The Importance of Coordinated Control Systems in Solar Generation Plants

Michael Mills-Price
Advanced Energy Industries, Inc.

Kei Hao
Schweitzer Engineering Laboratories, Inc.

Published in the
proceedings of the CIGRE-AORC Technical Meeting 2018 – International Conference on Global Energy Transition – Issues and Challenges
Gangtok, India
May 24–25, 2018

Previously published in
Wide-Area Protection and Control Systems: A Collection of Technical Papers Representing Modern Solutions, 2017

Originally presented at the
1st Annual PAC World Americas Conference, September 2014

The Importance of Coordinated Control Systems in Solar Generation Plants

Michael Mills-Price, *Advanced Energy Industries, Inc.*
Kei Hao, *Schweitzer Engineering Laboratories, Inc.*

***Abstract*—Solar photovoltaic (PV) power plants are emerging across the United States to meet state and local energy portfolio requirements. Coordination of the PV plant and its intertie with the existing distribution and/or subtransmission electrical system is essential for reliable, practical operations. This paper describes a PV plant control system in the field, its operation, and the practicality of solving challenges associated with interconnecting large utility-scale PV installations with the bulk market. In its most basic form, a plant control system monitors the overall operations of the generation plant and the point of interconnection (POI) and, based on the conditions, adjusts the equipment to meet operational, performance, and local interconnection requirements. It seamlessly adjusts the equipment operational points in response not only to commanded set-point changes but also to unpredictable conditions such as a fault or extreme weather.**

In addition to providing internal plant monitoring and control functions, the system also serves as a single-point interface with external systems, where it supplies plant data and accepts control commands from the area electric power system. This single-point interface simplifies the communications burden on the electric power system while providing the necessary functionality to maintain critical voltage support features for the bulk electrical system. This paper describes how the control system can be integrated, including both the internal and external PV plant equipment and devices, with many available communications protocols involved for each. Internal equipment and devices include PV inverters, weather stations, sun trackers, protective relays, revenue meters, local generators, and alarm systems. The external equipment includes weather forecast systems, power management systems, and supervisory control and data acquisition (SCADA) interfaces, to name a few.

This paper discusses in depth the architecture of the plant control. Based on the implemented architecture, the paper demonstrates several different control schemes, including open-loop, closed-loop, sequential step, and time constraint-based controls. These schemes cover a wide range of possible applications, and as such, a section of this paper discusses a few real-world examples. In order to achieve reliable and deterministic controls using a variety of communications protocols and associated media, the status indicators internal to the field equipment are leveraged as part of a more complex scheme. In addition to the communications status provided by the protocols, this paper describes how the latency bit (also known as heartbeat) technique can aid in achieving more reliable controls.

I. Introduction

The integration of solar photovoltaic (PV) power plants into existing electrical networks has increased rapidly in recent years. This is largely driven by state and country mandates to meet renewable energy portfolio requirements. Integrating these intermittent PV plants into existing electrical networks can lead to serious impacts on power quality, reliability, and the overall stability of the electric power system.

Fig. 1 illustrates the impact of adding a solar PV generation plant into an existing electrical network. The small portion of the electrical network, which could be part of a distribution or subtransmission network, comprises several branches of customer loads. When a PV generation plant is a good distance from a conventional generation plant and injects only real power into the network, the voltage fluctuations at the point of interconnection (POI) vary widely depending on the incident radiation. If the PV penetration is high, a sudden decrease in radiation can cause the voltage to drop below the prescribed variations (5 to 10 percent) and a protective relay to open the circuit breaker at the POI due to undervoltage elements [1] [2].

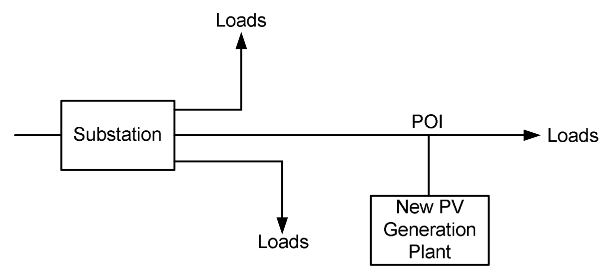

Fig. 1. PV Generation Plant Inserted Into Electrical Network

Additionally, if the network is designed and operated for unidirectional power flow (from the substation to the loads), the added PV generation can cause bidirectional power flow, resulting in issues with existing protection equipment. If the network is designed for bidirectional power flow, issues can still arise in regard to the substation bus, such as wide swings in real power flow and potential backfeeding of other parallel feeder circuits. Circuit design, coupled with electrical installation location, can potentially affect the voltage variations, grid stability, voltage regulation schemes, power quality, and protection and coordination [3].

The PV plant controller concept is to implement an aggregate control mechanism that leverages the individual PV generation inverters to match the amount of power (both real and reactive) needed and thus minimize any negative impacts on the electrical network [2] [3] [4] [5] [6]. In order to achieve this, coordination is necessary between the PV plant controller, substation, and the area electric power system. The control system of the PV generation plant needs to not only provide internal plant monitoring and control functions, but also interact directly with external systems, such as utility supervisory control and data acquisition (SCADA) systems and energy management systems (EMSs). These interactions are essential to meeting the operational, performance, and interconnection requirements of the broader coordinated control system discussed in this paper.

This paper proposes a system architecture for a coordinated control system and describes in detail the components and their interactions. The paper describes the key requirements for the communications protocols and the coordinated control system. Based on the proposed architecture, the paper demonstrates several different control schemes, including open-loop, closed-loop, sequential step, and time constraint-based control schemes that cover a wide range of possible applications. The final sections of this paper discuss several real-world examples.

