Enhancement of Reactive Power Capacity of a PV Grid in Smart Grid Applications

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Abstract: In the distributed generation environment, existing standards impose limits on the allowable feeder voltage variation. These stipulations must limit the power penetration level. In order to improve the voltage profile, a possible solution is to provide the reactive power support. This work proposes an auxiliary circuit in conjunction with the PV grid system, increases the reactive power compensation capacity. In spite of using the conventional discrete form of capacitor/inductor bank, the entire VAR range can be controlled. This enables the mitigation of large voltage variation on the feeder and this, in turn, increased PV penetration into the power system. The modelling, analysis and control design along with MATLAB Simulink results are discussed.

Keywords: Reactive power control, voltage profile, voltage source converter, photovoltaic power systems

1. Introduction

Solar photovoltaic (PV) are among the fastest growing energy sources in the world, with annual growth rates of 25-35% over the last ten years. The markets for solar PV have undergone a dramatic shift in the last five years. Prior to 1999 the primary market for PV was in off-grid applications, such as rural electrification, water pumping, and telecommunications. However, now over 78% of the global market is for grid-connected applications where the power is fed into the electrical network [1]. Substantial and consistent rise in load demand has led to new strategies for maximizing the production of electricity, including recourse to local (distributed) generation. To reduce transmission losses and improve voltage profile, it is necessary to support at least the reactive power demand through local generation (if not the total power demand)—even if that has to be done under strict guidelines. This is also in line with the new de-regulated regime based on distributed (local) power generation [2], [3]. The principle owner of the incoming Distributed Generation System (DGS), e.g., PV-DGS expects maximum power and reliable generation from his system. In the foreseeable future, it is anticipated that the utility would expect the DGS client to support the power system with ancillary activities (e.g., power factor correction, dynamic stability, reactive power support, etc.) apart from injecting active power into the grid. High reactive power demand of the distributed loads, their on/off operation, and line reactance are the major factors responsible for stretching the local area voltages all the way up to the stipulated limits, if proper compensating elements are not in place. They cause voltage sags and swells, deteriorating the quality of electricity and causing considerable adverse impact on the critical loads/devices/equipment. In the presence of inherent reactive power demand from the feeder side, high penetration PV sources may lead to extensive voltage variation because of the conventional methods of operation of inverters and variation in the solar radiation levels [4]–[7]. Canova et al. [4], Liu et al. [5], and Steffel et al. [7] have reported that reverse power flow over a feeder is a major cause of voltage rise in power grid during high solar radiation. This limits the maximum PV penetration level into a given feeder which is determined by the bus voltage variation [8].

Significant attention has been paid in recent times to the “issues related to high PV power penetration” and efforts have been made to mitigate the overvoltage (OV) and undervoltage (UV) problems because of the interface of widely varying power injection from photovoltaic sources. Some authors [9]–[11] have presented a conceptual solution for mitigating OV and UV issues in the distribution network by installing energy storages at either the consumer end or at the Load Dispatch Center (LDC). Unfortunately, the current technology doesn’t support economical energy storage systems yet. Moreover, expecting customer cooperation for this is not very practical.

Reactive power is a major influencing parameter in AC systems due to its impact on the line voltage profile. A dedicated Distribution Static Synchronous Compensator (D-STATCOM) at the Point of Common Coupling (PCC), for supplying reactive power demand and mitigating voltage variation in the area of dense Disperse Generation is a possible solution [15], [16]. Unfortunately, this is not economical. Nevertheless, it leads to the idea of compensating reactive power by Voltage Source Converter (VSC) of renewable energy sources itself, e.g., PV inverter. This, however, demands considerably higher VA rating of the PV inverter than what is required for dispatching only the maximum PV capacity. In spite of all the talks about D-STATCOM and PV inverters for compensation duty, the reality is that a large number of applications still use discrete, switchable inductor and capacitor banks for reactive power compensation and voltage regulation as an economical and simple solution even though it suffers from the following drawbacks:

1) Reactive power can only be controlled in discrete steps due to which accurate voltage regulation is not possible.
2) Switching of inductive and capacitive banks may result in resonance.
3) Switching ON of capacitor can lead to severe voltage dip, followed by transients and switching OFF of inductor is associated with high transient recovery voltage issues.

