ENHANCEMENT OF PV PENETRATION LEVEL BY INCREASING REACTIVE POWER SUPPORT TO THE PV GRID SYSTEM USING FUZZY LOGIC CONTROLLER

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Abstract: *— In the distributed generation environment, existing standards impose limits on the allowable feeder voltage variation. These agreements must limit the power penetration level. If the penetration level increases it leads to increased or decreased feeder voltage and causes reverse current flow in the feeder. In order to mitigate this problem we need reactive power support to the feeder. By the use of conventional capacitor or inductor banks we cannot achieve full range of voltage control (voltage regulation).this work proposes a novel scheme containing auxiliary voltage source converter with fuzzy logic controller that enables the smooth tracking of reactive power according to the load requirement. The proposed system configuration can conveniently retrofitted into the existing system with in PV station itself and reliving the utility from additional voltage support burden. This in turn increases the PV penetration level in the feeder. The corresponding modelling, analysis and control design along with MATLAB Simulink results are discussed.*

Keywords: *fuzzy logic controller, reactive power banks (RPB), photo voltaic systems, Point of Common Coupling (PCC).*

I. Introduction:

Significantly great rise in load demand has led to new strategies for maximizing the production of electricity, including the renewable energy sources such as wind, solar Photovoltaic (PV), tidal, etc. the solar PV-grid systems have gained importance in recent smart grid scenario because of their versatile characteristics and they have no environmental pollution. Due to this penetration of PV-grid system in to power system is increasing as load demand increases.

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 and some of the present day loads have a very unpredictable nature. This includes industrial loads which are reactive in nature. To reduce transmission losses and improve voltage profile, it is necessary to support at least the reactive power demand from local generation [1, 2].

The 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. Reactive power is a major influencing parameter in AC systems due to its impact on the line voltage profile. 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 distribute generation is a possible solution. Unfortunately this is not economical and having the following drawbacks [4]:

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 large voltage dip, followed by transients and switching OFF of inductor is associated with high transient recovery voltage issues.

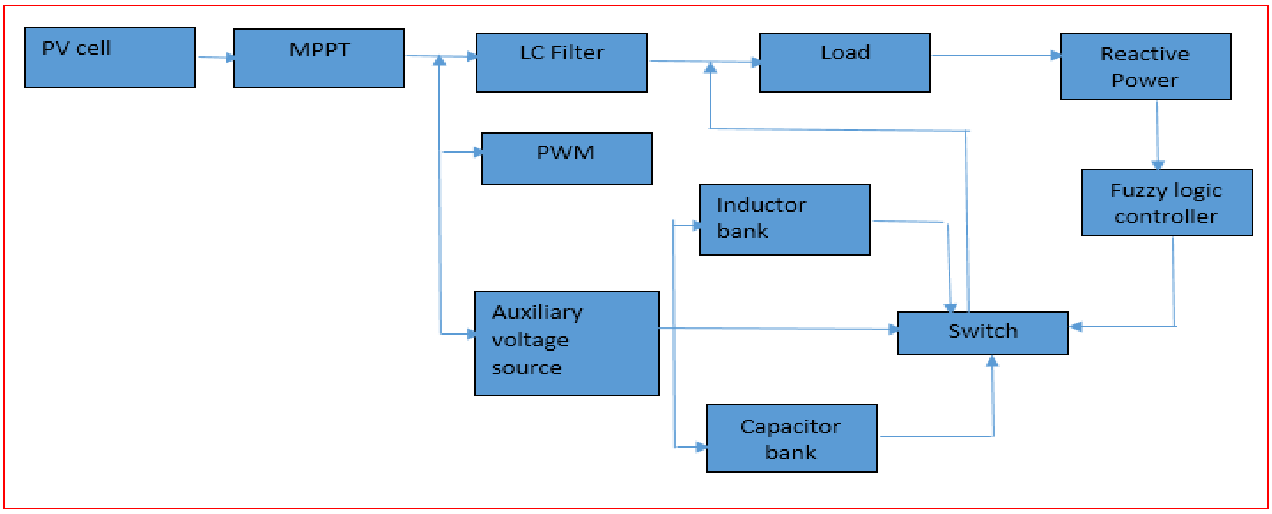


Fig. 1. Proposed power circuit of PV-DGS with auxiliary converter, RPB and fuzzy logic controller

