IMPROVING POWER QUALITY IN DISTRIBUTION FEEDERS WITH HIGH PV PENETRATION THROUGH INVERTER CONTROLS

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ABSTRACT

Voltage fluctuations caused cloud transients in distribution systems with a high level of distributed photovolaic systems is of concern to electric utility companies since this can lead to power quality issues. This article proposes a scheme that can minimize this problem by allowing grid-tie inverters to generate controllable amounts of reactive current in a way to neutralize the change in active current. Inverter over-sizing is not required by the implementation of this method. The performance of this technique is verified through computer simulations using PSCAD software.

INTRODUCTION

The number of distributed solar photovoltaic (PV) installations is growing rapidly, and this technology is expected to provide a significant share of the local electricity demand in the not too distant future. However, as this market grows, concerns about potential impact on the stability and operation of the electricity grid may create barriers to their future expansion. The main concern of electric distribution companies, as identified at a recent electric industry workshop sponsored by the US Department of Energy (DOE) [1], is the impact of PV power variability on voltage regulation.

Photovoltaic power output from a grid-connected array can change rapidly under the presence of moving clouds. With high levels of PV penetration, this may cause significant voltage fluctuations, possible voltage flicker, and excessive operation of the voltage regulating equipment [2]-[3]. While the aggregation of the power output from many dispersed PV systems over a wide geographical area tends to smooth out these variations, the level of smoothness is hard to predict as it as it depends on a large number of variables [4], and it is desirable to determine the worst case scenario.

One way to eliminate the above concern is to develop a scheme that will curtail the PV systems when signs of trouble begin to appear during cloudy days. While this method is simple, the communications and the switching devices needed to achieve this might be difficult to justify economically, except perhaps in areas where Advanced Meter Infrastructure (AMI) is already in place. Even in this latter case, a breaker with a capability to communicate with the smart meter is required. Another way to mitigate the effects of PV output variability is to use an integrated onsite energy storage system (e.g., a battery bank) that will generate and absorb energy as the PV array power fluctuates according to the solar resource [5]-[7]. However, this method is not economically feasible at present as current battery technologies are costly and have a relatively short life cycle. In addition, such batteries are required to operate at a partial state-of-charge, a condition in which they are known not to work as effectively as at or near full charge.

A promising method to alleviate the above problem is to replace existing inverters with new ones that are capable of providing ancillary services in addition to just active power generation. The concept of allowing PV inverters to provide reactive power injection while supplying active power from the PV systems is widely known as a desirable feature by the technical community [8]-[12]. The current standards, namely, IEEE Std.1547 and UL 1741, however, do not allow this to take place. But the pressure to make changes to these standards recently led to revisions (currently in draft form) that address both inverter low-voltage ride-through as well as active voltage regulation [13]. Some European countries have already revised their grid-tied inverter interconnection standards.

It is neither simple nor economical to convert current inverters which are optimally designed to provide only active power to ones with reactive power capability. In addition to larger current rating of various components, modifications to the controls, programming of the DSP, filters and protection devices are needed among other subsystems that that make up an inverter. The new design has to also optimize inverter efficiency and minimize the additional losses incurred by the reactive current flow.

This paper takes a closer look at the problem at hand, and proposes a simple and yet effective method to alleviate this problem through inverter controls. The main concern over high PV penetration in distribution feeders is fast voltage fluctuations caused during cloud transients; hence, a reduction of such temporary fluctuations will alleviate the problem. Voltage fluctuation is basically a result of the change in voltage drop across the distribution system impedance, and can be approximated by a sum of two components: *active* current times the *resistive part* of the impedance, and *reactive* current times the *reactive part* of the impedance.

With the presence of PV systems under fast-moving clouds, the change in voltage drop is solely a result of the change in the *active* current generated by the PV system as it flows through the *resistance* of the system impedance, i.e., change occurs only in the first component above. Hence, the problem can be theoretically eliminated if the second component can be modified to neutralize the change noted in the first component above. This can be achieved by making the PV inverter generate a controllable amount of reactive current under cloudy conditions to achieve this goal. No inverter overrating is required with the proposed scheme since the need for reactive current injection occurs only during low levels of power generation. The effectiveness of the proposed concept is simulated using PSCAD computer software.

PROPOSED CONCEPT

The specific innovation of this article is best described by quantifying the change in voltage drop due to a change in solar irradiance. First, consider the simplified electric circuit model of a distribution feeder in Fig. 1 below without distributed PV systems. In here, $R + jX$ represents the combined complex impedance of the transformer and cable resistance, and I_L is the lumped load current. The voltage drop (*VD*) is approximated by

$$VD_{w/o\,PV} = RI_L \cos\theta + XI_L \sin\theta \tag{1}$$

where θ is the load power factor angle. Note that *VD* is a sum of two components: the *active* part of the load current times the *resistance* of the impedance, and *reactive* part of the load current times the *reactance* of the impedance.

