Mitigating the Impacts of Photovoltaics on the Power System

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Abstract—**Integrating photovoltaic generation plants into electric power systems can impact grid stability, power quality, and the direction of power flow. To minimize such impacts, this paper proposes a simple and practical solution that uses high-speed control and radio communications to quickly reduce the output of the entire plant to match local loads and limit the amount of power flowing toward the closest substation. The paper discusses how the proposed curtailment algorithm can minimize the impacts on the power system, installed equipment, and protective relays while taking into account system parameters such as availability, latency, security, and dependability.**

I. INTRODUCTION

The integration of photovoltaic (PV) generation plants into existing electrical networks has increased rapidly in recent years. This is largely driven by state and national mandates to meet renewable energy portfolio requirements. Integrating the intermittent power of PV generation 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 PV generation plant to an existing electrical network. The small portion of the electrical network shown in the figure, which could be part of a distribution or subtransmission network, includes several branches of customer loads. Due to certain characteristics of PV generation (i.e., no rotating parts and no inertia), the output power fluctuations at the point of interconnection (POI) vary widely, depending on the incident solar radiation. If the PV penetration is high, a sudden decrease in solar radiation can cause the voltage to drop below the prescribed variations (5 to 10 percent) and protective relay undervoltage elements to open the circuit breaker at the POI [1] [2].

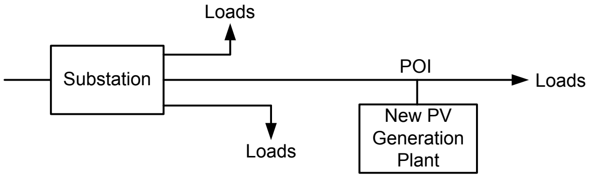

Fig. 1. PV Generation Plant Inserted Into Electrical Network

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 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 parallel feeder circuits. Circuit design, coupled with electrical installation location, can affect the voltage variations, grid stability, voltage regulation schemes, power quality, and protection and coordination [3].

This paper first describes a few key characteristics of PV generation. It then lists the impacts of PV installations on power systems and discusses different mitigation methods to address them. The paper proposes a solution to minimize the impacts by using the concept of coordinated control between the substation and the PV generation plant. The aggregate control mechanism leverages the PV inverters to match the amount of power (both real and reactive) needed and thus minimizes the impacts on the electric network [2] [3] [4] [5] [6]. The solution uses high-speed control and wireless communications to quickly reduce the output of the entire plant to match local loads and limit the amount of power flowing toward the substation.

II. PV GENERATION CHARACTERISTICS

While PV generation characteristics can be described at the PV module level, this paper describes them at the plant level. The characteristics that impact the power system are described in this section.

A. *Output Power*

Unlike conventional generation plants, PV generation plants do not have rotating parts (and thus no inertia), and their output power is highly sensitive to solar radiation. A sudden increase or decrease in solar radiation can cause large and fast variations of the output power. This occurs, for example, after sunrise when PV power output rises significantly and quickly. It is possible for the PV to reach its maximum power output in seconds; how quickly it reaches its maximum depends on the ramp rate of the inverters. A large and sudden variation can also occur when clouds sweep over the area where the PV is located. Once clouds start covering the area, PV output can quickly drop below 10 percent of maximum. A similar effect occurs when the clouds move away from the area.

Depending on the percentage of PV penetration, the variation in solar radiation can cause undesirable voltage fluctuations and impact the operation of protection equipment. These impacts are detailed in Section III.

B. *Ramp Rate*

The ramp rate is the percentage of change to the apparent power or rated power per second [7]. It is a physical characteristic of power-electronics-based devices that allows rapid changes to the output waveform, which can cause harmonic injection and transient behavior at the POI [8].

C. Ride Through

Another important characteristic of PV generation is the ride-through capability of the inverters. Regulations require inverters to rapidly disconnect from the power system during system events. The disconnection period is based on the voltage per-unit deviation. The existing IEEE 1547 low- and high-voltage limits, along with the new proposed limits (IEEE 1547a), are illustrated in Fig. 2. The black lines represent the existing IEEE 1547 limits. The remaining curves represent the proposed limits. The green lines (Limits B and C) represent the must-stay-connected limits, while the red lines (Limits A and D) represent the must-disconnect limits [8]. The impacts of PV generation on the power system depend on how long the inverters are connected to the grid after system events occur.

