Virtual Synchronous Machine Based PV-STATCOM Controller

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Abstract- This article presents the concept of Virtual Synchronous Machine (VSM) used as a controller for PV-STATCOM in which the solar photovoltaic inverter is often used as a dynamic reactive power compensator-STATCOM. The proposed controller evinces how the VSM based controller is better in voltage regulation and synchronization than the conventional controller for PV-STATCOM based system. Simulation results of both conventional and VSM based controller are shown to support the idea.

Keywords— *PV-STATCOM, VSM, reactive power compensation, controller*

I. INTRODUCTION

Due to high energy demand and severe pollution from conventional energy sources supported fossil fuels has prompted the expanded use of Renewable Energy Resources (RES). In India, RES accounts for around 22% of the nation's total energy capacity. Wind power accounts for the best at 46%, followed by solar energy with a portion of 36% and the remaining is captured by biomass at 12% and small hydro ventures obliging 6%. With the increasing participation of sustainable power source assets into the electric power grid system and the evolution from a centralized power producing systems to distributed generating systems are expected to present genuine difficulties to the operation and development of forthcoming power systems.

Due to increase in non-linear loads like induction motors, arc furnaces, etc. harmonics are injected into the system causing various power quality problems. To keep desirable power quality various types of flexible alternating current transmission system (FACTS) devices are utilized such as STATCOM, DSTATCOM, SVC, DVR, TCSC and UPFC. DSTATCOM has been incorporated in [1] in distribution system to prove its effectiveness in overcoming power quality concern of voltage sag. While in [2] voltage sag issue has been confronted using dynamic voltage restorer (DVR) and has shown promising outcomes.

With the sudden changes in loads, the system is always prone to faults; hence appropriate protection devices needs to be stationed in the system. However due to FACTS devices being used in the system can cause to deteriorate the performance of protection devices like distance relays, mho relays etc. Like in case of SVC at the mid-point of transmission line, a new algorithm that utilizes synchronized phasor measurement (SPM) was used to enhance the performance of distance relay [3]. New mho relay algorithm using phasor measurement unit (PMU) has been proposed in [4] when mid-point static synchronous series compensator (SSSC) was used.

Various topologies of voltage source inverter (VSI) have been compared in [5]. Multilevel VSI has shown upper hand over multiphase VSI in terms of harmonics reduction, complexity and cost effectiveness. Multilevel VSI based STATCOM has shown highly suitability for EHV system because of its better harmonic characteristics and better dynamic properties.

Research has been proposed on the employment of inverter connected to the photovoltaic array as STATCOM, normally when it is not in use for performing voltage regulation and improving system stability. The strategies for voltage control on PV solar farm to act as STATCOM are proposed [6], [7]. This concept of utilizing inverter connected at PV end as STATCOM is termed as PV-STATCOM [7]. During daytime the inverter capacity is used for active power control and during night time the whole inverter capacity is used for reactive power compensation [8].

For converters that are being interfaced with the grid, synchronization is a fundamental challenge and needs to be taken first into consideration before other functions. Typically in the existing PV-STATCOM controllers a phase-locked loop (PLL) is employed to coordinate the converters with the electric power grid [9]. A synchronous reference frame PLL (SRF-PLL) has shown promising results against negative component interruptions and harmonics. However, it is uncertain whether they will coordinate with one another and sustain in a very situation when there are many converters [10].

In the recent times, the d-q frame PLL based controller has been replaced by virtual synchronous machine (VSM) or synchronverter [13] concept, which controls grid-connected inverters by imitating the behaviour of a standard synchronous machine to get a stronger performance in terms of synchronization with the power grid and faster response than a physical synchronous machine which is achieved with the assistance of virtual inertia which is programmable during disturbances. VSM based controller eliminates PLL

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and hence it’s expected unsteadiness. VSM based controller remains harmonized with the electrical system whereas the d-q frame controllers rely on PLL to adapt its control system and operation. This property inhibits VSM based controller from interacting with one another and running into instability [12].

VSM based controller has been utilized with different configurations, some using only virtual inertia [13], [14], while some utilizing virtual impedance to it [15] and some proposing the complete model of synchronous machine [16]. In this paper both virtual inertia and virtual impedance will be utilized to make STATCOM to be operable as variable synchronous condenser. With virtual impedance the controller can almost nullify the harmonics produced by the inverter and can discard the harmonics from the electrical system, thus confirming better performance and immunity against harmonics. With virtual inertia in the circuit, the controller can naturally synchronize the compensator with the electrical grid without the risk of getting out of synchronism. Thus, with such features of VSM based controller it provides improved voltage regulation and synchronization than the conventional d-q frame PLL based controller.