II. Proposed System Architecture

The coordinated control system consists of a group of sensing devices, equipment controllers, data input devices and systems such as SCADA and human-machine interfaces (HMIs), the PV plant master controller, and communications devices and networks, as illustrated in Fig. 2. For simplicity, the communications devices and networks are omitted from the figure. Relevant details and functional descriptions of the PV inverters, microprocessor-based relays and meters, and SCADA and HMI systems can be found in [7] [8].

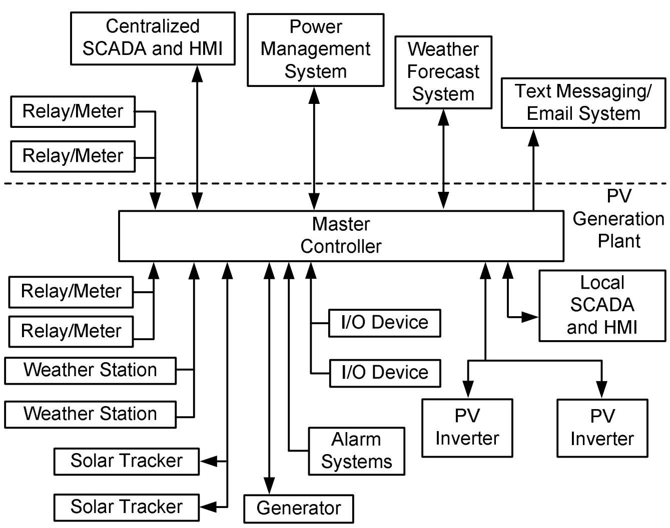

Fig. 2. System Architecture

The following subsections discuss the interactions between the control system components and the master controller.

A. Sensing Devices

Sensors in a PV generation plant include microprocessor-based protective relays, meters, input/output (I/O) devices, solar trackers, and alarm systems. The built-in support for custom logic and communications capabilities makes these devices ideal for serving as inputs to the master controller. Shifting more control logic to the sensing devices and minimizing the amount of data exchange with the master controller simplify the control interface and reduce the burden on the controller. The sensors that do not support built-in functions must have communications capabilities so that they can send the measured and observed quantities to the master controller and allow the controller to perform control functions. Although a sensing device can become a single point of failure for some applications, it is important to also consider device failure, communications failure, network throughput, and latency.

B. Equipment Controllers

The active coordinated control system requires equipment controllers such as inverters and solar trackers to support bidirectional communications. The equipment controllers must be able to accept control signals, respond to both normal and abnormal conditions, and provide their own operating status and alarming conditions so that the master controller can use them to coordinate with other equipment. This ensures the integrity of the generation system and ultimately the interconnection needs at the POI. The control signals vary widely depending on application needs. However, they can comprise set-point changes, operation modes, ride-through profiles, and on and off commands, to name a few.

C. Master Controller

The master controller acts as the coordinator of the entire control system by providing the required interfaces to ensure that all of the components are working together properly. It takes the operating statuses of the plant and the external systems and generates a set of control signals to each respective subsystem, adjusting the operation of the plant to meet operational, performance, and local interconnection requirements. In some cases, the master controller implements both coordinated control and data concentration functions. In such cases, the processing burden of the master controller must be carefully evaluated because of the vast amount of data required for the SCADA and HMI systems. In other cases, the coordinated control functions are separated from the data concentration and implemented on different controllers (monitoring on one, control on the other).

If one master controller is used in the control system, it becomes a single point of failure in the system. To increase the reliability and availability of the control system, more than one controller can be used. Either standby redundancy (also known as backup redundancy) or modular redundancy (or parallel) techniques can be implemented. The implementation of redundant controllers is beyond the scope of this paper.

D. Communications Systems and Networks

The communications systems and networks are crucial parts of the coordinated control system. Reference [7] provides details about the communications systems and networks that are essential for the control system. Security and cybersecurity are important and should be taken into serious consideration during implementation. However, for the sake of brevity, they are omitted from this paper.

Standard (open) communications protocols are preferred over proprietary communications protocols for use in the control system. Standard communications protocols offer the great advantage of interoperability among different manufacturers. Popular standard communications protocols include Modbus®, DNP3, IEC 61850, and IEEE C37.118. Experience has shown that using a single uniform communications protocol in the control system greatly facilitates and improves the maintainability and scalability of the system. In general, having interoperability among devices from different manufacturers enhances the reusability and portability of control solutions.

E. Weather Forecast Systems and Weather Stations

Due to the inherent variable, volatile, and intermittent nature of solar radiation, it is a great challenge for a utility to predict and forecast the amount of energy the PV generation plants produce at any given point in time. Accurate forecasting helps the utility and system operators better allocate resources to maintain the critical voltage and frequency support features of the bulk electric system. Weather stations and weather forecast systems are essential components to achieving an accurate forecast of power production. Weather forecast systems use diverse methods for predicting the power output of a PV generation plant, ranging from multipoint weather measurements and satellite and sky image observations and analysis to numerical weather prediction (NWP) models [9].

Local weather stations serve to provide real-time weather data to forecast systems. These data can be archived and used at a later time by forecast systems that use historical data in their models. In the proposed architecture, the master controller provides the interface between local weather stations and weather forecast systems.

Weather stations typically have a set of sensing devices that measure local weather conditions, such as ambient temperature, relative humidity, precipitation level, wind speed and direction, and barometric pressure. Other data may include solar radiation, PV panel temperature, and total sun peak hours. Most sensing devices support open communications protocols such as Modbus and provide analog values and alarm conditions such as a battery charger alarm to the master controller.

F. I/O Devices

I/O devices typically provide discrete signals that can come from transformers, uninterruptible power supplies (UPSs), circuit breakers, and fire and smoke alarms in the control building or switchgear. Some I/O devices provide the status conditions (or state) of the plant, and others provide alarm conditions for which the master controller needs to take immediate action.