Though the conventional method of reactive power compensation using D-STATCOM with discrete Reactive Power Bank (RPB) is a possible solution but it suffers from poor dynamic performance of reactive power control due to absence of feed forward compensation. Further asynchronous discrete reactive power bank switching leads to voltage transients. Moreover, a dedicate D-STATCOM may not be economical.

The proposed system have the following advantages [1]:

1) The proposed system includes the STATCOM functionality through the PV inverter itself, without much increasing the latter's VA capacity. Dedicated STATCOM is not needed for reactive power compensation.

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

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

4) The increased reactive power capacity can be utilized for reducing the under and over voltages. This enables increased PV penetration level. Reactive power demand of local loads can be feed by the Station, relieving the power system from reactive power support responsibility.

So 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 VSC_2 used for synchronization is 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 inverter.

II. Proposed System Description and Operation:

The proposed system operation and description and mathematical equations are mentioned in detailed in the [1]. In this novel scheme, fuzzy logic controller is used for reducing the settling time of d-q components of reactive component of station current.by using fuzzy logic controller the wave forms are more smoother than PI controller.

III. Fuzzy logic controller:

One of the reasons for the popularity of Fuzzy Logic Controllers is its logical resemblance to a human operator. It operates on the foundations of a knowledge base which in turn depends upon the various IF-THEN rules, similar to a human operator. Unlike other control strategies, this is simpler as there is no complex mathematical knowledge required. The FLC requires only a qualitative knowledge of the system thereby making the controller not only easy to

use, but also easy to design. Table 1 shows the fuzzy rules which are used for proposed method [2, 3].
In this proposed method the inputs to the fuzzy logic controller are V_{ref}, I_d and the corresponding fuzzy rules are mentioned in the below Table 1.

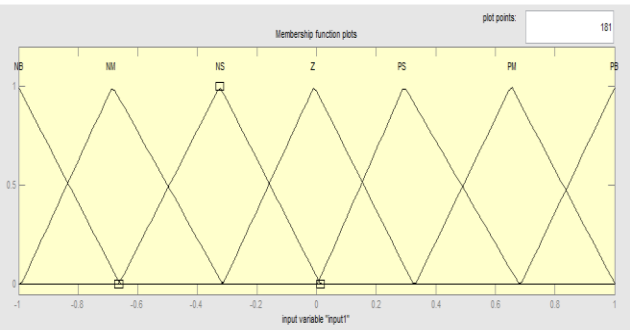
The first step towards designing a Fuzzy Logic Controller is choosing appropriate inputs which will be fed to the same. These input variables should be such that, they represent the dynamical system completely. Then the function of the Fuzzifier comes into picture. As discussed before, instead of using numerical variables, fuzzy logic uses linguistic variables for processing information. Corresponding linguistic variables and rules are shown in Table 1.

Table 1

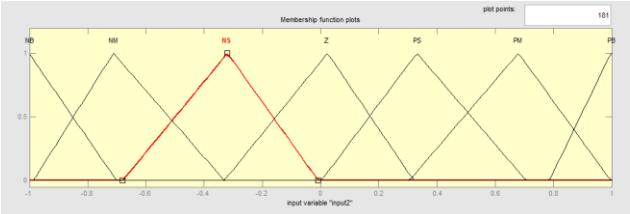
FUZZY RULES

V_{ref} / I_d	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NM	NM	NM	NS	Z	PS
NS	NB	NM	NS	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PM	PB
PM	NS	Z	PS	PM	PM	PM	PB
PB	Z	PS	PM	PB	PB	PB	PB

