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A Study On The Impact Of High Penetration Distributed Generation Inverters On Grid Operation And Stability

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Abstract: Recent advances in inverter technology have enabled ancillary services such as volt/VAR regulation, SCADA communications, and active power filtering. Smart inverters can not only provide real power, but can be controlled to use excess capacity to provide reactive power compensation, power flow control, and active power filtering without supplementary inverter hardware. A transient level inverter model based on the Solectria 7700 inverter is developed and used to assess these control strategies using field data from an existing branch circuit containing two Amonix 68kW CPV-7700 systems installed at the University of California, Irvine.

Keywords: Distribution systems, volt/VR control, DC/AC inverter, photovoltaics generation.
PACS: 88.8-H-, 88.80.Cd, 84.30Jc.

INTRODUCTION

In recent years, the deployment and use of direct current alternative energy sources such as flat plate and concentrator photovoltaics has increased. The incorporation of these sources into the existing electrical grid introduces a new element into the power distribution paradigm; the DC-AC inverter. Such inverters are highly dynamic nonlinear devices and, while much effort has been made to understand their behavior, it is current practice to model these renewable power sources and their respective inverters as traditional power sources using steady-state load flow methods. While such approaches are sufficient to describe steady-state behavior, they may not yield an accurate representation of inverter behavior in the case of faults, surges, line and load transients, islanding situations, and other transient conditions [1]. In this paper, a transient level inverter model is developed and applied to model an existing branch circuit containing two Amonix 68kW CPV-7700 systems. Advanced control strategies including local voltage regulation, reactive power support, active power filtering, and communications are applied to the standard inverter model and the effects on grid operation are investigated.

APPARATUS AND METHODOLOGY

System Description

The Amonix installation is located at the eastern side of the University of California, Irvine campus at 33° 38' 23.29" N, 117° 49' 30.33" W. The site contains two Amonix 7700 CPV systems with a combined peak measured output of 139 kW at 937 W/m2 direct normal irradiation and an average cell efficiency of 39%. Each system contains a 21 x 12 module array mounted on a two-axis tracker and a Solectria 7700 PVI inverter. The branch circuit that connects the installation to the UCI microgrid also services the student recreation center which represents a peak load of approximately 400 kW. Data have been collected over the course of 293 days at a 1-minute granularity from each CPV panel and at the points of common coupling of the inverters and the recreation center.

FIGURE 1. Two Amonix CPV-7700 systems installed at the University of California, Irvine.

Inverter Model Development

A voltage-sourced inverter model representative of the Solectria 7700 inverters installed at the UCI Amonix site was developed with the MATLAB SimPowerSystems platform. The model allows for transient level analysis not available through steady

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state modeling methods. The direct-quadrature transform method with proportional-integral controllers was utilized for the controller [2]. The inverter diagram is depicted in Figure 2. Advanced inverter controls such as voltage and reactive power regulation, SCADA communications, and active power filtering are implemented as an addition to the existing inverter structure. Data obtained from the Amonix installation, in conjunction with electrical one-line and building load data, were used to study the impact of the system on the UCI microgrid to determine maximum PV generation limits.

regulation is not allowed by the IEEE 1547 standard. However, the IEEE 1547.8 group is working to propose the removal of this limitation [5].

SCADA Communications

The addition of inverter communications to local SCADA systems may prove beneficial to grid operations by allowing for flexible grid operation, diagnostics, and power flow control. The synchronization of inverters, which react very quickly to changes, to other devices such as shunt capacitor banks and on-load tap changers that switch only a few