G. Text Messaging and Email Systems

One of the functions supported by the control system is the dispatch of text messages and emails. Certain alarms require human intervention after an event, and the master controller is responsible for providing the necessary information about the event to the text message or email systems.

H. Power and Energy Management Systems

Power management systems and EMSs interact with PV generation plants for two major purposes: to acquire plant data and to manage plant production. Production must be effectively managed in order to match energy demand and supply. The proposed architecture is meant to support slow or low-speed data communications between the parties. In this context, when power management systems provide set-point changes from either manual or scheduled operations, the response of the PV plant is in the order of seconds to minutes. The data received from the control system lag behind the real-time data in a similar time order. The architecture is not intended to support high-speed operations between external systems and the plant (e.g., generation shedding, where the expected response time is less than 1 second).

I. Solar Trackers

PV modules can be mounted either on fixed structures, where the PV modules are tilted at a fixed angle, or on a structure with solar trackers. In the second case, the solar trackers either adjust the position of the PV modules according to the position of the sun or direct the appropriate amount of sunlight onto the PV modules as the day progresses. Studies have shown that a solar tracking system can provide an efficiency improvement of up to 60 percent [10]. Although IEC 82/618/NP specifications require that the mechanical design of the tracker support some extreme weather conditions, the control system is ultimately responsible for sending command signals to position the PV modules in a stow position (a predetermined angle or position) to minimize impact when extreme conditions arise [11]. When other unpredictable conditions occur, such as faults, outages, or certain alarm conditions, some plant operations require that the entire plant be switched into a predetermined and known state. In that case, the master controller sends signals to the tracker controllers to position the PV modules at a specific position and angle.

Two types of solar trackers are often used in a PV generation plant. Single-axis trackers have one degree of freedom that acts as an axis of rotation. Dual-axis trackers have two degrees of freedom that act as axes of rotation. In normal operations, the master controller does not send command signals to the tracker controllers. However, when such needs arise, the signals can be classified into three groups. The first group is the raw data (e.g., a specific angle in degrees for the single-axis trackers). The second group is a set of commands defined as part of the interface between the master controller and the tracker controllers. Each command is usually represented by one bit. Upon receiving the commands, the tracker controllers take a series of actions. The third group consists of discrete signals that represent operation modes and switch between on and off commands.

J. Generator

As discussed previously, one operational requirement can be to put the entire plant in a predetermined state under certain unpredictable and undesirable conditions. When an outage or a fault occurs, it can leave a big portion of the plant with no electric power. Typically, the control room of the plant has backup batteries that can last for a few hours and thus support functions of the critical devices, such as protective relays, circuit breakers, communications equipment, and the main controllers. The battery system is not designed to energize the PV inverters, solar trackers, communications network devices, and other devices in the field. This is where a generator is needed to provide sufficient, minimal electric power so that the equipment can remain powered until the control system is able to put the equipment into the predetermined state. When the generator is in operation, the main controllers must ensure all interconnect and circuit breakers at the POI (all intertied to the utility) are open and locked. Closing must be prevented because this prevents backfeed, and it must be ensured by the coordinated control system. Once the operation is complete, the generator is powered off and disconnected from the system.

The interactions between the control system and the generator include turning the generator on and off, opening and closing the disconnect or breaker of the generator, and collecting some I/O signals that monitor the status of the generator (e.g., fuel level).

III. Coordinated Control System Requirements

This section discusses some key requirements for the communications protocols and master controller for control system operations.

A. High-Speed Versus Low-Speed Communications Protocols

A high-speed communications protocol is a protocol in which a message can reach its destination in milliseconds. A well-known standard is IEC 61850, which includes a high-speed, multicast protocol: Generic Object-Oriented Substation Event (GOOSE) messaging. It is a nonroutable Ethernet Open Systems Interconnection (OSI) Layer 2 broadcast/subscription protocol [12]. Other high-speed proprietary protocols include point-to-point serial-based protocols.

Low-speed communications protocols have less-strict time constraints that can be in the order of seconds. Such protocols include DNP3 (polled data), Modbus, IEC 61850 Manufacturing Message Specification (MMS), and so on. Some applications require low latency variation in low-speed command signals from the master controller to the destinations. Large latency variation can affect the performance of the control strategies, which is discussed in Section IV.

B. Technical Requirements for Master Controller

One of the key technical requirements for the master controller is to support multiple programs and tasks, where each task has its own task cycle. This allows the coordinated control system to separate control functions for different applications and delegate tasks based on their time requirements. The automation controllers that meet the IEC 61131 standard support these features. In addition, the master controller must support both low- and high-speed communications protocols.

Although not required, using automation controllers that support libraries greatly improves the scalability, reusability, and robustness of the system. Libraries can be used to encapsulate proven control functions and strategies, and to present an application interface to the user. This helps avoid undesirable changes to the core functions due to user error or inexperience.

IV. Control Schemes

This section discusses some traditional control schemes and illustrates how these schemes can be applied in implementing a coordinated control system in a PV generation plant.

In a continuous control system, a process or plant is the system to be controlled. A process variable is the process output that can be measured by the system. A control variable is the process input that can be adjusted by the control system.

A. Open-Loop Control

Based on the proposed architecture, the set point can be changed from either the centralized SCADA and HMI system or the local SCADA and HMI system in an open-loop control scheme. Once the control system receives the set-point changes, it verifies that the set point is within the acceptable range and sends the output control signal (or control variable) to the end device via communications protocols. The control system needs to ensure which SCADA and HMI system is in control based on what the local/remote switch indicates. This local/remote switch not only avoids possible control conflicts between the two SCADA and HMI systems but also provides safety when operator personnel are working at the plant or site.

Examples of open-loop control include limiting the output power of the inverters, setting the same power factor to all inverters, and positioning all or a portion of the panel modules at specific angles (positions) for maintenance.