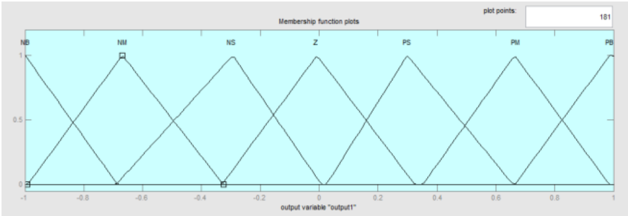
The fuzzy membership functions for input1, input2, and output are shown below Fig. 2



2(a)



2(b)



2(c)

Fig .2. a) Membership function for input1 b) Membership function for input2 c) Membership function for output.

IV. Modelling and Controller Design:

A. Current Controller Design for Main Inverter:

Both the inverters are controlled in the synchronously rotating reference frame. Indirect current control (applied to the inner current loop) is implemented by controlling the terminal voltages of the two inverters [9]. The PV inverter, is grid tied voltage source inverter. Its DC link voltage is regulated by the outer voltage regulation loop with the active power component of current. Up on activation, maintains the voltage of RPB equal to grid voltage by outer AC voltage regulation [9].

The voltage at the grid side of the converter can be described as equation (1)

$$E_{abc} = L\frac{d}{dt}i_{abc} + v_{abc} + Ri_{abc} \quad (1)$$

Where $v_{abc}$are converter input voltages, while i_{abc} are grid currents, E_{abc} are grid voltages, R and L are resistance and inductance respectively between the converter and the grid.

Three-phase currents and voltages are transformed in *dq* reference frame by means of *abc* to dq transformation, where ω is the system frequency in rad/s is given by (2)

$$\begin{bmatrix} E_d \\ E_Q \end{bmatrix} = L\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \omega L\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + R\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} v_d \\ v_q \end{bmatrix} \quad (2)$$

The governing circuit equations in synchronously rotating reference frame after segregating the components into real and imaginary parts can be written as equation (3) and (4)

$$\frac{di_d}{dt} = -\frac{r}{L}i_d + \omega_0 i_q + e_d - \frac{1}{L}v_d \quad (3)$$

$$\frac{di_q}{dt} = -\frac{r}{L}i_q - \omega_0 i_d + e_q - \frac{1}{L}v_q \quad (4)$$

Where v_d, v_q are the direct and quadrature components of the transformed grid voltages. If voltage vector is aligned with d-axis, $v_q = 0$. i_d, i_q are the current components, L and r are the filter elements of VSC_1.

Where e_d, e_q are VSC_1 generated voltage components with sinusoidal PWM switching technique.

$$e_d = \frac{V_{DC}}{2}m_d \qquad e_q = \frac{V_{DC}}{2}m_q$$

m_d, m_q are the modulation indexes

$$m_d = \frac{2}{V_{DC}}[u_d - L\omega_0 i_q + v_d]$$

$$m_q = \frac{2}{V_{DC}}[u_d + L\omega_0 i_q + v_q]$$

Assuming C_{DC} is large so V_{DC} link voltage may be considered as stable over the region of interest, so equations (3), (4) forms second order linear model of VSC_1 with

i_d, i_q $\Rightarrow$ State variables

m_d, m_q $\Rightarrow$ control inputs

v_d, v_q $\Rightarrow$ Are used for the feed forward compensation

The transfer function can be obtained to design the inner current control loop is given by (5)

$$G_{i(s)} = \frac{I_d(s)}{U_d} = \frac{I_q(s)}{U_Q} = \frac{1}{LS+r} \quad (5)$$

The transfer functions for controlling i_d, i_q are same with plant pole

$$LS + r = 0$$

$$S = -\frac{r}{L}$$

Since $-\frac{r}{L}$ is very small plat pole is located close to the imaginary axis and effects the transient response of the current. PI controller is used to control the current components i_d,i_q with transfer function.

$$G(S) = \frac{K_p S + K_i}{S}$$

The location of the PI controller 'zero' is chosen such that $\frac{K_i}{K_p} = \frac{r}{L}$ eliminates the plant pole and gives desired response.