The primary objective of this paper is to give a comprehension of the VSM based controller for grid-connected solar PV system inverters for better synchronization and voltage control. The paper will continue as follows: section II will refer to VSM, section III describes the conventional controller for PV-STATCOM, section IV introduces the design of VSM based controller implemented to the solar PV system inverter, section V gives the simulation results and the conclusion in section VI.

II. VIRTUAL SYNCHRONOUS MACHINE

In conventional power systems, the synchronous machine (SM) with excitation control and speed governor offer ideal highlights to support the system operation. SM with its dynamic properties gives the odds of altering the active and reactive powers, the reliance of the grid frequency on the rotor speed, and featuring the rotating mass and damping windings effects as well as steady operation. The dynamic attributes of SM can be emulated with power electronic converters and are characterized in broad term as a virtual synchronous machine (VSM). The core part of VSM is the utilization of swing equation to remain in synchronization with others [18].

$$\begin{aligned}
&\frac{d\delta}{dt} = \omega - \omega_n \\
&M\frac{d^2\delta}{dt^2} = P_{dc} - P_{ac} - D(\omega - \omega_n) \\
&M\frac{d\omega}{dt} = P_{dc} - P_{ac} - D(\omega - \omega_n)
\end{aligned} \tag{1}$$

where,

δ is power angle,

ω is detected frequency,

ω_n is grid frequency,

M is angular momentum,

D is the damping coefficient

P_{dc} is input real power from the dc side of the inverter

P_{ac} is output real power from the ac side of the inverter

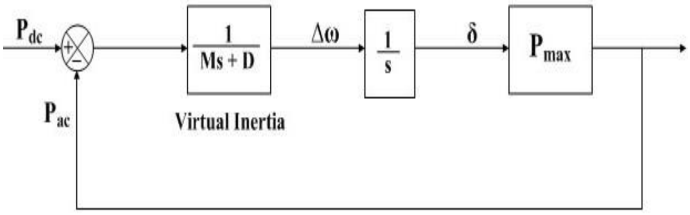

Fig. 1 Virtual synchronous machine controller block diagram

M and D in the context of VSM can be termed as virtual angular momentum and virtual damping coefficient respectively. Fig. 1 depicts the basic block diagram of VSM based controller. VSM concept can be explained taking analogy of the conventional synchronous machine as considering an imaginary rotating shaft with an angular frequency of ω which is being driven by P_{dc} and decelerated by P_{ac}. If ω is larger than ω_n, δ will get larger thus increasing P_{ac} and then ω will be reduced by the unsteadiness in the input and output powers. In steady state, the powers will be exactly equal and hence making system frequency equal to the grid frequency, thus showing perfect synchronism.

III. CONVENTIONAL CONTROLLER

The testbed considered is as shown in Fig.2, where the solar PV arrays are assisting the electric power grid. The solar PV system inverter can be controlled as STATCOM during daytime as well as night time. During night time it provides the full inverter capacity while during the daytime, provides remaining capacity of the inverter after active power generation for reactive power compensation [6]. The voltage source inverter is modelled to perform as STATCOM has an output voltage of v, equivalent impedance of Z_s consisting of filters and transformer and the corresponding current, i. The grid is modelled as a voltage source of magnitude v_g, with impedance Z_g consisting of both filters and transformer and an injecting current of i_g, thus depicting a weak grid.

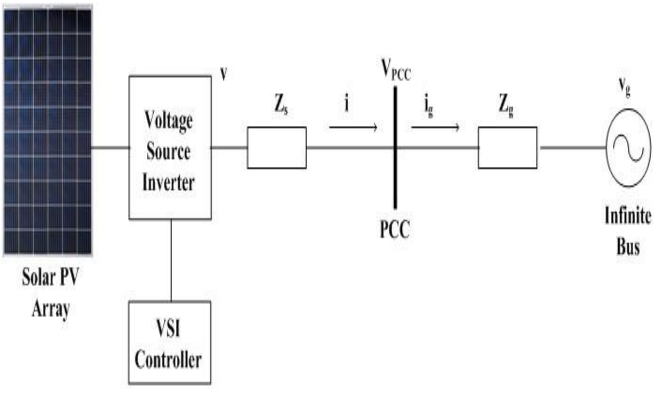

Fig. 2 Test bed single line diagram

Fig. 3 depicts the control diagram of conventional controller for PV-STATCOM system active power control at daytime and reactive power compensation during night-time. A PLL based control is employed to keep up synchronization with the PCC. The voltage based control is done employing a current controller used in dq0 frame [9].