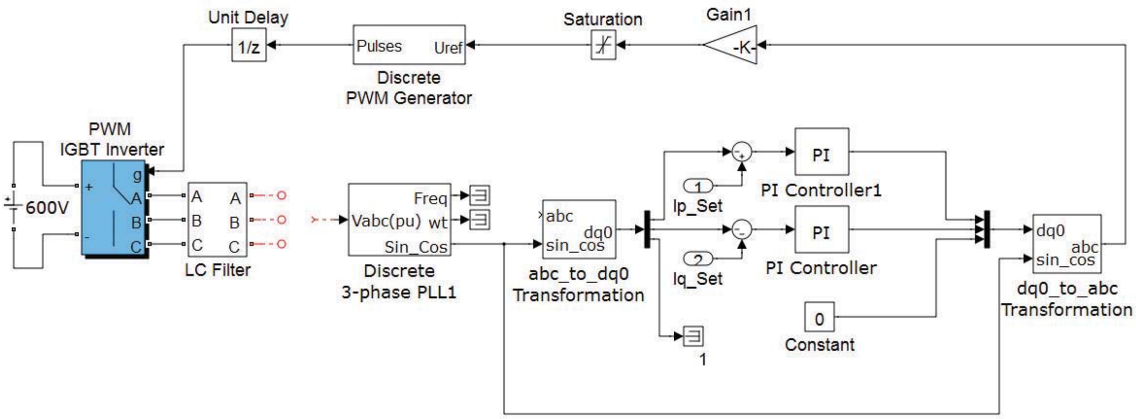

FIGURE 2. MATLAB/SimPowerSystems inverter model.

Reactive Power Support

At constant power factor output, line voltages decrease as real power production falls [3]. A common and abrupt occurrence of this in PV systems is due to sudden changes in insolation, such as panel shading due to clouds, animals or other sources of obstruction. To mitigate this, it is possible to utilize spare inverter capacity to produce reactive power to regulate line voltage [4]. Inverters are based on the same power electronics technology as reactive power compensation devices such as STATCOMs and are topologically similar. The flexibility, fast response, and physical proximity to loads make the inverter ideal for providing reactive power support.

This is especially effective in situations where inverters output minimal real power, such as shaded and nighttime conditions, where the majority of inverter capacity may be devoted to reactive power generation. In this research, an active volt/VAR compensator is added to the standard inverter model and effects on maximum allowable PV penetration is analyzed. It is important to note that at the time of writing, distributed generation based active voltage

times a day to relatively slow variations may increase overall maximum acceptable PV penetration limits. Additionally, results from volt/VAR control simulations indicate a possibility of multi-inverter instability when volt/VAR control is enabled which may be corrected through inverter communications.

SCADA communication is modeled as an external input for real and reactive power set points, as opposed to stand-alone controls and data outputs for real and reactive power generation and inverter status. Both inverters at the UCI Amonix installation are modeled with SCADA communications in combination with other advanced controls and maximum generation limits are assessed.

Active Power Filter

Many modern electronic loads are non-linear and inject considerable harmonic distortion into the power grid, resulting in poor power quality, overheating, and possible damage to sensitive electrical loads. With appropriate modifications, the DC-AC inverter may be configured to provide active power filtering functionality. The active power filter operates by supplying harmonic current so that only real power is drawn or injected to the grid at the point of common coupling. Here, the inverter model is modified to implement an active power filter based on the current-sine multiplication method in addition to real and reactive power generation [6].

Harmonic distortion measurements obtained from a Shark 200 power quality meter located at the Amonix installation point of common coupling were used to develop simulation scenarios to assess the effectiveness of inverter-based active power filtering.

Simulations

Line impedance data in conjunction with field data are used to create a simulated test environment to assess advanced inverter controls. Measured data from the Amonix installation include voltage, current, phase, harmonic content, and cell current at a 1-minute granularity. Direct insolation, diffuse insolation, and temperature data is also gathered at a 1-minute granularity. Real and reactive power measurements are taken from the recreation center feeder at a 15-minute granularity. Simulations are used to determine the maximum amount of allowable PV generation, and to determine the impact of high penetration inverters on grid operation and stability.

RESULTS

Volt/VAR Control

Active volt/VAR regulation is shown to dramatically increase the maximum amount of permissible installed PV generation before over-voltage conditions are met. Additionally, low voltage transients due to sudden solar insolation attenuation are greatly reduced. In distribution circuits where R >>X, inverter capacity limits are met before voltage stability limits are exceeded. The presence of two or more volt/VAR regulating inverters in close proximity is found to give rise to undampened oscillations in real and reactive power outputs, in severe cases resulting in cascading inverter failure. This may be remedied by shifting controls from a stand-alone configuration to a SCADA communications system.

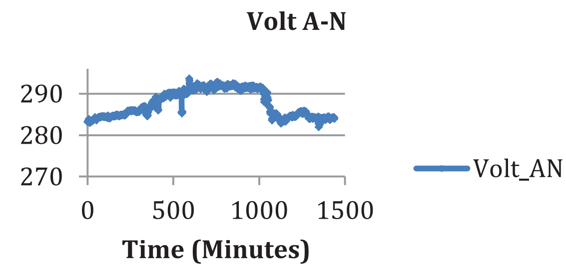

FIGURE 3. Measured line voltage from the UCI Amonix installation. Combined panel output at 113kW at unity power factor.

