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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, includinga recourse to local (distributed) generation. To reduce transmission losses and improve voltageprofile, it is necessary to support at least the reactive powerdemand through local generation (if not the total power demand)—even if that has to be done under strict guidelines. Thisis 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 expectsmaximum 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 reactances 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 impacton 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 andvariation 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 under-voltage (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 customercooperation 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 theidea of compensating reactive power by Voltage Source Converter(VSC) of renewable energy sources itself, e.g., PV inverter.This, however, demands considerably higher VA ratingof the PV inverter than what is required for dispatching only themaximum PV capacity.In spite of all the talks about D-STATCOM and PV invertersfor compensation duty, the reality is that a large number of applicationsstill use discrete, switchable inductor and capacitorbanks for reactive power compensation and voltage regulationas an economical and simple solution even though it suffersfrom the following drawbacks:

1) Reactive power can only be controlled in discrete steps dueto which accurate voltage regulation is not possible.
2) Switching of inductive and capacitive banks may result inresonance.

3) Switching ON of capacitor can lead to severe voltage dip,followed by transients and switching OFF of inductor isassociated with high transient recovery voltage issues.

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

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

1) The proposed system incorporates the STATCOM functionalitythrough the PV inverter itself, without drasticallyincreasing the latter's VA capacity. Dedicated STATCOMis obviated for reactive power compensation.
2) The reserve reactive power range of PV inverter can beenhanced up to 300%.
3) The scheme covers complete controllable range of reactivecompensation smoothly (and not in discrete steps) despiteusing discrete banks. Hence, it can be used for precisevoltage regulation.
4) The associated control scheme of the proposed systemand analytically derived controllers ensure fast trackingresponse of the reactive power. Therefore, dynamic behaviour of the system is improved substantially due tobetter controllability of reactive power compensation.
5) The increased reactive power capacity can be utilizedfor mitigating under and over voltages. This facilitatesincreased PV penetration level. Reactive power demandof local loads can be fed by the PV station, relieving thepower system from reactive power support responsibility.

The upcoming PV generating stations can be planned withexisting reactive power banks such that the proposed schemecan be conveniently retrofitted into the existing systems withreactive power banks. The additional used for synchronizationis of much lower VA capacity as it is meant to supplyonly the power losses in the bank. This is expected to be an attractiveand economical investment proposition to enhance thereactive power capacity of the station by up to 300% of the dedicated VAR capacity of the inverter.