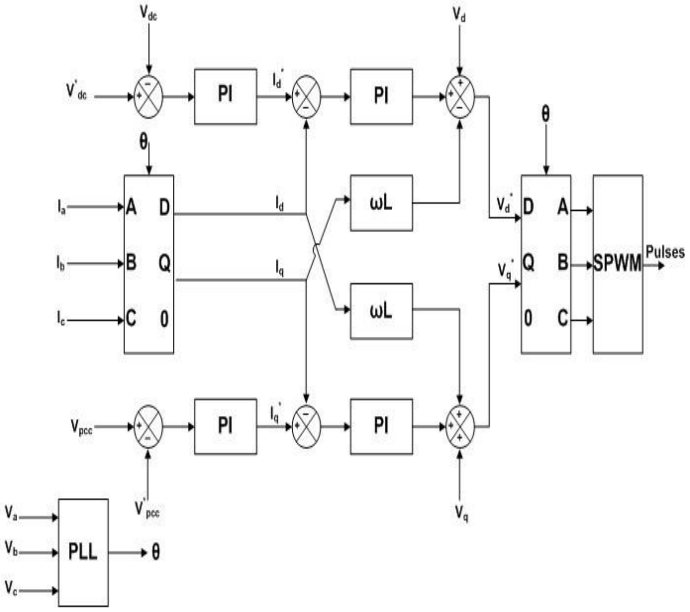

Fig. 3 PV-STATCOM conventional dq0 frame controller

The application of the voltage based control is done using a current controller used in dq0 frame; P and Q are the active and reactive power that is to be controlled. By controlling the DC-link voltage, the real power, P is controlled. Then the P and Q power signals are transformed into d and q frame components of the reference current with the help of equation 2:

$$\begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix} = \frac{1}{v_{gd}^2 + v_{gq}^2} \begin{bmatrix} v_{gd} & -v_{gq} \\ v_{gq} & v_{gd} \end{bmatrix} \begin{bmatrix} P^* \\ Q^* \end{bmatrix} \qquad (2)$$

The switching signal for voltage source inverter is generated by two current control loops in dq0 frame. The upper current control loop adjusts the DC link voltage through two PI controllers and injects real power into the power grid. The lower current control loop controls the reactive power flow.

IV. VSM BASED CONTROLLER DESIGN

Fig. 4 shows the VSM based controller implemented for solar PV system inverter which acts like a STATCOM. The main portion which incorporates the swing equation is within the part with virtual damping coefficient, D and virtual inertia, M. It provides the frequency and phase data of an imaginary rotating mass which synchronizes with the power grid in steady state with a phase difference referred to as power angle, rather than using PLL to trace the grid voltage. There are two voltage loops: first to manage the error in the dc-link voltage, V_{dc} through a PI controller. This is often necessary to take care of the dc bus voltage.

The second voltage loop is to control the magnitude of the PCC bus voltage, V_{pcc}. The error in the magnitude of PCC bus voltage, V_{pcc} is regulated through a PI controller which