Open-loop control often uses low-speed communications protocols, where response time is less relevant.

B. Feed-Forward Control

PV generation plants experience disturbances from the grid when load changes and switching operations occur. Other factors that can distort a process variable (e.g., measurement at the POI) include the internal components of the plant. Such components can be the impedance and resistance of the cables, transformer impedances, and so on. If the distorted quantities are known or can be measured, the control system can take them into account, calculate the corrective set point(s) that are affected by these quantities, and send the corrective set points to the end devices. This type of control is known as feed-forward control.

Although open-loop control schemes are easier to implement than feed-forward control schemes, disturbances and internal distortions can cause the measured process variables to deviate from the set points. One solution to minimize the distortion in an open-loop control scheme is to calculate or measure the relationship between the set point and the process variable and then create a lookup table or a function and incorporate it into the control system. Although the feed-forward scheme can minimize certain known distortions, it cannot entirely eliminate the unpredictable temporal variations of the disturbances.

Feed-forward control also often uses low-speed communications protocols where response time is less critical.

C. Closed-Loop Control

A closed-loop control scheme implementation is shown in Fig. 3. A closed-loop control system consists of a controller, sensing devices to provide process variable measurements, and the process or the plant. The controller compares the desired set point with the measured process variable, calculates the control variable to maintain the desired set point, and sends the set point to the end devices. The difference between the desired set point and the process variable is also known as the error. The advantages of closed-loop control compared with open-loop control include increased speed of response, reduced error, disturbance rejection, and reduced sensitivity to modeling errors [13] [14].

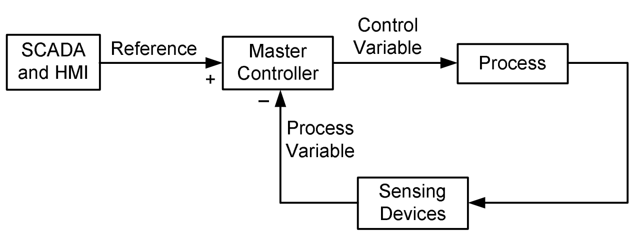

Fig. 3. Closed-Loop Control

Example use cases of closed-loop controls include measuring wind speeds from weather stations and positioning the PV modules at specific angles or maintaining a power factor at the POI. In the first example, the set point is the high wind speed and the process variables are the wind speeds measured by the weather stations. If one of the wind speeds is greater than the set point, the controller sends the commands to the solar tracker controllers and the tracker controllers position the PV modules at a predetermined angle or position. In the second example, the set point is the power factor at the POI, the process variable is the power factor measured by a meter or protective relay at the POI, and the control variable can be either the inverter power factor set point or both real and reactive power set points. Reference [8] provides a detailed discussion of the implementation and performance of the power factor controller using closed-loop control and a proportional and integral (PI) controller.

Depending on the application, a proportional integral derivative (PID) may be needed. When implementing PID control, considerations must be taken when choosing the PID control parameters. Improper selection of these parameters can cause the system to become unstable and not converge to the set point. Simulations and field parameter tuning are usually required to ensure the performance of the system.

D. Sequential Step Control

When the control algorithm follows a sequence of steps, it is considered a sequential step control scheme. A simple sequence usually has no parallel branches or operations and certain steps can be skipped depending on the status or state of the controlled system. Sequences that support parallel operations can be of two types: a selection of one sequence out of many is called exclusive divergence or branching, and multiple sequences being executed simultaneously are called simultaneous divergence or AND branching [13]. This control scheme is used in applications where a sequence of steps must be followed when a certain event occurs or when a certain condition is met (e.g., a fault).

An example usage of this control scheme applicable to a solar PV plant is when the plant experiences a power outage. Some PV plants are actually tied to two independent electric power system branches. The main branch is where the plant is connected, and it is responsible for exporting and providing power to the electronics of all components of the plant. The secondary branch is usually only used when the main branch experiences an outage. The control system uses this secondary source to put the entire generation plant into a predefined state by following a sequence of steps. Typically, the secondary source is not designed for exporting power and the control system must ensure this by turning off the inverters as one of the first steps in the control sequence. Once the entire plant is on the secondary source, the control system will be under a strict time constraint within which it must ensure that the plant does not export any power to the utility.

When a secondary source is not available or when both primary and secondary sources fail, a small local generator can be used to provide energy for the control system to put the entire plant into a known state. When the control system performs the sequential step controls, it must ensure that there are no two sources in parallel. Paralleling two sources without an appropriate synchronization mechanism can cause catastrophic consequences.

Using flow chart diagrams is a good method for designing the sequence step control. A flow chart diagram describes all of the steps that the control system performs, along with all of the associated conditions.

Fig. 4 illustrates a simple example of such a flow chart diagram. The logic first checks if the main source is available. If it is not available, the controller checks the secondary source. If the secondary source is also not available, the controller closes the generator breaker. In this example, the breaker status is used to determine the availability of the sources. In real applications, the relay determines the status of the sources and uses voltage elements as well as the breaker status to determine the availability of a source.

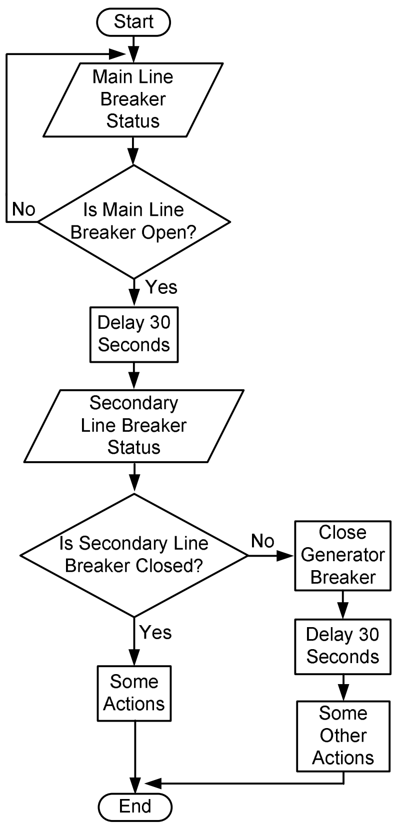

Fig. 4. Flow Chart Diagram Example

While IEC 61131 sequential function chart (SFC) language is uniquely suited for programming sequences, other programming languages can also be used.