Loop transfer function

$$G_{i(s)}G_{Ci(S)} = \frac{K_P}{LS}$$

Ideally, any band width can be achieved for the current control loop by adjusting K_P.But in practice, it is limited by the switching frequency(f_S) of the converter. Thus $\omega_{Ci} = (1/10) \times (2\pi f_s)$, where ω_{Ci} is the cut-off angular frequency Thus, close loop transfer function of the current control loop, G_{CL} can be reduced to first order with unity gains given (6):

$$G_{CL}(S) = \frac{1}{\frac{S}{\omega_{Ci}}+1} \quad (6)$$

$K_p = L\omega_{Ci}$ And $K_i = r\omega_{Ci}$

B. Design of DC link voltage controller for VSC_1:

Controllers for the inner current loops were designed assuming that $V_{DC}$is fairly constant during the reference current tracking operation. In practice, it is not possible to connect a very large capacitor at the DC link because firstly it is not economical and secondly a big capacitor will adversely affect the dynamic response of the DC link voltage [7].

The power balance condition across the DC and AC ports of the PV inverter can be used to model the DC link by expressing the capacitor voltage as a function of i_d, $P_{PV}(PV\ power\ output)$and $P_{loss}(inverter\ power\ loss)$

$$P_{PV} = \frac{d}{dt}\frac{1}{2}C_{DC}V_{DC}^2 + P_{loss} + \frac{3}{2}v_d i_d \quad (7)$$

To avoid non-linearity, V_{DC}^2 term can be considered as a state as well as an output variable of the plant model for the DC link voltage control. If P_{loss} is neglected it can be written as (8)

$$\frac{1}{2}C_{DC}\frac{d}{dt}V_{DC}^2 = P_{PV} - P_g = p \quad (8)$$

$P_g = \frac{3}{2}v_d i_d$ And p is a new control variable

Using (8), the transfer function for the DC link voltage control can be written as (9)

$$G_v = \frac{V_{DC}^2(S)}{p(s)} = \frac{2}{C_{DC}S} \quad (9)$$

The feed-forward compensation signal may be provided by the PV-Maximum Power Point Tracking (MPPT) [7].The plant originally has a pole at origin, hence with additional integral term added to the controller so that the phase of loop transfer function is extended to $-180°$.

A lead compensator is the best choice to provide a phase boost (θ_{boost}) at required ω_{cutoff} of the gain plot.the DC link voltage controller G_{Cv} has the following form

$$G_{Cv}(s) = \frac{h}{s}\frac{s + \frac{r}{\alpha}}{s + r}$$

Where $r = \omega_{Cv}\sqrt{\alpha}$

$$\alpha = \frac{1 + sin\theta_{boost}}{1 - sin\theta_{boost}}$$

C. Current Controller for Auxiliary Inverter:

The primary responsibility of VSC_2 is to regulate the AC terminal voltages of the C_p, and L_p banks when the main switch s is off, the inner current control loop structure of VSC_2 is same as that of VSC_1.