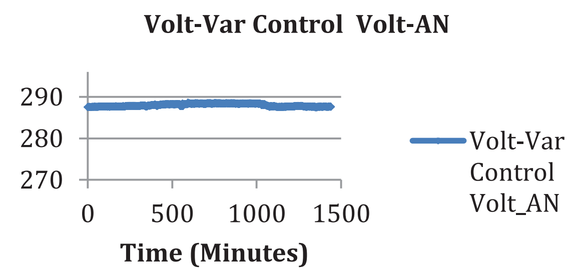

FIGURE 4. Simulated line voltage with advanced controls (VVC+COMM+APF). Voltage regulation improved by 4.4% while transmission efficiency improved by approximate 6%. Maximum allowable generation capacity increased by 57%.

TABLE 1. Maximum allowable generation limits as determined by ANSI C84.1 voltage tolerance boundaries. VVC = Volt/VAR control. COMM = Communications. APF = Active Power Filter. *Poor performance due to multi-inverter instability.

Advanced Control Technology	Max. Allowable Gen. (Local Load = 400kW)	Max. Allowable Gen. (Local Load = 100kW)	Total Current Harmonic Distortion (up to 40^{th})
Standard	384 kW	217kW	0.78%
VVC*	189 kW*	72kW*	28.5%*
VVC + COMM	601 kW	344 kW	1.22%
VVC + APF*	192 kW*	74kW*	21.3%*
VVC + COMM + APF	605 kW	347 kW	< 0.01%

SCADA Communications

The addition of inverter communications to local SCADA systems in conjunction with volt/VAR control greatly increases the maximum amount of allowable installed generation capacity by providing capabilities such as real power curtailment, power flow control, and reducing the effects of multi-inverter instability. The use of SCADA communications also allows for remote control from facility operators, allowing for flexible and autonomous control. Technical challenges include implementation of the SCADA network and development of an acceptable control scheme.

Active Power Filtering

Active power filtering is shown to reduce current harmonic distortion and marginally increase maximum generation limits. No detrimental multi-inverter active power filter interactions have been revealed in this study.

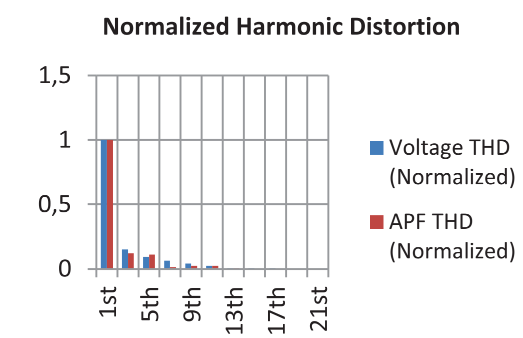

FIGURE 5. Active power filtering total harmonic distortion reduction. VVC-enabled multi-inverter system scenario.

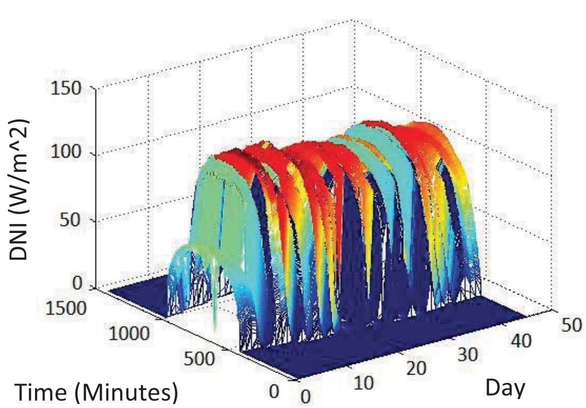

FIGURE 6. DNI data from the UCI Amonix installation. Data are used to construct simulation scenarios.

CONCLUSION

The effectiveness of advanced inverter controls is assessed based on the ability to increase PV generation limits while maintaining acceptable system conditions. Active voltage and reactive power regulation, communications, and active power filter capabilities have been evaluated individually to understand their fundamental effects and to identify regulatory and technology barriers. Active voltage and reactive power compensation coupled with local SCADA communications shows great promise in increasing the capacity limits of grid-tied distributed generation resources, and improving grid reliability and operation.

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