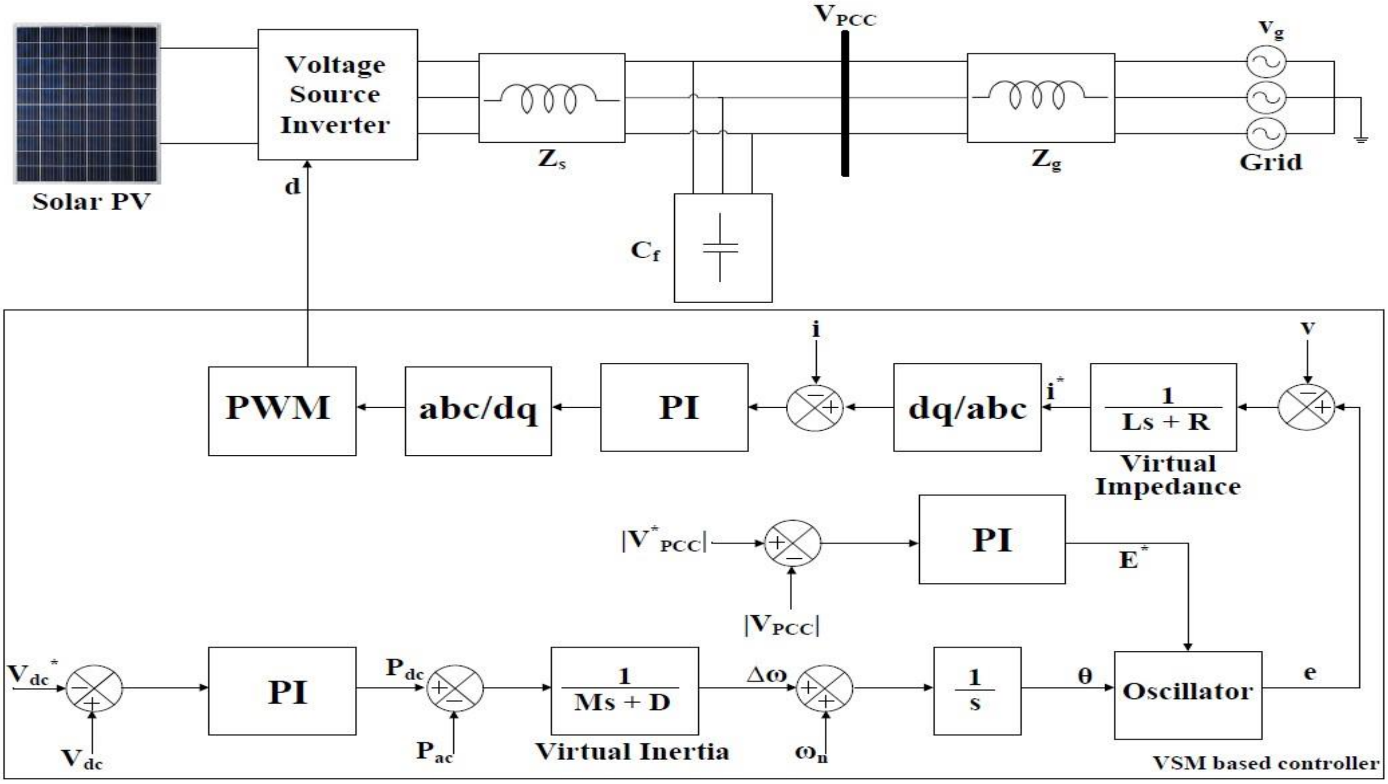

Fig. 4 VSM based PV-STATCOM controller

generates a virtual emf, E^*. The virtual emf, E^* is transformed into abc frame back emf, e through an oscillator with a phase position of θ obtained from the virtual inertia. The back emf is then deducted from the STATCOM terminal voltage, v, and divided by the virtual impedance to generate the reference current, i^*. The current loop is acknowledged inside the d-q frame to control the compensating current in the VSM controller, producing the duty cycle, d for the inverter.

V. SIMULATION RESULTS

To check the legitimacy of the proposed control strategy for the grid-connected operation, a simulation has been performed by using MATLAB Simulink. The circuit parameters utilized in the simulation are virtual inertia (M) of $5 \times 10^{-3}\omega_n$, virtual damping factor (D) of ω, virtual resistor (R) of 0.1/π, virtual impedance (L) of 50, PV array of 250 kW and grid voltage 25 kV values.

A. *Conventional Method Controller*

Fig. 5 shows the PCC voltage, at t=0.2 sec an additional load of 12 MW and 8 MVAR is connected, at t=0.3 sec the additional load is decreased to 7 MW and 5 MVAR, again at t=0.4 sec the load is increased to a level of 15 MW and 10 MVAR and finally at t=0.5 sec the load is decreased to 4 MW and 2 MVAR. Fig. 6 shows the expanded view of the disturbances caused on the PCC voltage profile due to changes in load magnitudes. The conventional controller shows an abrupt changes in the voltage profile due changes in load magnitude. This transients in the voltage waveform can be harmful to the electric system as the settling time of the transients are quite large, which could cause serious damage to the physical system. Fig. 7 shows the active and reactive powers profiles at the PCC.