The AC voltage control of the RPB (Reactive Power Banks) using synchronous frame transformation represents 4th order control problem corresponding to $d - q$ variables for C_p and L_p respectively shown in (14)

The vector differential equation corresponding to inductive RPB is as follows equation (12) and (13)

$$L_p\frac{di_{Lp}}{dt} = -rL_p i_{Lp} + v_{Ax} \qquad (12)$$

And for capacitor bank

$$C_p\frac{dv_{Ax}}{dt} = i_{Ax} - i_{Lp} \qquad (13)$$

The $d - q$ components of the vectors can be segregated and represented in the state space form as follow equation (14)

$$\begin{bmatrix} \dot{v}_{dAx} \\ \dot{v}_{qAx} \\ \dot{i}_{dLp} \\ \dot{i}_{qLp} \end{bmatrix} = \begin{bmatrix} 0 & \omega & \frac{-1}{C_p} & 0 \\ -\omega & 0 & 0 & \frac{1}{C_p} \\ \frac{1}{L_p} & 0 & \frac{-r_{Lp}}{L_p} & \omega \\ 0 & \frac{1}{L_p} & -\omega & \frac{-r_{Lp}}{L_p} \end{bmatrix} \begin{bmatrix} v_{dAx} \\ v_{qAx} \\ i_{dLp} \\ i_{qLp} \end{bmatrix} + \begin{bmatrix} \frac{1}{C_p} & 0 \\ 0 & \frac{1}{C_p} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \qquad (14)$$

D. Compensator Design for PV Station Reactive Power:

The reactive power generation by the PV station is the combined response of the latter's inner current control (sitting in the control loop of reactive power component of current) and that of capacitive RPB (whenever switch is closed). This may be represented by the following non-linear equation [using as a switch function S (1, 0)]:

$$i_{qstn} = i_q + S[i_{qcp}] + i_{qcf} \qquad (16)$$

The response of the inner reactive power component of the main inverter VSC_1 is governed by equation (17) (18)

$$G_{CL}(S) = \frac{1}{\frac{S}{\omega_{Ci}}+1} \qquad (17)$$

Where$i_{qcp} = -\omega_0 C_p v_d i_{qcf} - \omega_0 C_f v_d$

The plant model can be written as

$$i_{qstn}(s) = \frac{1}{\frac{S}{\omega_{ci}}+1} i_q^*(s) \underbrace{+ S\omega_0 C_P v_d(s) S\omega_0 C_f v_d(s)}_{\text{Is taken as N}} \qquad (18)$$

$$\therefore \frac{i_{qstn}(s)}{N} = \frac{1}{\frac{S}{\omega_{Ci}}+1}$$

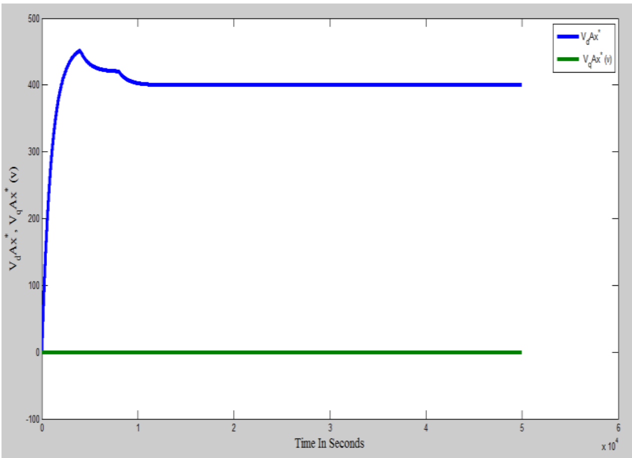
$\therefore$ PI controller with feed forward compensation is found to be stable

$$K_p = \frac{\omega_{Cstn}}{\omega_{Ci}} \quad K_i = \omega_{Cstn}$$

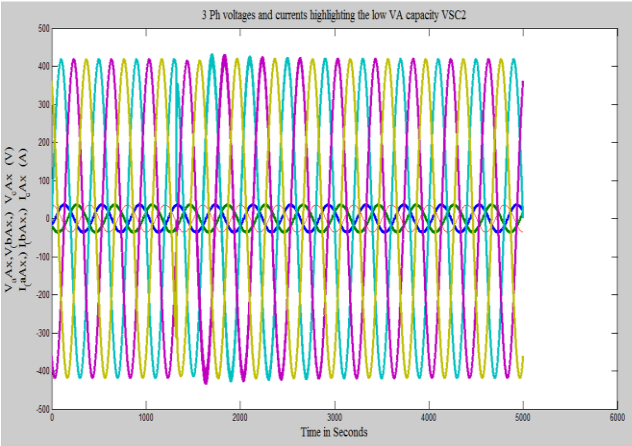
V. Comparison of results:

By using PI controller the mathematical equations are becoming very complex and corresponding results are shown below.