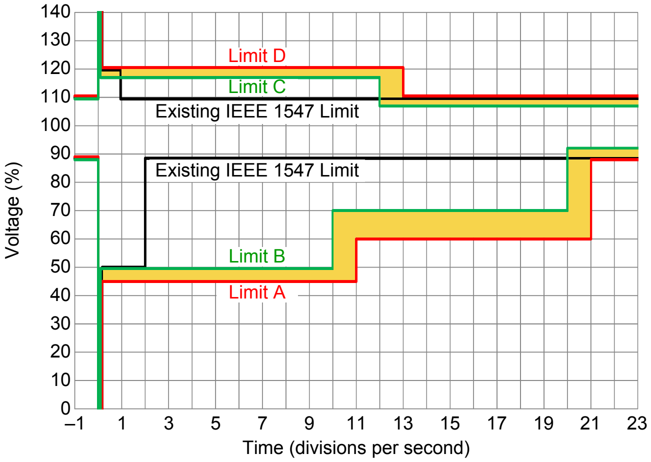

Fig. 2. Existing IEEE 1547 and Recommended IEEE 1547a Voltage Ride-Through Limits

III. IMPACTS ASSOCIATED WITH GRID-TIED PV INSTALLATIONS

The introduction of PV installations into power systems that were originally designed to operate in one direction (i.e., from the substation to customer loads) can significantly impact the power flow direction, voltage, utility protection equipment, and customers. The severity of the impacts depends on the PV penetration. A high penetration can cause significant voltage fluctuation as the result of changes in solar radiation. A penetration above 10 percent can reduce voltage by more than 6 percent [1]. This section describes the impacts of PV installations on power systems and their consequences.

A. Voltage Regulation

When a PV generation plant is added to a distribution system, the injection of power into the system affects voltage regulation device operations. Radial distribution systems regulate the voltage with the help of load tap changer transformers located at substations. To compensate for losses along distribution lines, some feeders have voltage regulators and shunt capacitors installed along the line. Typical voltage regulation is based on the assumption of one-way power flow. PV generation plants connected to distribution systems can change the voltage profile along a feeder as a result of injecting power. How PV generation plants impact voltage regulation depends on the distribution system, the location of the plant, and the voltage regulation equipment.

In addition, because PV plants only inject power during the day and the voltage needs to be maintained day and night, the voltage regulation equipment likely requires different voltage settings during the day than at night. Implementations have shown that voltage regulation equipment operates more frequently when PV installations are present. The increase in the number of operations can reduce the lifespan of this equipment [9].

B. Overvoltage

When PV power output rises significantly and suddenly due to increased solar radiation, it can cause overvoltage in a distribution feeder. Voltage rises can cause equipment damage and protection malfunctions. Some utilities consider a 5 percent rise above the nominal voltage a violation [9]. In addition, customers located close to a PV installation may experience overvoltage if the voltage regulation schemes are not adjusted appropriately.

C. Undervoltage

A sudden drop in solar radiation can cause a sudden reduction in output power. When this happens, the load on the feeder experiences a sudden increase. This quickly results in an undervoltage condition. To prevent islanded operation of PV installations, all inverters are equipped with over- and undervoltage relay protection as well as ride-through capabilities. Typically, PV inverters trip when the system voltage drops below the range specified by the IEEE 1547 standards. When the voltage drops below the limit, the PV generating units can trip due to the operation of the undervoltage relay.

D. Reverse Power and Backfeeding

When a PV installation is located far away from a substation with loads between them, the power can flow in opposite directions from the two sources toward the loads. Power flow can change direction in distribution power systems when the PV generation is larger than local consumption. This reverse power can cause power quality issues resulting from voltage variations [10].

Backfeeding occurs when PV generation on a feeder exceeds feeder demand and losses and the excess flows into parallel feeders through a substation bus or flows out of the substation [9]. This can occur when PV penetration is high during low-load periods. As the penetration level increases, backfeeding occurs more often and at a higher loading level.

E. Islanding

Islanding occurs when PV generation continues to energize a portion of the power system that has been separated from the utility grid. The separation can be caused by many factors, such an opening of the feeder breaker, recloser, or sectionalizer. Typically, this is not desirable because an island can cause safety issues for maintenance crews. In addition, power quality can deteriorate because the system voltage and frequency are no longer available. On the other hand, PV installations do not experience reconnection issues because they do not require synchronization, as compared with synchronous generators.