E. Time Constraint-Based Control

A time constraint-based control scheme is one where a specific function or operation must be accomplished within a certain time limit. For instance, California Electric Rule 21 does not allow power export at the substation for more than 2 seconds. In this type of control scheme, the sensing devices must send a signal using high-speed communications protocols. As soon as the control system receives the signal, the control system must process it within a specific time limit (task cycle) and provide an output either directly or by sending a message to the end device using high-speed protocols.

Because this type of control requires high-speed communications protocols, too much data between the sending device and the controller could compromise the throughput of the network and other simultaneous control applications. To overcome this, a small set of discrete signals is recommended. This requires the sensing devices to have some processing capabilities and to be able to produce the set of signals.

V. Latency Bits

The proposed architecture and the operation of the control system rely heavily on the communications systems, networks, and protocols. In some applications, the control system or end devices are required to perform certain tasks immediately after detecting a communications failure. One approach is to rely on the status indicators internal to the equipment. Although providing the communications status by protocols has been proven successful in many applications, latency bit and watchdog methods can offer a more robust solution in detecting communications failures.

As discussed in [8], long control cycles in power factor controllers can cause the system to become unstable and unable to converge to the set point. Because large latency variation or random network latency can be larger than the control cycle, this can cause the performance of a closed-loop control system using a PI controller to deteriorate. Although heartbeat and watchdog solutions cannot prevent network latency variations, they are able to indicate whether performance has been compromised.

Latency bits (also known as heartbeats) can be implemented easily in the master controller and the end devices that support custom logic. Basically, the master controller generates a train of pulses consisting of alternating zeroes and ones. The end devices periodically check for the alternating bits in the pulses, and when the bits fail to alternate between two checks, a communications failure is considered to have occurred. Similarly, a watchdog uses a counter instead of pulses. When the end devices detect no counter increment, they declare a communications failure.

VI. Example 1: SCADA and HMI Control

In this example, consider two PV generation plants located 500 feet from each other. The rated capacity of each plant is 20 MW, and each has ten pads. Each pad has four 500 kW PV inverters. The PV modules are mounted on fixed structures at a fixed angle. The master controller is located in the main switchgear along with protective relays, utility revenue meters, and plant owner revenue meters. The backbone of the communications network is a fiber-optic cable ring, and all of the communications devices support Ethernet communications.

The internal components of the system include a local SCADA and HMI system, a master controller, 40 PV inverters, four protective relays, four revenue meters, ten transformer I/O sensors, two discrete I/O devices, and two weather stations. The external components of the system include a global SCADA and HMI system, an EMS, and an independent system operator system.

Modbus TCP/IP is used between the master controller and all internal devices, except for two utility revenue meters. These meters and all external systems use DNP3 to communicate with the master controller.

The control requirements for these two plants are to change the set points of the PV inverters and switch the individual inverters or a group of inverters on and off from either a local or global SCADA and HMI system. The EMS is only allowed to change set points. The set points include the power output, power factor, and ramp rate of the PV inverters. These set-point changes apply to all 40 plant inverters. The system does not have a local/remote switch, which means that either a global or local SCADA and HMI system or EMS can change the set points. The master controller interfaces with the independent system operator system to provide plant data.

In this application, the master controller is used to provide the interface for the described control functions and acts as a data concentrator that collects data from the devices in the field. This solution has been proven effective in meeting all of the control requirements. In this example, the two plants operate independently and their implementations are almost identical.

VII. Example 2: Power Factor Control

Consider a PV generation site with three 1 MW inverters and about 40,000 solar panels. The controller and a protective relay are located inside a switchgear cabinet at the POI. The inverters are about 600, 1,200, and 1,800 feet away from the controller. The SCADA and HMI system is located in another state.

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. A DSL modem connected to a local Internet provider is used for communication between the SCADA and HMI system and the controller. The communications protocol between the controller and the protective relay is a proprietary communications protocol. The protocol between the controller and the SCADA and HMI system is Ethernet Modbus TCP/IP, and the protocol between the controller and the inverters is serial Modbus RTU. Fig. 5 illustrates the closed-loop control implementation.

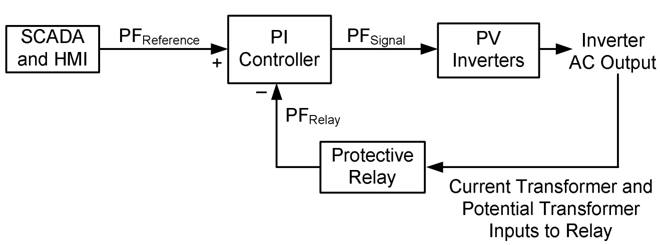

Fig. 5. Power Factor Closed-Loop Control Scheme

Fig. 6 shows the PI controller implementation, where K_p and K_i are the proportional and integral constants, respectively. The integral constant can be written as $K_i = K_p/T_i$, where T_i is the integration constant.