The simulation results shows the smooth tracking of reactive power and Transient performance highlighting seamless interface during of RPB.

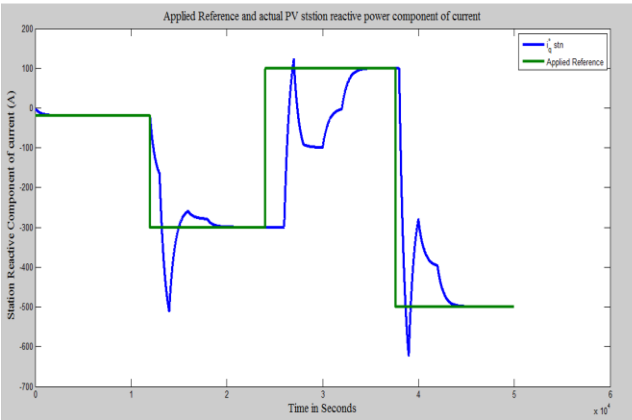


3(a)

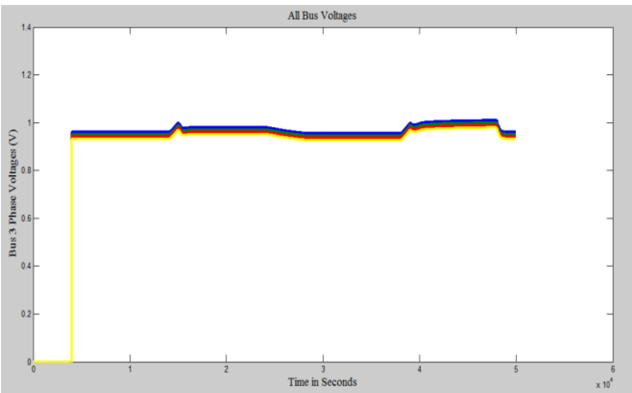


3(b)

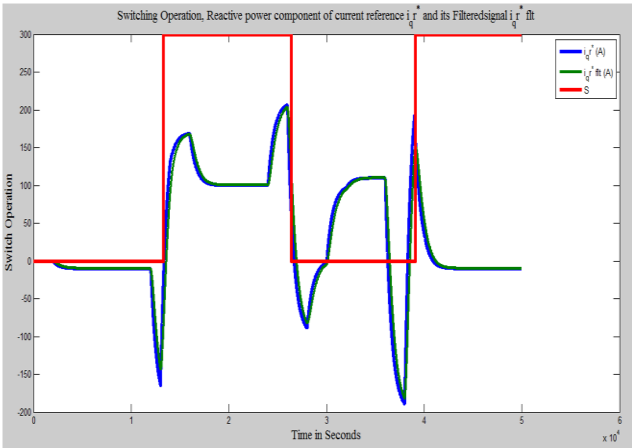
Fig. 3. (a) Tracking performance of the $d-q$ components of terminal voltage of RPB. (b) 3-Ph voltages and currents highlighting the low VA capacity.