When a fault occurs at a location that is fed from both the grid and PV generation, the grid-side breaker opens to clear the fault. Once the breaker is open, the voltage collapses and the PV installation ride-through mechanism operates. The PV installation can feed power to the fault for a few cycles up to two seconds, depending on the ride-through algorithm decisions.

IV. SOLUTIONS TO MITIGATE IMPACTS

This section describes solutions to the impacts of PV installations on the power system that have been proposed in technical literature.

A. *Overvoltage Mitigation*

Overvoltage can be limited by using the volt-ampere reactive (VAR) mode of the inverter. When the voltage increases on a feeder, the VAR mode control scheme can dynamically respond by tuning the power factor to sink reactive power as needed to mitigate the voltage that is above the desired level. In case the reactive power is not sufficient to reduce the overvoltage, power curtailment is another way to maintain grid stability [11].

B. *Undervoltage Mitigation*

PV output is high when it is sunny, but when clouds appear PV output power can drop very quickly. The voltage drops as quickly as the power, resulting in an undervoltage condition. One solution to mitigate this voltage fluctuation condition is to limit the amount of PV output power injected into the grid [11]. Another solution is to use weather predictions to reduce the expected amount of output power when clouds are expected. This requires the use of real-time weather measurements and weather forecast algorithms. The weather forecast software needs to be integrated with the PV inverter controllers.

C. *No Power Export or Limited Export*

Many utilities do not allow PV power to be exported or limit the export amount. The PV power is typically used for local loads. The reasons are related to the voltage rise, fault currents, and coordination issues. The goal is to not propagate these impacts throughout the power system.

D. *Anti-Islanding*

While there are many anti-islanding techniques, they can be classified into two categories: one depends on remote devices and the other depends only on local devices. Local anti-islanding techniques can be further divided into passive and active detection techniques. The remote islanding detection technique is based on communication between the utility and the PV site. Remote detection techniques have higher reliability than local detection techniques but are more expensive to implement.

One of the simplest methods to detect an island is to monitor the trip status of the substation circuit breaker. As soon as the breaker trips, a high-speed signal is sent to trip the POI breaker. In practice, most utilities use this technique as an interconnection requirement, especially when no export is allowed. This technique is also known as transfer trip.

V. PROPOSED SOLUTION

Based on the mitigation methods described in Section IV, utilities recommend a solution that includes the following capabilities [1] [12] [13]:

- Dynamically controlled PV output power (power curtailment).
- A minimum import relay or reverse power relay to disconnect the PV system if the power flow from the utility drops below a set threshold.
- Power factor control.

Based on these requirements, the solution proposed in this paper includes the following:

- A closed-loop power factor controller.
- A closed-loop plant output power controller.
- A closed-loop voltage controller.
- A power curtailment controller that can be controlled by load conditions and weather conditions.
- A non-export or limited-export controller.

These controllers are implemented in the master (plant) controller, and the solution offers three modes of operation: constant output power, variable output power, and constant voltage at the POI.

In the constant output power mode, the plant output is constant and is set by the operator. This mode uses the closed-loop plant output power controller. The power factor of the PV installation can be adjusted based on demand either from supervisory control and data acquisition (SCADA) and a human-machine interface (HMI) or as measured by the substation. The non-export or limited-export controller is enabled and has the ability to prevent or limit backfeed. To avoid a sudden output power drop due to weather conditions, the power curtailment controller can be enabled and controlled by the weather forecast system. When the weather forecast system is controlling the output power, the closed-loop plant output power controller should be disabled.

In the variable output power mode, the plant output is the total amount that can be produced by the inverters with the given solar radiation. This mode uses the power curtailment controller and can curtail output power when the PV generation exceeds local loads or when the weather conditions cause a sudden power drop. The closed-loop power factor controller is enabled to meet the demand. The non-export or limited-export controller is enabled and is used as a backup when the power curtailment controller fails or cannot react fast enough to the sudden load-change conditions.

In the constant voltage control mode, the voltage at the POI is maintained. The controller adjusts the amount of reactive power of the PV installation to maintain the voltage. The output power and the power factor vary accordingly. The non-export or limited-export controller can be enabled.

