen fuel cell propulsion to achieve 100 mpg efficiency. Over the past 8 years, he has been involved in three start-ups in the renewable energy field, focusing primarily on utility scale generation of electricity from photovoltaic technologies at costs competitive with combustive power.

Kei Hao received his Ph.D. in Electrical Engineering from the University of Wisconsin–Madison, his M.S.E.E. from the University of Wisconsin–Milwaukee, and his B.S.E.E. from La Universidad de la Republica, Uruguay. He has experience in the fields of control and automation systems, wireless communications systems, and power system automation and protection. In 2010, he joined Schweitzer Engineering Laboratories, Inc. as an engineer in the engineering services division. He is a member of IEEE and a registered professional engineer in the state of California and has authored and presented several technical papers.

Robin Jenkins has a B.S.E.T. degree from California State University, Chico. From 1984 to 1988, he was employed as a systems integration engineer for Atkinson System Technologies. From 1988 to 1999, he was with the California Department of Water Resources, where he worked as an associate and then senior control system engineer. From 1999 to 2007, he worked for Schweitzer Engineering Laboratories, Inc. (SEL) as a senior integration application engineer. From 2007 to 2009, he rejoined the California Department of Water Resources as the control systems branch chief. Since 2009, he has been employed by SEL, where he currently holds the position of integration application engineer and is responsible for technical support, application assistance, and training for SEL customers in Northern California.

Rick VanHatten received his B.S.E.E. from South Dakota State University in 1974 and is an IEEE PES member. He has broad experience in the field of power system engineering, operations, and protection. Upon graduating, he served for 32 years at Iowa Public Service, Midwest Resources, and MidAmerican Energy, where he worked in substation, distribution, and transmission engineering, system operations, and substation operations managing various engineering groups. He has led a variety of utility projects to design and build electric and gas metering shops, plan for Y2k contingencies, and consolidate utility switching practices. In 2006, he joined Schweitzer Engineering Laboratories, Inc., where he is an engineering supervisor. Previously, he worked for two years for Cooper Power Systems in the energy automation solutions group, formerly Cannon Technologies, in the area of substation automation and integration.

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