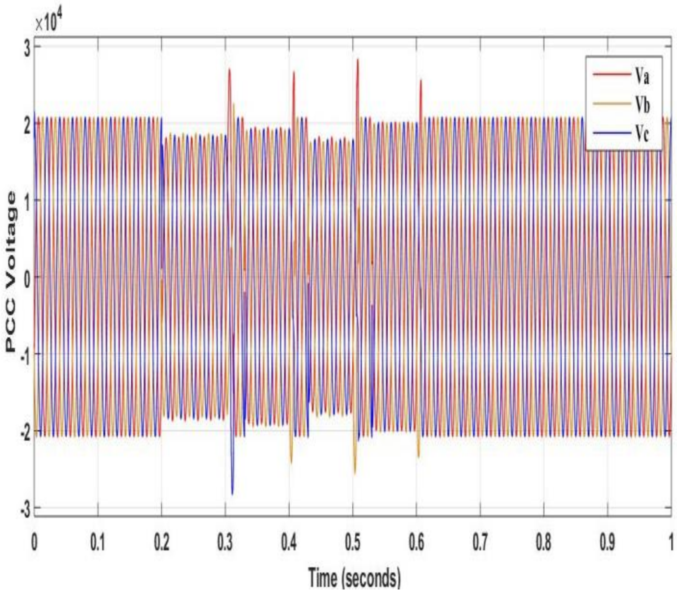

Fig. 5 Conventional controller PCC output voltage

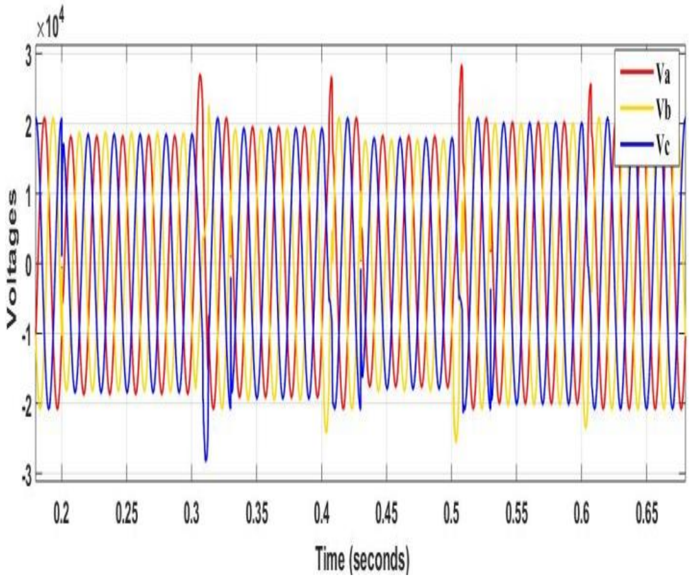

Fig. 6 Expanded view of Fig. 5

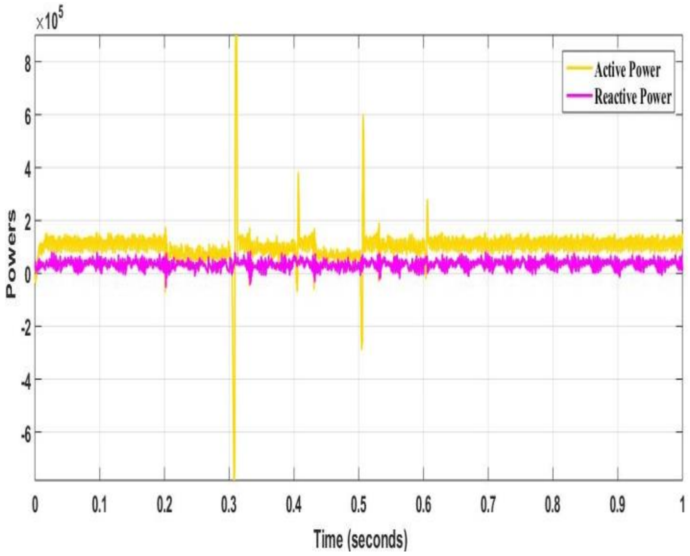

Fig. 7 Conventional method active and reactive power

B. *VSM based Controller Method*

Fig. 8 shows the PCC voltage, at t=0.2 sec an additional load of 12 MW and 8 MVAR is connected, at t=0.3 sec the additional load is decreased to 7 MW and 5 MVAR, again at t=0.4 sec the load is increased to a level of 15 MW and 10 MVAR and finally at t=0.5 sec the load is decreased to 4 MW and 2 MVAR. Fig. 9 shows the expanded view of PCC voltage which is being affected by the changes in the load magnitudes. The simulation results proves that the transients in voltage profile in the VSM based controller method are much lower than the conventional controller and has much lesser settling time of the transients. Thus, with a much lower transients and settling time, the system can have minimal effect on the system's health condition. Fig. 10 shows the nature of active and reactive power at the PCC.