A. Architecture

The proposed mitigation solution consists of protective relays, meters, PV inverter controllers, a plant master controller, a substation controller, a weather forecast system, weather stations, SCADA and HMIs, and communications devices and networks, as illustrated in Fig. 3. For simplicity, the communications devices are omitted from the figure. Relevant details and functional descriptions of the equipment can be found in [7], [8], and [14].

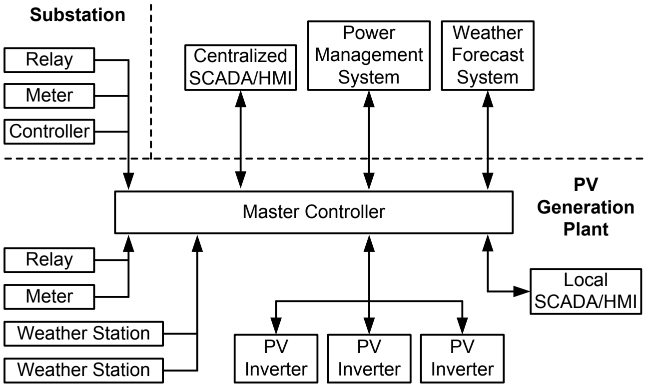

Fig. 3. Proposed Solution Architecture

1) Substation Devices

The protective relays in the substation provide protection to substation assets, such as transformers, feeders, and buses. The relay that interfaces with the main breaker uses minimum import or reverse power elements. Once it senses the minimum import or reverse power condition, the relay sends a signal using a high-speed communications protocol to the PV site so that the master controller can either turn off all inverters or trip the POI breaker. This relay is also used to implement the conditions for power curtailment. The substation controller makes decisions about power factor needs to mitigate voltage issues and support reactive demand. The controller uses information from the main breaker and feeder relays, operating conditions, SCADA and HMIs, and power management systems to determine the power factor set point of the PV system.

2) Communications Systems and Networks

The communications systems and networks are crucial parts of the solution. References [7] and [8] provide details about the communications systems and networks that are essential for the system. Security and cybersecurity are important and should be given serious consideration during implementation. However, for the sake of brevity, they are omitted from this paper.

Standard (open) communications protocols are preferred to proprietary communications protocols in the system. Standard communications protocols offer the advantage of interoperability among different manufacturers' devices. 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 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 the solution.

3) 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 [15]. Other high-speed proprietary protocols include point-to-point serial-based protocols, such as MIRRORED BITS® communications.

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 others.

4) Technical Requirements for Master Controllers

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 system to separate control functions for different applications and delegate tasks based on their time requirements. 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 provide an application interface to the user. This helps avoid undesirable changes to the core functions caused by user error.

5) Weather Forecast Systems and Weather Stations

Due to the inherently variable, volatile, and intermittent nature of solar radiation, it is a great challenge for a utility to predict and forecast the amount of energy PV generation plants will produce at any given 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 for achieving an accurate forecast of power production. Local weather stations provide real-time weather data to forecast systems.

The goal is to use the forecast system to smoothly reduce PV output power when clouds are expected. This can prevent undervoltage issues. The forecast system determines the amount of power expected to be produced by the PV installation and send the curtailment conditions to the master controller. Then, the master controller sends the control signals to the PV inverters accordingly.

B. Implementation

Fig. 4 shows an implementation of the proposed solution.

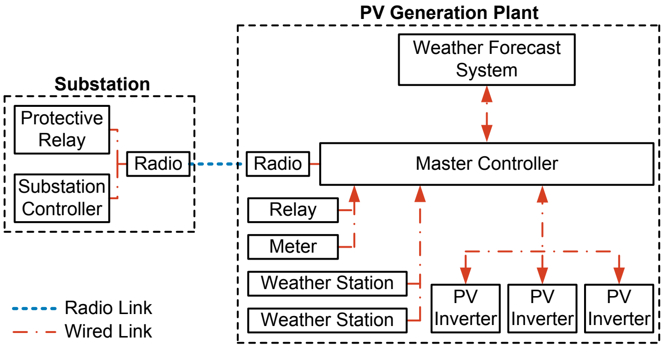

Fig. 4. Implementation of the Proposed Solution

1) Wireless Communications

Usually, a PV generation plant is tapped off of (or interconnected to) an existing power line, such as a distribution power line. The distance between the POI and the closest substation can range from a few hundred yards to miles. Although fiber-optic cables provide an effective means of communication, their cost can be quite high for the required distance. A pair of radios that support high-speed communication can be a more economical and attractive solution.