Though the conventional method of reactive power compensation using D-STATCOM with discrete reactive power bank (RPB) is a feasible solution [17], it renders a poor dynamic performance of reactive power control due to the absence of feedforward compensation. Further, asynchronous discrete reactive power bank switching causes voltage transients. Moreover, a dedicated D-STATCOM may not be economical.

To overcome the above drawbacks to enable the use of capacitors and inductor banks for reactive power compensation, this work proposes a new system configuration shown in Fig. 2. In the proposed scheme, the switching operation of the Reactive Power Banks (RPB) is integrated with the control scheme of the main PV inverter to generate controlled reactive power over the entire range. Any deficit reactive power requirement of the local Electric Power System (EPS) is supplied by RPB. Transient issues, which might arise due to incompatibility of line and bank terminal voltages, are overcome by the auxiliary converter. The proposed scheme, explained in detail in the next section, offers the following advantages:

1) The proposed system incorporates the STATCOM functionality through the PV inverter itself, without drastically increasing the latter’s VA capacity. Dedicated STATCOMs obviate reactive power compensation.

2) The reserve reactive power range of PV inverter can be enhanced up to 300%.

3) The scheme covers complete controllable range of reactive compensation smoothly (and not in discrete steps) despite using discrete banks. Hence, it can be used for precise voltage regulation.

4) The associated control scheme of the proposed system analytically derived controllers ensure fast tracking response of the reactive power. Therefore, dynamic behaviour of the system is improved substantially due to better controllability of reactive power compensation.

5) The increased reactive power capacity can be utilized for mitigating under and over voltages. This facilitates increased PV penetration level. Reactive power demanded by local loads can be fed by the PV station, relieving the power system from reactive power support responsibility.

The upcoming PV generating stations can be planned with existing reactive power banks such that the proposed scheme can be conveniently retrofitted into the existing systems with reactive power banks. The additional used for synchronization of much lower VA capacity as it is meant to supply only the power losses in the bank. This is expected to be an attractive and economical investment proposition to enhance the reactive power capacity of the station by up to 300% of the dedicated VAR capacity of the inverter.

2. System Description and Operation

The proposed PV station configuration is shown in Fig. 1 as the main PV-grid inverter, which may be a part of a single- or two-stage topology. The DC link voltage, is controlled through a controller, thereby the PV generated power may be represented by an equivalent current source. An L-C filter is used for coupling with the grid. Fixed value capacitor bank and inductor bank are used with their breakers and to provide bulk reactive power support. The auxiliary converter is used with reactive power banks to regulate the latter’s voltages equal to the grid voltage by drawing power from the DC link or PV source, while switch is open. The active power drawn by to regulate its AC output voltage is not significant because it only needs to feed the losses in the auxiliary network, including the inductor-capacitor bank. The reactive power capacity of both banks are reconsidered equal. The control strategy incorporated for all switches, S, S1, S2, and S3. Thelow power rheostat is required for momentary changeover of the switch, across bank. The reactive power injected by serves as feedback for controlling S, S1, S2, and S3. In conjunction with the system ensures smooth coupling of the RPBs with the grid under various conditions and facilitate complete control of the reactive power supplied by the station. System is designed such that the reactive power capacity of is at least half the individual capacity of or bank.

During low Qstn demand, the S and S3 are open, S1 and S2 are closed. VSC2 is activated. Hence VSC1 controls and meets the reactive power demand. If Qstn increases and hits the maximum limit of reactive power VSC2 gets off, S and S3 are closed, S2 is open, Qstn=QVSC1+Qcp. If Qstn demand decreases and hits the minimum limit of reactive power, VSC1 is stopped.
power VSC2 is activated by S open, S3 open and S2 close (Qstn=QVSC)