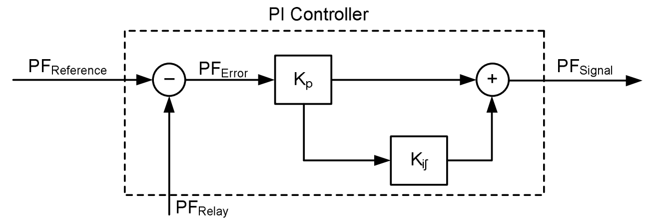

Fig. 6. PI Controller

The power factor error is $PF_{Error} = PF_{Reference} - PF_{Relay}$. The integral term is approximated by a difference equation and leads to the recursive equation in (1).

$$PF_{Integral\_New} = PF_{Integral\_Old} + \frac{K_p}{T_i} \bullet CRTL_{Cycle} \bullet PF_{Error\_New} \quad (1)$$

where:

$PF_{Integral\_Old}$ denotes 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 shown in (2).

$$PF_{Signal\_New} = K_p \bullet PF_{Error\_New} + PF_{Integral\_New} \quad (2)$$

Expanding this equation, the signal can be expressed in recursive form as shown in (3).

$$PF_{Signal\_New} = PF_{Signal\_Old} + K_p\left(PF_{Error\_New} - PF_{Error\_Old}\right) + \frac{K_p}{T_i} \bullet CTRL_{Cycle} \bullet PF_{Error\_New} \quad (3)$$

The controller uses this equation to update its output control signals.

The controller is implemented using IEC 61131 structured text. The main control requirement of this generation plant is to maintain a certain power factor measured at the POI. The power factor can be either leading or lagging and can be changed from the SCADA and HMI system.

The system performance shows that the power factor is kept in the range of 5 percent of the reference set point under normal conditions [8].

VIII. Example 3: Nonexport or Limited Export Power Control and Power Curtailment

Fig. 1 illustrates a simplified view of a small electrical network for a small size city. The network consists of a substation and three 12.47 kV feeders. A 3.5 MW PV generation plant is inserted into the middle section of the third feeder.

Fig. 7 shows the average daily load of the city. It shows a typical load profile of a residential city, where the load is small in the morning when most people are at work and starts to increase in the afternoon when they arrive home. Load typically reaches its peak in the evening when residents turn on air conditioners and other household appliances.

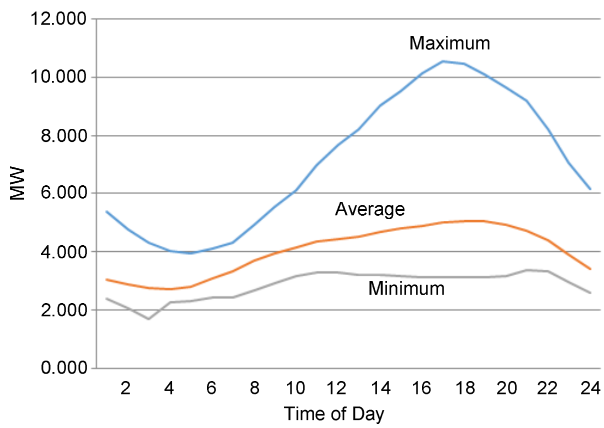

Fig. 7. Average Daily Load

Fig. 8 shows the typical load as the year progresses. Because this city is located in California, it shows the load is higher in the summer than in any other season. The repeated small dips shown in the figure represent the load on weekends. In this particular residential area, the power consumption during weekends appears to be smaller than that of weekdays.

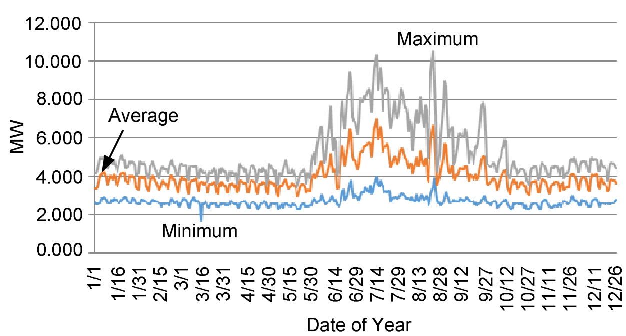

Fig. 8. Yearly Load Profile

Because the minimum daily and weekend loads can be smaller than 3.5 MW, there is a high chance that power will be exported to the utility. Due to this concern, one of the main control requirements is a nonexport condition.

The intertie of the PV generation plant to the feeder is a recloser. The PV plant is about 150 feet away from the recloser and about two miles from the substation. The main components of this system are the master controller, a recloser control, a protective relay, seven 500 kW PV inverters, and a small local SCADA and HMI system. The protective relay is located in the substation outside of the PV generation plant.

The control system requirements can be summarized as follows:

- When the relay detects a power export (power measured at the substation is less than zero), the control system must disconnect the PV generation plant from the feeder within 2 seconds.
- When the relay detects a low load condition (defined by a threshold), the control system must turn off all inverters. The reason for this requirement is that every time the PV generation is disconnected from the feeder, an operator must go to the plant and manually close the recloser. This can be time-consuming and can also depend on the availability of the operators.
- When the relay detects a load lower than a second threshold, which is known as the curtailment condition, the control system must curtail the power output of the inverters. Similarly, every time the PV inverters are switched off, they take minutes to ramp up their production. Repeated on/off operations not only degrade the performance of the plant, but also introduce behaviors similar to the cloud effect that can negatively impact the stability of the network.
- The power factor measured at the POI must be maintained at a set point, and the set point can be changed from the local SCADA and HMI system.

The system is composed of two communications media that share a common master controller. A fiber-optic network is formed among the PV inverters and the master controller. The second network is a radio link between the master controller and the substation. The master controller communicates with the inverters using Modbus TCP/IP. The radio link has three channels, one of which is used for control and another for the substation (local) SCADA and HMI system. The control channel uses a proprietary high-speed point-to-point serial communications protocol. The data collection channel uses the Modbus RTU serial communications protocol. Because the master controller and the recloser controller are in the same enclosure, they communicate via a serial copper cable using a proprietary high-speed point-to-point protocol.