Because the radios must support high-speed communications protocols, serial radios or Ethernet radios that support IEC 61850 are suitable. In addition, the application may require sending analog values (set points) from the substation to the PV generation plant for the closed-loop controllers. Serial radios that support multiple channels meet the communications requirements, with one channel used for discrete high-speed data points and a second channel used for the analog values. For serial radios, a proprietary communications protocol, such as MIRRORED BITS communications, with a 9,600 bps data rate is fast enough for the high-speed control of the application. For Ethernet radios, the IEC 61850 protocol is configured to support both discrete and analog data points. IEC 61850 GOOSE messages meet the communications requirements. In order to prevent a large and unnecessary transfer of analog values, the dead band of the analog values should be carefully evaluated.

2) Closed-Loop Power Factor Controller

Fig. 5 illustrates the closed-loop power factor controller implementation. The controller resides in the master controller and interfaces with the PV inverters, protective relays, SCADA and HMIs, and substation controller.

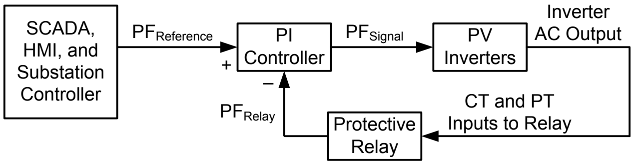

Fig. 5. Closed-Loop Power Factor Controller Implementation

Fig. 6 shows the proportional and integral (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. The power factor error (PF_{Error}) is $PF_{Reference} - PF_{Relay}$.

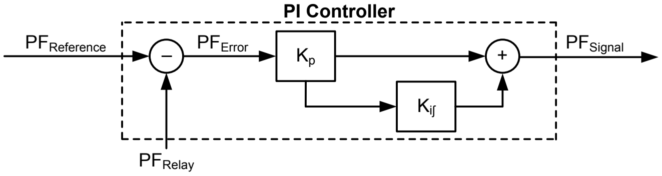

Fig. 6. PI Controller Implementation

The integral term is approximated by a difference equation and leads to the recursive equation shown 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 integral term at 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 (2), 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 (3) to update its output control signals.

The controller is implemented using IEC 61131 structured text. It is capable of maintaining 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 or the substation controller.

The system performance shows that the power factor is kept in the range of 5 percent of the reference set point under normal conditions [7].

3) Closed-Loop Plant Output Power Controller

The main objective of the closed-loop plant output power controller is to limit the total output power of the PV plant to a specific amount. This amount is less than the maximum generated by the PV at its full, rated capacity. The total output might be smaller than the specified amount if there is insufficient solar radiation.

The implementation of this device is exactly the same as that of the closed-loop power factor controller. The reference is the output power amount, and the real-time PV output power is measured by the relay. Once the control signal is computed, the master controller knows the total amount needed from the inverters. The controller divides the amount equally among the online inverters and sends the control signals accordingly.

4) Closed-Loop Voltage Controller

The closed-loop voltage controller maintains a constant voltage at the POI. The controller adjusts the reactive power of the PV inverters to maintain the voltage. Its implementation is exactly the same as that of the closed-loop power factor controller. The reference is the voltage at the POI measured by the relay. The controller computes the amount of reactive power needed, divides the amount equally among the online inverters, and sends control signals to the inverters.

5) Power Curtailment Controller

The relay at the substation provides signals for power curtailment. A simple solution is to have two thresholds: a curtailment threshold and a rise threshold. The curtailment threshold is the smaller of the two. When the relay detects a load that is lower than the curtailment threshold, the relay sends a high-speed control signal so that the master controller at the PV generation plant can curtail the output power. The high speed is needed so that the PV generation can quickly match the load, avoiding any export or triggering of the non-export controller. When the relay detects a load that is higher than the rise threshold, the relay sends a high-speed control signal so that the plant can start increasing PV generation.

Multiple curtailment thresholds are possible and each threshold can use a different curtailment algorithm. For instance, higher curtailment thresholds lead the controller to curtail more slowly and lower curtailment thresholds allow the controller to curtail more quickly. The rationale behind this is that the lower the threshold, the higher the chance of triggering the non-export controller if the curtailment controller does not react quickly enough.