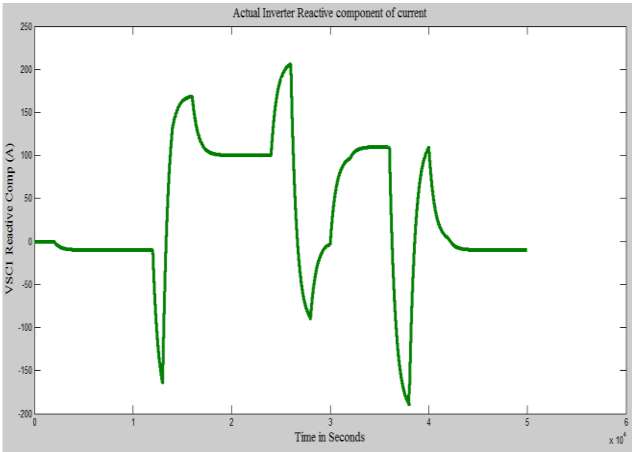
4(a)



4(b)



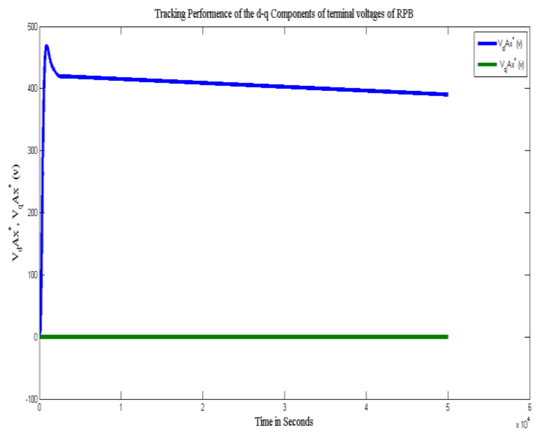
4(c)



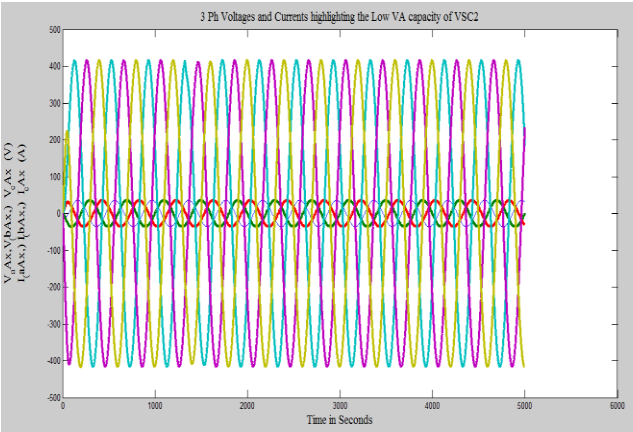
4(d)

Fig. 4. PV station reactive power control performance. (a) Applied reference and actual PV station reactive power component of current. (b) All bus voltages. (c) Switch operation, reactive power component of current reference and its filtered signal. (d) Obtained reference and actual inverter reactive power component of current.

The results obtained by using fuzzy logic controller are smoother than the results obtained by using PI controller. The settling time of d-q component of station reactive current is reduced and transient behavior of the system is increased. The corresponding fuzzy logic controller results are shown below.

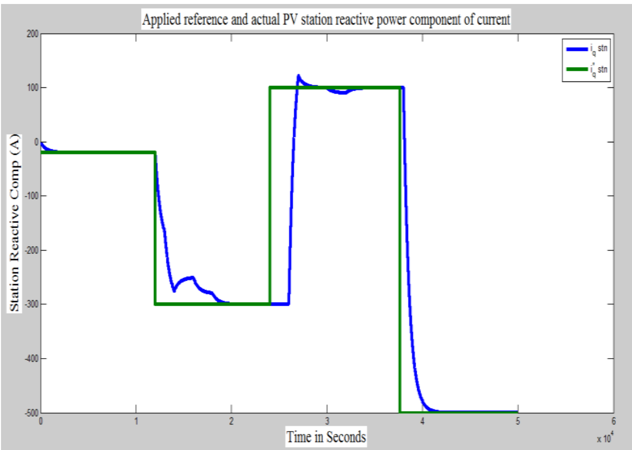


5(a)