The power factor control is implemented as described previously. The nonexport and power curtailment controller is implemented as shown in Fig. 9. The quantity of power *P* is measured by the relay at the substation. The relay is programmed to generate four bits of data based on the thresholds X1, X2, X3, and X4. Then the data are sent to the master controller. As soon as the controller receives the data, it sends the control signals as follows:

- In normal operation, the measured power (*P*) is above X4.
- If the measured power drops to equal or less than X3, the controller sends a curtailment command to the inverters.
- If the measured power drops to equal or less than X2, the controller sends a turn off command to the inverters.
- If the measured power drops to less than X1 (zero), the controller sends a trip command to the recloser control.
- If the measured power increases to greater than X4, the controller sends a power increase command to the inverters.

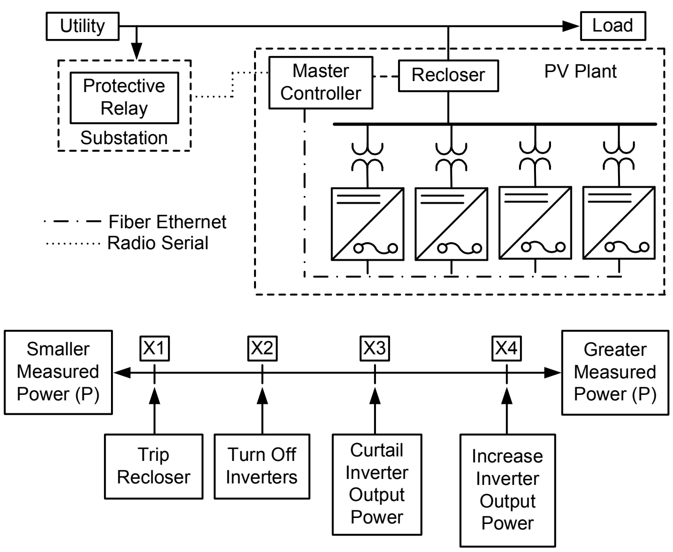

Fig. 9. Nonexport Control Scheme and Power Curtailment

In this implementation, the control system effectively enforces the nonexport condition by first attempting to curtail the output of the inverters. If that fails, it attempts to switch off the inverters. If both fail, the controller trips the recloser as a last resort. The purpose of having the thresholds X3 and X4 is to allow for dynamic adjustments to the inverter output power to match the load. Although these two thresholds, were selected by the city based on historical data, they are not optimal. The city chose to keep the selected thresholds and no optimization was conducted.

A. Power Curtailment Algorithms

1) Simple Steps

The simplest power curtailment algorithm is to immediately reduce the amount of power to a fixed number (e.g., 20 percent [or another percentage depending on the application] of the rated value when *P* drops below X3). When *P* increases to greater than X4, the controller sends the commands to raise the output to the maximum as shown in (4).

$$
\begin{aligned}
P_{SP} &= P_{Max} \text{ if } P > X_4 \\
P_{SP} &= P_{Min} \text{ if } P < X_3
\end{aligned}
\tag{4}
$$

where:

P_{SP} is the output power set point sent to the inverters.

$P_{Min} = 0.2 \bullet P_{Max}$.

This algorithm can be effective for applications where the plant needs to rapidly reduce its production to a certain amount. However, the sudden drop in the plant output power can negatively impact the local-area power system depending on the PV penetration. To avoid a sudden increase of output power, the ramp rate of the inverters can be used to limit the rate of increase. By combining the algorithm and the ramp rate, this power curtailment scheme can be applied to numerous applications.

2) Linear Curtailment

Instead of reducing the output power in one step, the output power can be reduced incrementally in multiple steps. In this implementation, the power curtailment algorithm follows a linear equation as shown in (5).

$$
\begin{aligned}
P_{SP} &= P_{SP} - 10\frac{kW}{s} \bullet T_i \text{ if } P < X_3 \\
P_{SP} &= P_{SP} + 10\frac{kW}{s} \bullet T_i \text{ if } P > X_4
\end{aligned}
\tag{5}
$$

where:

T_i is the time interval between consecutive power set-point changes.

In this example, 10 kW per second is used to either increase or decrease the output power. Because the controller sends the set point periodically, the output experiences the multiple step effects shown in Fig. 10.

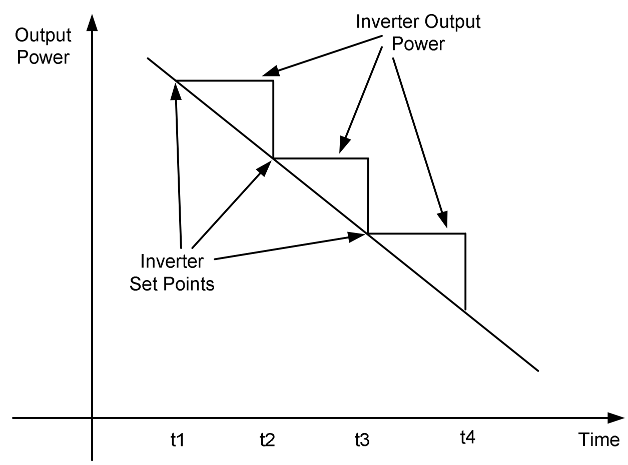

Fig. 10. Power Curtailment Using Linear Equation

In this example, the two power curtailment methods were tested, which showed that the simple step algorithm was more effective in reducing the output power rapidly.

3) Other Algorithms

Two other algorithms that can be considered are nonlinear equations for the curtailment and multiple ramp rates. The controller can use an exponential decay equation for the curtailment, where the output reduces rapidly at first and then slows down. The exponential equation can be used for the power increase. The second algorithm uses multiple ramp rates for changing power set points—one set for power increase and another set for power decrease.