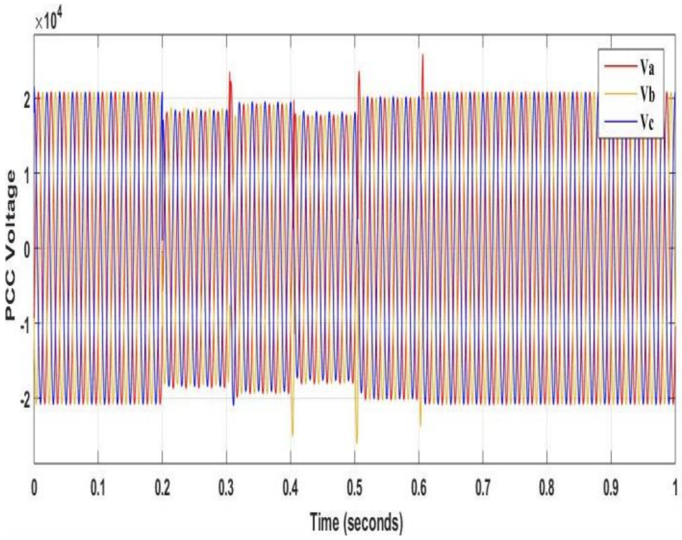

Fig. 8 VSM based controller PCC output voltage

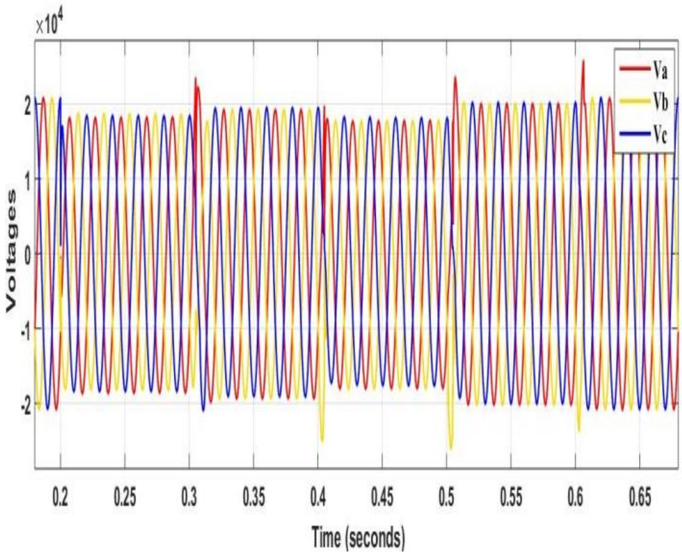

Fig. 9 Expanded view of Fig. 8

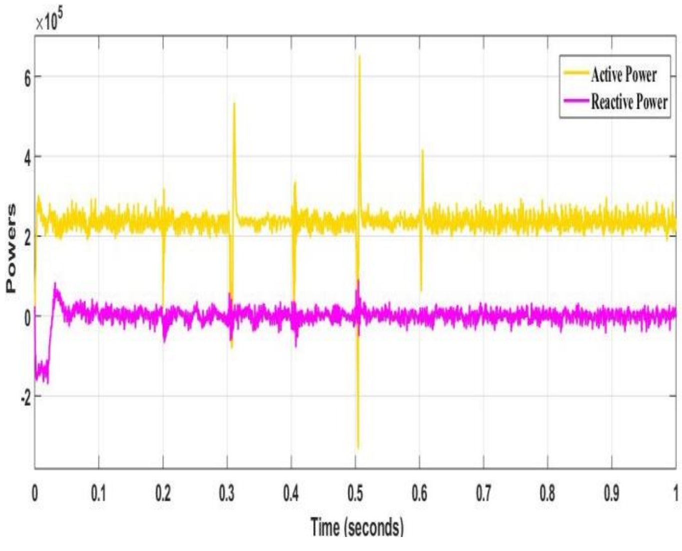

Fig. 10 VSM based controller active and reactive power

VI. CONCLUSIONS

This paper has presented a VSM based controller for the PV-STATCOM system. The examined control system has been validated by simulation outputs to be capable of providing auxiliary services like contribution in local voltage or reactive power regulation, primary frequency control, and inertia emulation for influence to the spinning reserve. The simulated system was evaluated at different load magnitudes and found that VSM based controller had much better performance than the conventional PLL based controller.

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