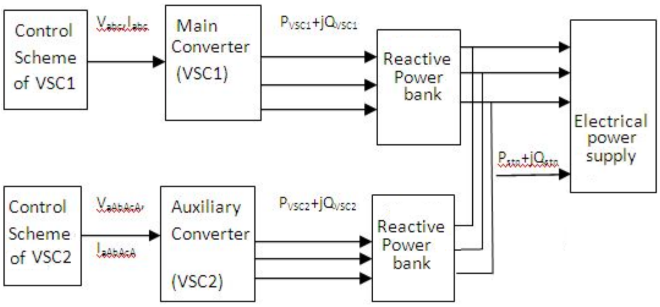

Figure1: Block Diagram representation of Proposed System

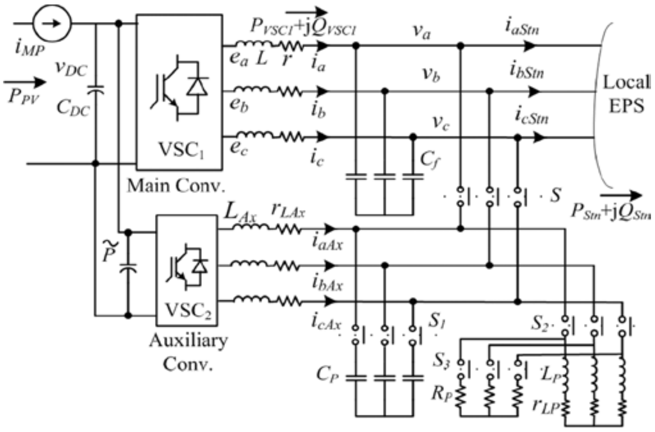

Figure 2: Proposed power circuit of PV-DGS with auxiliary converter and RPB

2. System Description and Operation

The proposed PV station configuration is shown in Fig. 1 is the main PV-grid inverter, which may be a part of asingle- or two-stage topology. The DC link voltage, is controlled through, therefore the PV generated power maybe represented by an equivalent current source. An L-Cfilter is used for coupling of with the grid. Fixed valuecapacitor bank and inductor bank are used withtheir breakers and to provide bulk reactive power support.The auxiliary converter is used with reactive powerbanks to regulate the latter's voltages equal to the grid voltageby drawing power from the DC link or PV source, while switchis open. The active power drawn by to regulate its ACoutput voltage is not significant because it only needs to feed thelosses in the auxiliary network, including the inductor-capacitorbank. The reactive power capacity of both and banks areconsidered equal. The control strategy incorporated foralso handles the operation of switches S,S1S2, and S3. Thelow power rheostat, is required for momentary changeoverof the switches, across bank.The reactive power injected by serves asfeedback for controlling S,S1 S2, and S3. In conjunction withthe system ensures smooth coupling of the RPBs with the gridunder various conditions and facilitate complete control of thereactive power supplied by the station . System is sodesigned that the reactive power capacity of is at leasthalf the individual capacity of or bank.

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

2.1 Modelling and Control design

2.1.1Current Controller design for the main inverter

Assume that the AC system voltage in the VSC systems

$$V_{sa}(t)= Vs \cos(\omega_0 t+\Theta_0) \quad (1)$$

$$V_{sb}(t) = Vs \cos(\omega_0 t+\Theta_0 - \frac{2\pi}{3}) \quad (2)$$

$$V_{sc}(t) = Vs \cos(\omega_0 t+\Theta_0 - \frac{4\pi}{3}) \quad (3)$$

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

$$L \frac{did}{dt}= -ri_d + L \omega_o i_q + e_d - v_d \quad (4)$$

$$L \frac{diq}{dt} = -ri_q - L\omega_o i_d + e_q - v_q \quad (5)$$

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 rare the filter elements ofVSC1 ;e_d,e_q are generatedvoltages components with sinusoidal PWMswitching technique, where

$e_d= \frac{Vdc}{2} m_d$; $e_q= \frac{Vdc}{2} m_q$

The Modulating indexes:

$$m_d= 2/V_{dc}(u_d - L\omega_o i_q + v_d) \quad (6)$$

$$m_q= 2/V_{dc}(u_q - L\omega_o i_d + v_q) \quad (7)$$

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

$$G_i(s) = \frac{1}{Ls+r} \quad (8)$$

The loop Transfer function is given by:

$$G_i(s) = \frac{Kp}{Ls} \quad (9)$$

Cut Off Frequency

$$\omega_{ci}= \frac{1}{10} *(2\pi f_s) \quad (10)$$

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

$$G_{cL} = \frac{1}{\frac{s}{\omega ci}+1} \quad (11)$$

2.1.2 Design of Controller for Auxiliary Converter:

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

$$L \frac{didax}{dx}= -ri_{dax} + L\omega_o i_{qax} + e_{dax} - v_{dax} \quad (12)$$

$$L \frac{diqax}{dx}= -ri_{qax} - L\omega_o i_{dax} + e_{qax} - v_{qax} \quad (13)$$

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

$$Lp\frac{diLp}{dx} = -r_{Lp} i_{Lp} + V_{ax} \quad (14)$$

Applying KCL leads to the following

$$Cp \frac{dVax}{dx} = i_{ax} - i_{Lp} \quad (15)$$

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

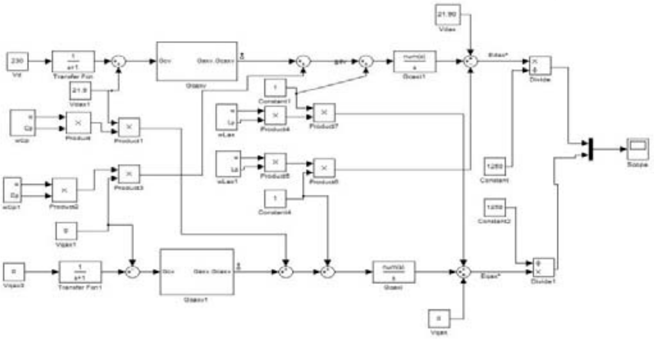

Figure 3: Control Scheme for Proposed System

Figure 4: Tracking performance of the components of terminal voltage of RPB.

From the figure 4, the d-q components of VSC_2 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 figure5. The control scheme for main inverter and Auxiliary inverter can be modelled in MATLAB.