The power curtailment controller is implemented as shown in Fig. 7. This implementation also includes the non-export and limited-export controller. X3 is the curtailment threshold, and X4 is the rise threshold discussed previously. The X1 and X2 thresholds are part of the non-export or limited-export controller. The quantity of power (P) is measured by the relay at the substation. The relay is programmed to generate four control signals based on the X1 through X4 thresholds. The signals are sent to the master controller. As soon as the master controller receives the signals, it implements them as follows:

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

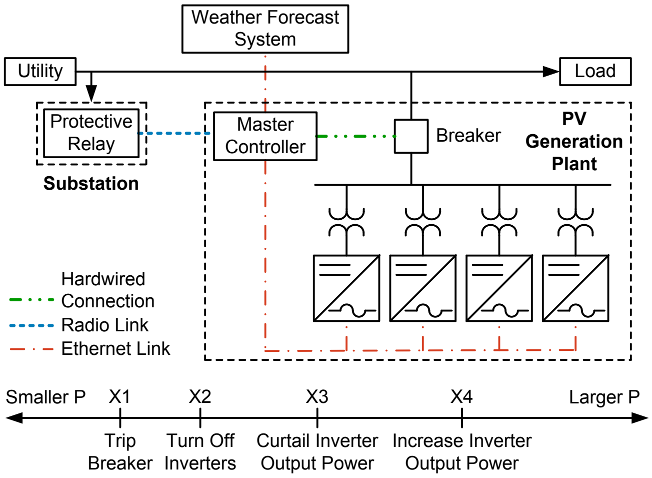

Fig. 7. Power Curtailment Implementation

a) Power Curtailment Algorithms—Simple Steps

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

$$\begin{aligned} P_{SP} &= P_{Max} \text{ if } P > X4 \\ P_{SP} &= P_{Min} \text{ if } P < X3 \end{aligned} \tag{4}$$

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.

b) Linear Curtailment

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

$$\begin{aligned} P_{SP} &= P_{SP} - 10\frac{kW}{s} \bullet T_{ic} \text{ if } P < X3 \\ P_{SP} &= P_{SP} + 10\frac{kW}{s} \bullet T_{ic} \text{ if } P > X4 \end{aligned} \tag{5}$$

where:

T_{ic} is the time interval between consecutive power set-point changes.

In this example, the output power is either increased or decreased by 10 kW per second. Because the controller sends the set point periodically, the output experiences the multiple step effects shown in Fig. 8. Implementations have shown that the simple step algorithm is more effective than the linear method in rapidly reducing the output power.

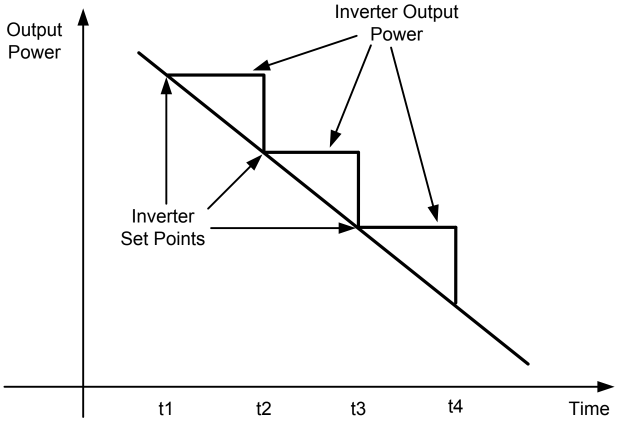

Fig. 8. Power Curtailment Using Linear Equation

c) Other Algorithms

Two other algorithms that can be considered are nonlinear equations for the curtailment and multiple ramp rates for multiple thresholds. 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 also 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.

6) Non-Export Controller

The non-export controller uses the X1 and X2 thresholds shown in Fig. 7. When the relay detects power export (power measured at the substation is less than X1, i.e., zero), the control system must disconnect the PV generation plant from the feeder in less than 2 seconds.

When the relay detects a very low-load condition (i.e., power measured is less than X2), 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 might need to go to the plant and manually close the breaker. This is a common utility practice that can be time-consuming and can also depend on the availability of the operators.