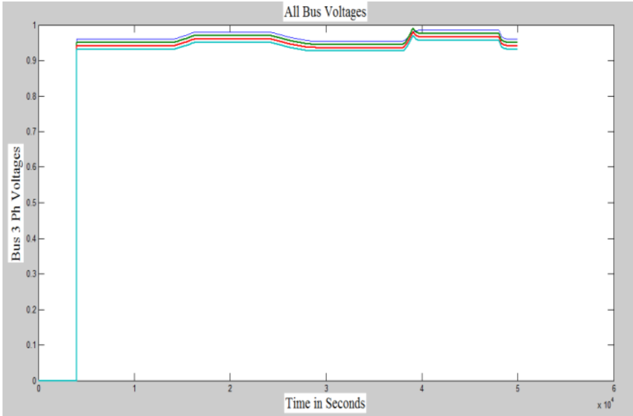


5(b)

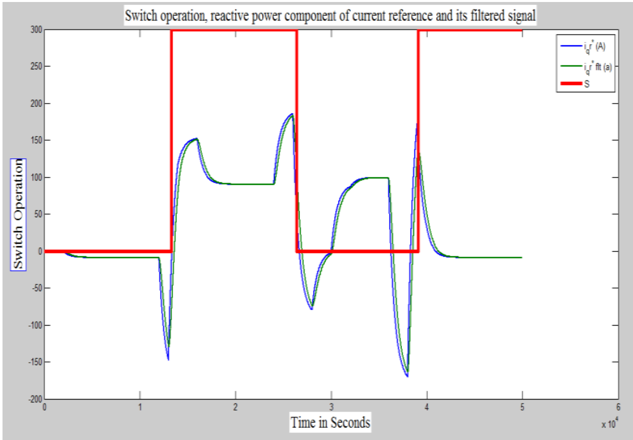
Fig. 5. (a) Tracking performance of the $d-q$ components of terminal voltage of RPB. (b) 3-Ph voltages and currents highlighting the low VA capacity.



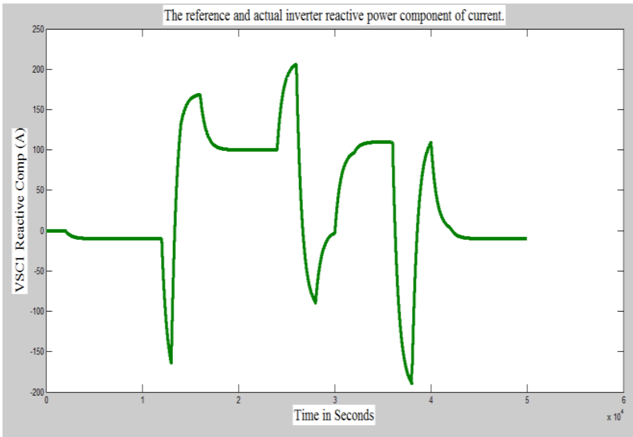
6(a)



6(b)



6(c)



6(d)

Fig. 6. PV station reactive power control performance. (a) Applied reference and actual PV station reactive power component of current. (b) All bus voltages. (c) Switch operation, reactive power component of current reference and its filtered signal. (d) Obtained reference and actual inverter reactive power component of current.

VI. Conclusion:

Distributed power generation has gained importance for reducing the stress on the power grid. The upcoming power grid is likely to be crawl with a large number of inverter driven DGS units.it would be highly desirable to have this DGS units also compensate reactive power in addition to the local power generation. The proposed scheme has demonstrated a possible method of increasing the reactive power support of the inverter driven DGS. The detrimental effects on the wave forms of the feeder voltages and regulation can be overcome by using fuzzy logic controller. The proposed method using auxiliary voltage source, RPB and fuzzy logic controller addresses these problems by eliminating switching transients and providing full range of reactive power control.an important feature of this work is that it can be conveniently implacable for existing systems with capacitor and inductor banks.

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