2.1 Modelling and Control design

2.1.1 Current Controller design for the main inverter

Assume that the AC system voltage in the VSC systems

\[ V_{sa}(t) = V_s \cos(\omega_0 t + \Theta_0) \]  
\[ V_{sb}(t) = V_s \cos(\omega_0 t + \Theta_0 - \frac{\pi}{2}) \]  
\[ V_{sc}(t) = V_s \cos(\omega_0 t + \Theta_0 - \frac{\pi}{2}) \]  

The governing circuit equations in synchronously rotating reference frame after segregating the components into real and imaginary parts can be written as below [15]:

\[ L \frac{di_d}{dt} = -r_i i_d + L \omega_i q + e_d - v_d \]  
\[ L \frac{di_q}{dt} = -r_i q - L \omega_i d + e_q - v_q \]  

Where \( v_d, v_q \) are the direct and quadrature components of the transformed grid voltages. If voltage vector is aligned with \( d \)-axis are the current components; \( L \) and \( r \) are the filter elements of VSC1; \( e_d, e_q \) are generated voltage components with sinusoidal PWM switching technique, where

\[ e_d = \frac{v_{dc}}{2} m_d \; ; \; e_q = \frac{v_{dc}}{2} m_q \]

The Modulating indexes:

\[ m_d = \frac{2}{V_{dc}} (u_d - L \omega_i q + v_d) \]  
\[ m_q = \frac{2}{V_{dc}} (u_q - L \omega_i d + v_q) \]

The transfer function can be obtained to design the inner current loops:

\[ G(s) = \frac{1}{L s + 1} \]  
\[ G(s) = \frac{K_p}{L s} \]  

Cut Off Frequency

\[ \omega_c = \frac{1}{10} \ast (2\pi f_s) \]

Thus the closed loop TF can be reduced to first order with unity gain is

\[ G_{cl} = \frac{1}{\omega_c s + 1} \]

2.1.2 Design of Controller for Auxiliary Converter:

Similarly the equations for auxiliary converter as same in the main converter,

\[ L \frac{di_{dx}}{dx} = -r_i i_{dx} + L \omega_i q_{dx} + e_{dx} - v_{dx} \]  
\[ L \frac{di_{qy}}{dx} = -r_i q_{dx} - L \omega_i d_{dx} + e_{qy} - v_{qy} \]

The vector differential equation corresponding to the inductive RPB is as follows:

\[ L_p \frac{dl_p}{dx} = -r_i l_p + V_{ax} \]

Applying KCL leads to the following

\[ C_p \frac{dv_{ax}}{dx} = i_{ax} - i_{lp} \]

2.2 Performance Evaluation of Auxiliary converter

The proposed scheme [Fig. 2] is modeled in MATLAB Simulink. The power converters are accurately represented by detailed switch models. First we investigate the performance of the auxiliary converter – RPB configuration

![Figure 3: Control Scheme for Proposed System](image)

![Figure 4: Tracking performance of the components of terminal voltage of RPB](image)

From the figure 4, the d-q components of VSC2 faithfully track the reference inputs. This implies that the inner current control loops are working satisfactorily.

2.3 Simulation Results

Figure 2 can be modelled in a MATLAB Simulink.The Solar connected grid system can be shown in the figure 5. The control scheme for main inverter and Auxiliary inverter can be modelled in MATLAB.

![Figure 5: Simulink model for proposed system](image)
A 100-kW array connected to a 25-kV grid via a DC-DC boost converter and a three-phase three-level Voltage Source Converter (VSC). Maximum Power Point Tracking (MPPT) is implemented in the boost converter by means of a Simulink model using the “Incremental Conductance + Integral Regulator” technique. PV array delivering a maximum of 100 kW at 1000 W/m² sun irradiance. 5-kHz boost converter increasing voltage from PV natural voltage (272 V DC at maximum power) to 500 V DC. Switching duty cycle is optimized by the MPPT controller that uses the “Incremental Conductance + Integral Regulator” technique. 1980-Hz (33*60) 3-level 3-phase VSC (blue blocks). The VSC converts the 500 V DC to 260 V AC and keeps unity power factor. 10-kvar capacitor bank filtering harmonics produced by VSC. 100-kVA 260V/25kV three-phase coupling transformer. Utility grid model (25-kV distribution feeder + 120 kV equivalent transmission systems).