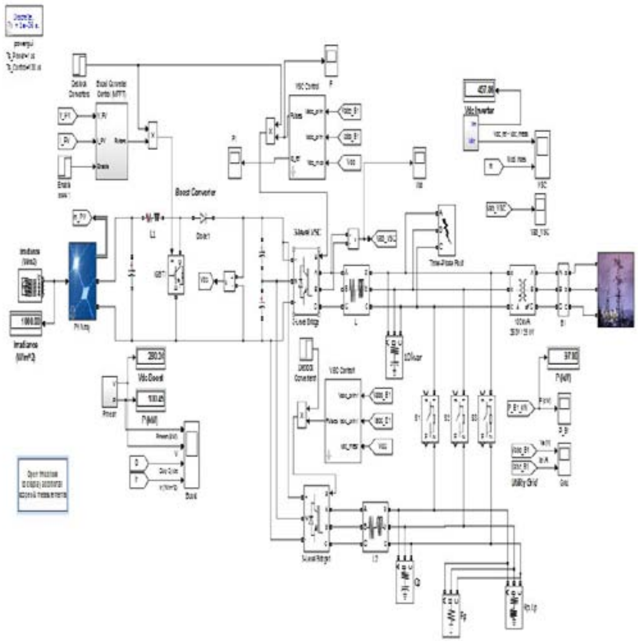

Figure 5: Simulink model for proposed system

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:

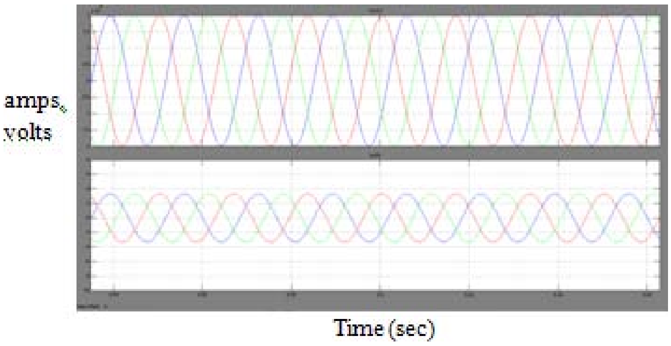

Figure 6a: Voltage and current waveform (Without proposed system)

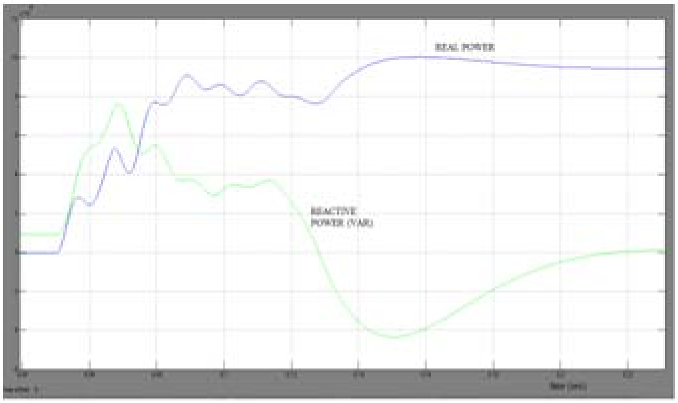

Figure 6b: Real and Reactive power (Without proposed system)

Figure 6a & 6b shows that the waveforms of voltage current ,real and reactive power. From these waveforms the nearly 99 KW of real power can be penetrated into the utility grid. In the normal operation,DClink is regulated byVSC1 .HenceVSC2,must be activated only afterDClink is stabilized at the referencevalue set byVSC1 . In order to synchronize bank voltagesgenerated byVSC2 with the grid frequency andmagnitude, d-q components of grid voltage vector are applied as input referencesignal to the outer AC voltage control loop of VSC2.

Case 1(a): With Fault Condition

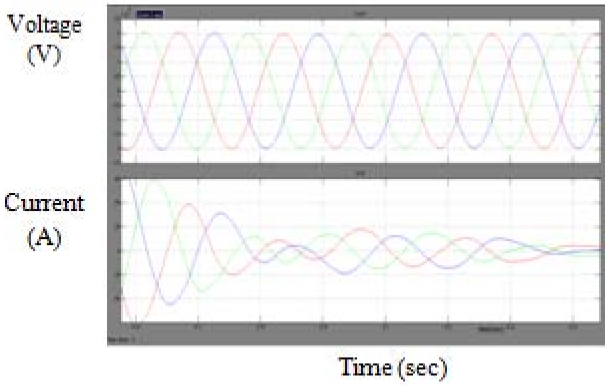

Figure 7a: Voltage and current waveform with fault condition

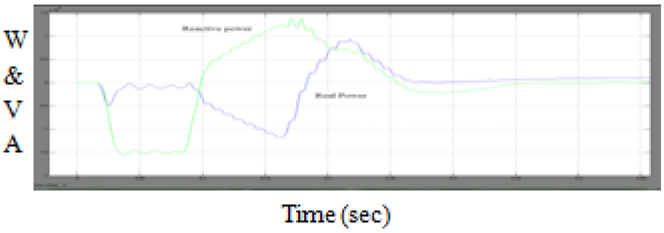

Figure 7b: Real and Reactive power with fault condition

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:

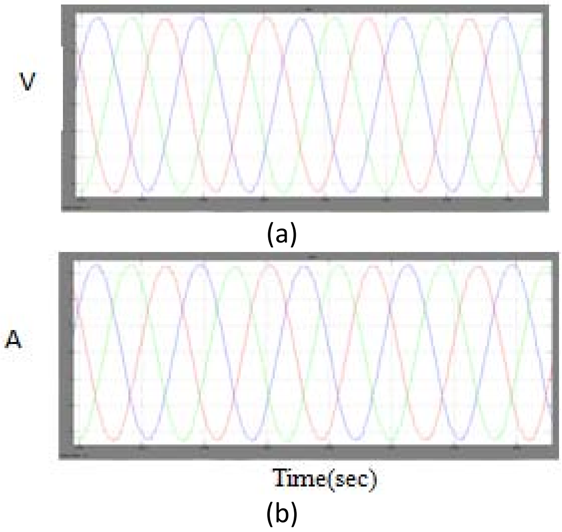

Figure 8 :(a) Volatge waveform and (b) Current waveform(With Proposed System)

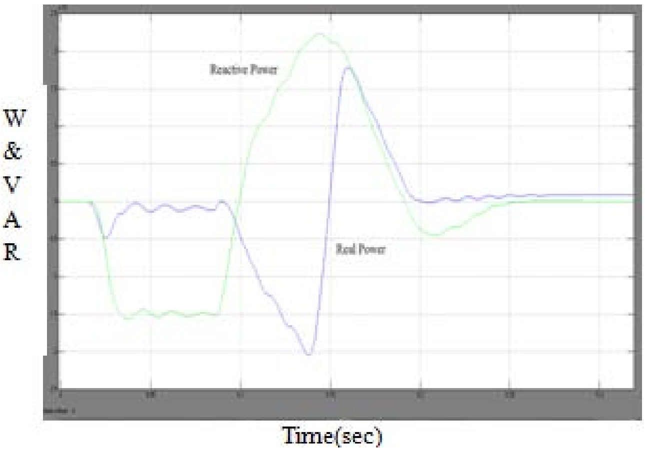

Figure 8c: Real and Reactive power(With Proposed System)

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 associatedwith the capacitor bank in the proposed system, ensuresthat the bank voltages are synchronized with the grid in frequencyand magnitude during the switching of S [Figure 8(a)].

Appendix

Table 1: Data Obtained from Simulation

Cases	Output Power	Reactive Power (Var)
1	99.04 KW	$7.5*10^4$
1(a)	29.18KW	$1.4*10^6$
2	97.80KW	$2.5*10^6$

Table 2: Controllers used in the System

Converters	*Subsystem*	*Form*	*Parameter*
VSC1	Inner current loop control	$G_ci(s)=\frac{(Kps+ki)}{s}$	$\frac{0.6283s+6.7232}{s}$
	Outer AC voltage control	$G_{CV}(s)=\frac{h}{s}\frac{s+r/a}{s+r}$	$\frac{16565}{s}\frac{s+252.4}{s+3517}$
VSC2	Inner current loop control	$G_ci(s)=\frac{(Kps+ki)}{s}$	$\frac{6.283s+628.3}{s}$
	Outer AC voltage control	$G_{CV}(s)=\frac{h}{s}\frac{s+r/a}{s+r}$	$\frac{24547}{s}\frac{s+520.6}{s+3033}$

Table 3: Parameters Used in the system

Elements	Vsc1	Elements	VSC2
VA Capacity	1 MVA	VA Capacity	25 kVA
L	200µH	L_{Ax}	500µH
$R=r+r_{on}$	2.14mΩ	r_{Ax}	0.05Ω
C_{dc}	1000µF	C_p	3700µF
W	2π50 rad/s	L_p	2.738Mh
C_f	150µF	rL_p	0.05Ω
Switching frequency	5 kHz	Switching frequency	20kHz

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.

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