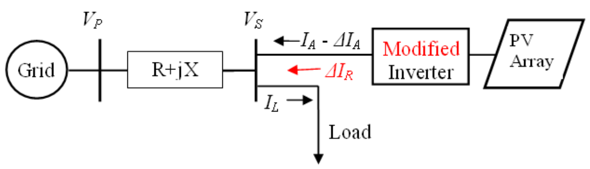


Fig. 1: Feeder Circuit Connecting Grid to Customer Load and PV System.

The presence of PV systems results in active current injection I_A into the distribution system as shown in Fig. 1. This current is in phase with the voltage at the interconnection point since present-day inverters are designed to operate at unity power factor. The above expression of VD becomes

$$VD_{with\,PV} = R(I_L \cos\theta - I_A) + XI_L \sin\theta\,. \tag{2}$$

Note that PV system reduces only the first component of VD (i.e., across the *resistive* part of the impedance).

Now consider a situation where fast change in solar irradiance over an incremental time step Δt occurs. This results in a drop in PV current by ΔI_A, which leads to a change in the following voltage drop ΔVD:

$$\Delta VD_{with\,PV} = -\Delta I_A R\cos\theta\,. \tag{3}$$

The negative sign simply means that a decrease in solar irradiance leads to an increase in voltage drop. Note that in cases where the resistive part of the impedance is very small, the change in voltage drop due to cloud transients can be negligible. However, a noticeable change in voltage will occur if *R* and/or the change in PV current are relatively large.

The proposed scheme requires modifications to the inverter so that it can supply reactive current as needed during cloud transients, in addition to the active current. This is illustrated in Fig. 1 where ΔI_R is the reactive current. This feature modifies the change in voltage drop as follows:

$$\Delta VD_{with\,PV} = -\Delta I_A R\cos\theta + \Delta I_R X \sin\theta \tag{4}$$

The amount of reactive current that is needed to neutralize the change on voltage drop caused by ΔI_A can now be determined:

$$\Delta VD_{with\,PV} = 0 \quad \Rightarrow \quad \Delta I_R = \frac{R}{X\tan\theta}\Delta I_A \tag{5}$$

Under a special case where the local load is disconnected, the amount of reactive current that needs to be injected for voltage drop compensation becomes

$$\Delta VD_{with\,PV} = 0 \quad \Rightarrow \quad \Delta I_R = \frac{R}{X}\Delta I_A\,. \tag{6}$$

Note that the total inverter current cannot exceed its rated value since no call for reactive current can take place under maximum solar irradiance. Therefore, no inverter over sizing is required. Modifications to the inverter may only include upgrading the DC side buffer capacitor and modifying the controls and re-programming the DSP according to the desired operation.

SIMULATION OF PROPOSED METHOD

To evaluate the performance of the proposed method, a PSCAD model of the system in Figure 1 was initially developed. The data of each subsystem below was selected to closely match an actual local system.

PV Array Data

Rated power	2 kW
Open circuit voltage	330 V
Short circuit current	8.35 A
Voltage at max-power	270 V
Current at max-power	7.2 A
Eq. parallel resistance	2.4 kΩ
Eq. series resistance	3.12 Ω
Number of cells	480

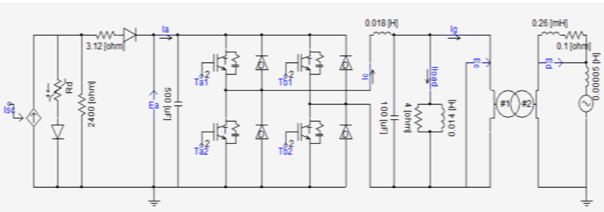
Inverter Data

Rated power	2,100 W
Buffer capacitor	500 µF
Inverter topology	Single-stage, current control
Switching frequency	15 kHz (PWM)
Rated output voltage	120 V, 60 Hz
Output L-C filter	18 mH – 100 µF
Isolation transformer	120/208 V (60 Hz)

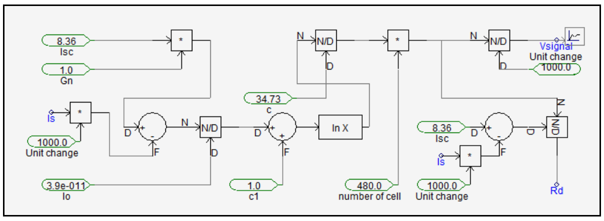
Utility Side

Nominal voltage	208 V
Cable impedance	0.1 + j0.1 Ω
Local load	13.5 kVA @ 80% Pf

Figure 2 below shows the circuit layout along with the control and signal generator blocks using PSCAD simulation software. Herein, maximum power point tracking is achieved with PWM control, while the reactive current control is achieved through phase shift control.