Case 1: Without Proposed System:

Case 1(a): With Fault Condition

Figure 7a: Voltage and current waveform with fault condition

Figure 7b: Real and Reactive power with fault condition

The three phase fault can be occurred in the transmission line, the amount of real power penetration into the grid could be reduced. Here 29 KW of real power can be penetrated into the grid.

Case 2: With Proposed System:

Figure 8: (a) Voltage waveform and (b) Current waveform(With Proposed System)
From the figure 8c, the more amount of real power can be penetrated into the grid system as compared to the case 1(a) even in the three phase fault. Hence the proposed system can overcome the problems represented in the case 1(a). The proposed scheme, the auxiliary converter associated with the capacitor bank in the proposed system, ensures that the bank voltages are synchronized with the grid in frequency and magnitude during the switching of S [Figure 8(a)].

### 3. Conclusion

In the distributed power generation is being contemplated found reducing the stress on the power grid. The future power grid is likely to be abound with a large number of inverter driven DGs. In additional to the local power generation, it would be highly desirable to have these DGs units also compensated reactive power. However, reactive power compensation without hampering power quality is a challenging task. It is in this context that the presented work assumes significance. The proposed scheme has demonstrated a viable method of enhancing the reactive power of 2MW is increased as compared to the main inverter. Hence the more amount of power can be penetrated into the system.

### References


### Appendix

#### Table 1: Data Obtained from Simulation

<table>
<thead>
<tr>
<th>Cases</th>
<th>Output Power (KW)</th>
<th>Reactive Power (Var)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>99.04</td>
<td>7.5*10^4</td>
</tr>
<tr>
<td>1(a)</td>
<td>29.18</td>
<td>1.4*10^6</td>
</tr>
<tr>
<td>2</td>
<td>97.80</td>
<td>2.5*10^6</td>
</tr>
</tbody>
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#### Table 2: Controllers used in the System

<table>
<thead>
<tr>
<th>Converters</th>
<th>Subsystem</th>
<th>Form</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>VSC1</td>
<td>Inner current loop</td>
<td>$G(s) = \frac{Kp+Ki}{s} \Rightarrow \frac{0.6283s + 6.7231}{s}$</td>
<td></td>
</tr>
<tr>
<td>VSC1</td>
<td>Outer AC voltage control</td>
<td>$G(s) = \frac{1658s + 252.4}{s + 3517}$</td>
<td></td>
</tr>
<tr>
<td>VSC2</td>
<td>Inner current loop</td>
<td>$G(s) = \frac{6.283s + 628.3}{s}$</td>
<td></td>
</tr>
<tr>
<td>VSC2</td>
<td>Outer AC voltage control</td>
<td>$G(s) = \frac{24547s + 520.6}{s + 3033}$</td>
<td></td>
</tr>
</tbody>
</table>

#### Table 3: Parameters Used in the System

<table>
<thead>
<tr>
<th>Elements</th>
<th>Vsc1</th>
<th>Elements</th>
<th>Vsc2</th>
</tr>
</thead>
<tbody>
<tr>
<td>VA Capacity</td>
<td>1 MVA</td>
<td>VA Capacity</td>
<td>25 kVA</td>
</tr>
<tr>
<td>L</td>
<td>200µH</td>
<td>L_Ax</td>
<td>500µH</td>
</tr>
<tr>
<td>R=r+r_{on}</td>
<td>2.14mΩ</td>
<td>r_Ax</td>
<td>0.05Ω</td>
</tr>
<tr>
<td>C_z</td>
<td>1000µF</td>
<td>C_p</td>
<td>3700µF</td>
</tr>
<tr>
<td>W</td>
<td>2π50 rad/s</td>
<td>L_p</td>
<td>2.738Mh</td>
</tr>
<tr>
<td>C_{f0}</td>
<td>150µF</td>
<td>r_Lp</td>
<td>0.05Ω</td>
</tr>
</tbody>
</table>

**Switching frequency**: 5 kHz **Switching frequency**: 20kHz


**Author Profile**

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