The implementation effectively enforces the non-export condition by first attempting to curtail the output of the inverters. If that fails, the controller attempts to switch off the inverters. If both fail, the controller trips the breaker as a last resort, which is typically required by the utility.

7) Limited-Export Controller

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 X1 threshold is the maximum power export allowed in the system and is negative when power is imported.

VI. SYSTEM PARAMETER CONSIDERATIONS

When designing and implementing the solution, many factors should be considered in the overall system performance. While numerous parameters can be discussed, this paper considers the following:

- Availability.
- Latency.
- Security.
- Dependability.

A. Availability

Availability is the ratio of time a system is functional to the total time it is required to function. A high availability is desirable. For instance, an availability of 99.95 percent implies 265 minutes of outage per year, and an availability of 95 percent equates to 438 hours of outage per year. For the proposed solution, the availability is most critical for the non-export or limited-export controller. The availability and the integrity of data are critical for the closed-loop controllers.

The availability of the relays and controllers can be determined by the mean time between failures (MTBF) and the mean time to repair. Reference [16] provides the availabilities of a variety of power system devices, such as relays, current transformers, and others. It shows that the availability of the hardware equates to 316 ms of outage per year. Considering this, the radio link availability is more critical than that of the hardware.

The radio link availability is the ratio of the time the radio link provides good data to the total time the radio transmits data. The link availability varies by manufacturer and from one line to another. Reference [17] suggests that an availability of 99.95 percent for a radio link is sufficient for a protection system. Because the non-export and limited-export controller can be treated as a protection scheme, the suggested availability is reasonable for the solution.

B. Latency

Latency is defined as the delay between an input into a system and the desired output. In general, the latency of relays is quite consistent. For automation controllers that support multiple programs and tasks, and in which each task can have its own task cycle, the latency is quite deterministic. On the other hand, the communications network can experience variable latency that can affect the performance of the system. For the solution presented in this paper, the network latencies to consider are those of the radio link and the wired network links.

The radio link latency depends on the protocol used, the technology, and the type of communications [17]. Serial radios typically experience less variation than Ethernet radios. The wired network latency depends on the network topology, protocol, routing mechanism, and the amount of traffic on the network. To ensure the operation of the system, it is critical to determine the average, minimum, and maximum latency expected for a given operation.

As discussed in [7] and [14], long control cycles in power factor controllers can cause the system to become unstable and unable to converge to the set point. Large latency variations or random network latency can be larger than the control cycle, which can cause the performance of a closed-loop control system using a PI controller to deteriorate. When evaluating the system, it is important to ensure that the latency does not affect the controller algorithms.

C. *Security and Dependability*

Security is defined as the degree of certainty that the system will not operate incorrectly. It is the ability of a system to refrain from unnecessary operations.

Dependability is defined as the degree of certainty that the system will operate correctly. Dependability is easy to ascertain by testing that the system will operate as intended.

As availability decreases, dependability also decreases [16] [17]. One way to achieve dependability is to have redundant components in the system. While this is feasible, the complexity and cost increase and security is likely to decrease. These tradeoffs must be carefully evaluated.

Besides the availability of the hardware components, such as relays, master controllers, network devices, radios, PV controllers, and so on, the availability of the communications between devices and data integrity are crucial to the correct functioning of the proposed solution. For instance, the use of latency bits or counters between two communicating devices is preferred for detecting communications failures rather than relying on status indicators internal to the equipment [14]. It is also critical for the controllers to perform a sanity check and ensure that the data are always in the valid range before performing any computation or sending them out [8]. These steps help improve the dependability of the system.

VII. CONCLUSION

PV generation plants continue to increase in number and can greatly impact the electrical networks they are integrated into. As a result, it is becoming increasingly important to employ mitigation schemes using architectures like the one proposed in this paper to solve the practical challenges associated with interconnecting utility-scale PV installations with the bulk electric system. 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 solution has been shown to meet utility interconnection and operational requirements in several implementations. The control mechanism of the proposed solution considers the entire plant output as a single generator and serves as a single-point interface for individual inverters and external systems. The proposed solution mitigates the impacts discussed and is applicable to a wide range of PV installations. The solution offers two modes of operation that can be used based on the grid and local operation needs. The use of radios simplifies installation and reduces costs as compared with fiber-optic cables.

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