(a)



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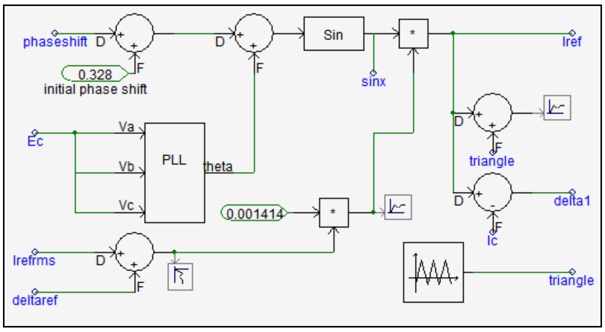

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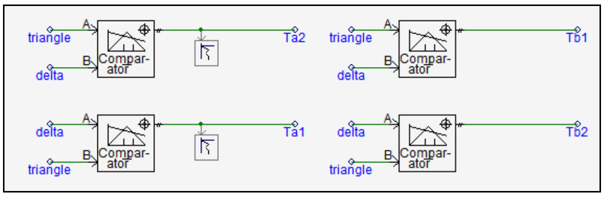
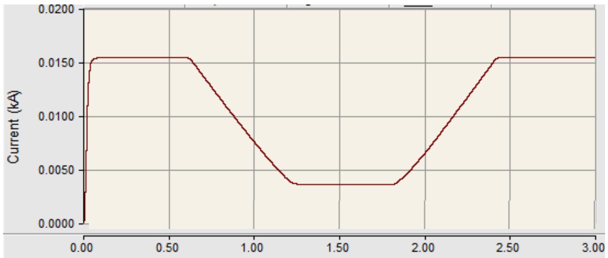


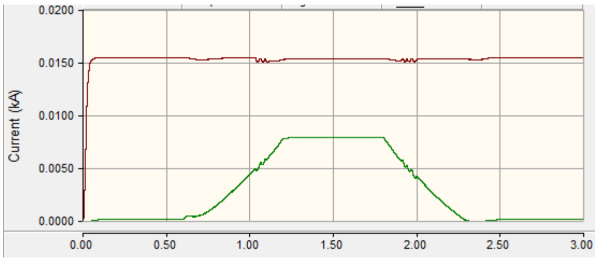
(d)

Fig. 2: (a) PSCAD Circuit Model, (b) PV Array Block, (c) Control Scheme, (d) Switching signal Generation.

Figure 3 (a) shows the active current was initially steady at nominal value, then a single dip due to temporary cloud coverage lasting two seconds occurs before the current returns to its initial value. Fig. 3(b) shows the reactive current generated by the inverter through the proposed control scheme, and the resulting RMS current flowing in the supply cable. This graph clearly shows the voltage dip that may be caused by the cloud transient is practically eliminated by the controller.



(a)



(b)

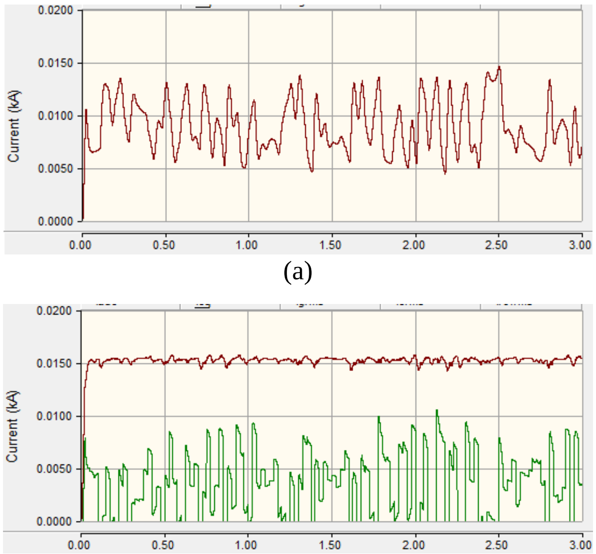
Fig. 3: (a) Active Current Dip (b) Reactive Current (Green) and Total RMS Current (Red).

Fig. 4 further illustrates the effectiveness of the proposed scheme by varying solar irradiance in a rather random fashion to simulate variable-clouds condition. Graph (a) shows the variation in active current, and graph (b) shows the pulses of reactive current produced by the inverter controller and the resulting cable current. In summary, the proposed scheme appears to significantly reduce the voltage fluctuations and the rate at which the change.

The proposed scheme, if it turns to be economically viable as far as its implementation in future grid-tied inverters, will eliminate the number one concern of electrical distribution companies over high PV penetration, namely voltage fluctuations on cloudy days. It will therefore allow a wider expansion of PV systems, provide better power quality for customers, and be beneficial to electric utility companies as it leads to less wear-and-tear of their voltage regulation equipment (transformer tap changing and shunt capacitor switching).

CONCLUSIONS

This paper presented a simple and yet effective method to minimize voltage fluctuations in distribution systems with a high penetration level of distributed photovoltaic generation under variable clouds. The concept is based on injecting controllable amounts of reactive current during large swings in solar irradiance such that voltage drop in the distribution feeder is neutralized. The method is implemented in PSCAD for performance evaluation. The simulation results verified the feasibility and effectiveness of the proposed method. The method does not require an oversized converter, but knowledge of feeder impedance and local load power factor is necessary for optimal performance. Future plans include the hardware design and implementation followed by laboratory testing.



(a)

(b)

Fig. 4: (a) Active Current Fluctuations due to Cloud Transients, (b) Cable Current and Reactive Current Injection.

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