B. Limited Export Power

In cases where export power is allowed but limited, the same control algorithm can be used to meet the requirement by simply changing the thresholds programmed in the protective relay. The threshold X1 is the maximum power export allowed in the system and is negative when taking the imported power as positive.

IX. Example 4: Solar Tracker Control and Sequential Step Control

Consider a 20 MW PV generation site similar to the one described in Example 1. The PV modules are mounted on a structure with single-axis solar trackers instead of a fixed structure. In addition, the plant is tied to two independent electric power system branches and has a generator on-site.

The control requirements for this site are as follows:

- Stow all trackers when high winds occur.
- Position all trackers at predefined angles. One is the angle for cleaning the PV modules.
- Turn off the PV inverter and put all of the trackers in the stowed position when the site experiences a power outage. This is the requirement to switch the entire plant into the predetermined or known state. When the inverters are turned off, they must be turned back on manually from the SCADA and HMI system.

In this application, the solar trackers are divided into ten zones, where each pad is a zone. Each zone has 26 individual controllers, and each controller manages a predetermined number of PV modules. In order for the master controller to communicate with a manageable number of devices, a programmable logic controller (PLC) is used in each zone. In this case, the master controller communicates with ten PLCs and the PLCs communicate with individual tracker controllers. However, because the master controller must be able to control individual tracker controllers as a control requirement, the master controller needs to send 26 commands to the PLCs. As discussed previously, discrete data are being exchanged between the master controller and the PLCs.

A closed-loop control scheme is used to stow the trackers when high winds occur. To position the trackers at a predefined angle, the master controller sends one bit of data to all 260 tracker controllers.

The control logic briefly described in Sections II and IV puts the entire plant in a known state after a power outage. The flow chart diagram in Fig. 11 illustrates a simplified sequence of steps. In this example, some of the logic that normally resides in the master controller has been shifted to the protective relays. As shown in the diagram, the protective relays are responsible for which secondary source is available and the master controller assumes there is always a secondary available. It could be the second branch of the electrical network or the local generator. Tests have shown that closed-loop control combined with sequential step control meets the control requirements.

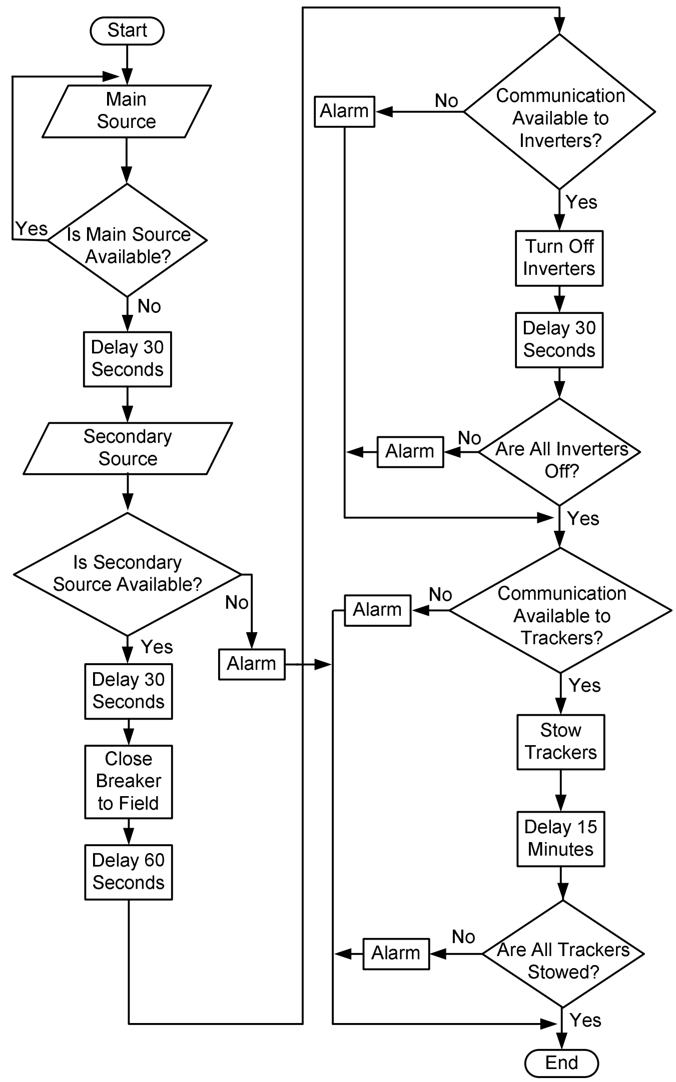

Fig. 11. Simplified Flow Chart Diagram to Turn Off Inverters and Stow Trackers

X. Conclusion

Solar PV power plants continue to emerge and can greatly impact the electrical networks into which they are being integrated. As a result, it is becoming increasingly important to employ aggregate control schemes using the proposed architecture to solve the practical challenges associated with interconnecting large utility-scale PV installations with the bulk market. Interconnection needs, plant size and location, and utility operational practices drive the need for a flexible and configurable solution set to assist in the integration of these renewable resources. The proposed control system solution serves as a single-point interface with internal and external systems, simplifying the communications burdens while providing the necessary functionality to meet a wide range of end control requirements. This paper provides a discussion of differing control techniques that leverage this flexible set of equipment, showcasing some of the capabilities of the control techniques and showing how challenges with distributed power plants can be overcome.

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XII. Biographies

Michael Mills-Price is the technology development lead for the solar energy business unit at Advanced Energy Industries, Inc. Michael is the principal designer responsible for bringing new technologies to market and continues to lead teams toward advanced systems control to broaden the scope and lessen the impacts associated with widespread photovoltaic adoption. Michael received his Bachelor of Science and Masters of Science in Electrical Engineering from Oregon State University (OSU), is a registered professional engineer, and is an active member of IEEE. Michael is also an adjunct professor at OSU, teaching senior level energy storage and energy distribution systems courses.

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.

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