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Control Algorithm for Regulating Voltage and Frequency of Grid Connected PV System

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Abstract: **Growing environmental concerns and extinction of fossil fuels have shifted the focus on renewable energy resources. Among these alternatives, solar Photovoltaic (PV) energy has been looked upon as the most viable resource and hence it has resulted in proliferation of PV systems integrated to the grid. In addition to all the cherished benefits of PV power as a renewable source, large scale grid connection has led to unprecedented challenges that are being faced by utilities. One of the most serious issues with greater percentage of PV generation is that as these do not participate in grid frequency or voltage regulation, even a small perturbation in frequency or voltage may result in a disaster leading to total blackout. A novel control algorithm has been proposed in this work which offers the advantages of inertia & damping and enables the inverter to regulate the voltage and frequency. Simulated results are obtained in MATLAB/Simulink platform that shows the inverter capability to respond effectively for the grid side fluctuations.**

Keywords: **Photovoltaic (PV), renewable energy resource, inverter, voltage, frequency, grid.**

I. INTRODUCTION

With growing trend of Distributed Energy Resources (DER) replacing the conventional resources [1], power system (PS) operation is undergoing major transformation. Solar power is dominating the realm of renewable energy resources and grid connection for PV power has been the focus of research in the past few years due to its inherent advantages of being clean, economic, compact and also due to government policies and incentives to promote its widespread implementation. Various standards and practices have been formulated globally for proper connection and operation of these systems [2] and its effects on the grid power quality have been analyzed. Extensive research in material science and power electronics has led to the invention of new technologies which are highly efficient.

Numerous inverter topologies which can be used to integrate solar panel with the grid have been reported in literature [3],[4]. But as the penetration of these systems into the grid is increasing, there are various challenges that are being faced by the PS operators [5]-[7]. The integrated PV systems can be described as non-inertial generators as these systems lack inertia and damping. Thus in contrast to those of the conventional synchronous generators, any variation in load leads to large frequency fluctuations. As the reactive power cannot be injected by the PV systems, thus these systems are designed to shut down and isolate themselves from the grid as soon as any perturbation in voltage or frequency is detected on the grid side to prevent the formation of unintentional islands and thereby do not have any ride-through capability [5]. With the increasing number of grid integrated PV systems, there have been cases where a small fault on the grid side escalated into a major blackout due to a high number of solar PV operating without consideration towards grid dynamics. Obviously, grid stability and reliability is compromised when such systems continue to operate in this way. Thus the situation demands for a feasible solution to the aforementioned problem.

Therefore, the present scenario demands the designing of modern control mechanisms which can facilitate effective PV penetration. There are some techniques available in the literature [6]-[9], where either voltage control or frequency control through traditional droop method has been employed. However, not many work is found where both voltage and frequency regulation through active and reactive power control is carried out. Authors in [7] have presented an approach based on virtual synchronous machine (VISMA) which is shown to improve the performance of virtual synchronous generators (VSG). However, their performance relies heavily on the reference current or voltage tracking and inverter behavior changes for larger tracking error. Another attempt has been made in [11], where virtual inertia has been provided by adding a temporarily energy storage. But in this case system dynamics as seen from grid side comes to be different to that of synchronous generators.

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This paper presents a novel control algorithm for enhancing the PV performance in order to extract maximum benefits of interfacing with the grid. The methodology for applied inverter control strategy is based on the concept of synchroconverter. This offers the advantages of virtual inertia and damping to the PS and hence enables the inverter to regulate the frequency or voltage. A single controller, having the capability of frequency-watt control and voltage-VAR control has been presented, which is designed to work under normal and abnormal grid conditions providing a feasible solution to tackle the challenges for grid connection of PV system. Thus it makes feasible that PV system interfacings not only cater to power requirements, but can also participate in grid stabilization and are tolerant to faults on the grid.

II. METHODOLOGY FOR PROPOSED ALGORITHM

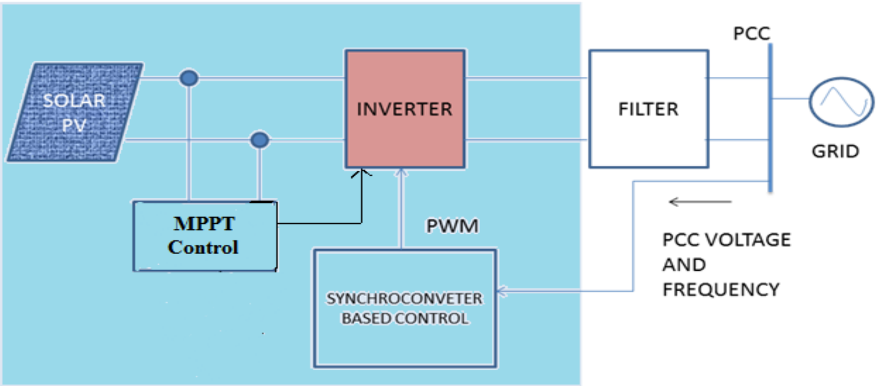

Fig. 1. PV system interfacing with incorporated controllers

The overall configuration of the grid connected PV system with incorporated control schemes is shown in the Fig.1. The basic idea behind the synchroconverter controller is to enable the inverter which is interfaced between the PV and grid to mimic a conventional synchronous generator in terms of both frequency and voltage droop control. The MPPT controller is based on model based (MB) algorithm which senses the panel voltage and current by estimating the real parameters and then adjusts the operating point. The key advantage of this MB algorithm is that it gives an effective and efficient tracking in the dynamic environmental conditions where the temperature, solar radiation and shading of panels changes quickly.

The control part of the synchroconverter mainly consists of voltage droop mechanism and the frequency droop mechanism. These mechanisms are implemented via nested feedback loops. The control part interacts with the power part and enables the synchroconverter to operate under different conditions on the grid. It can also automatically change the mode of operation of the synchroconverter as and when needed. It senses the current injected into the grid by the inverter at point of common coupling (PCC) and calculates the output voltage of the inverter, both magnitude and phase. This voltage is to be obtained at the output terminals of the inverter for successful operation of the inverter. The output of the control part consists of gate pulses to be applied to the inverter switches. The control mechanism and its implementation can be categorised as follows:

A. Voltage Droop Control

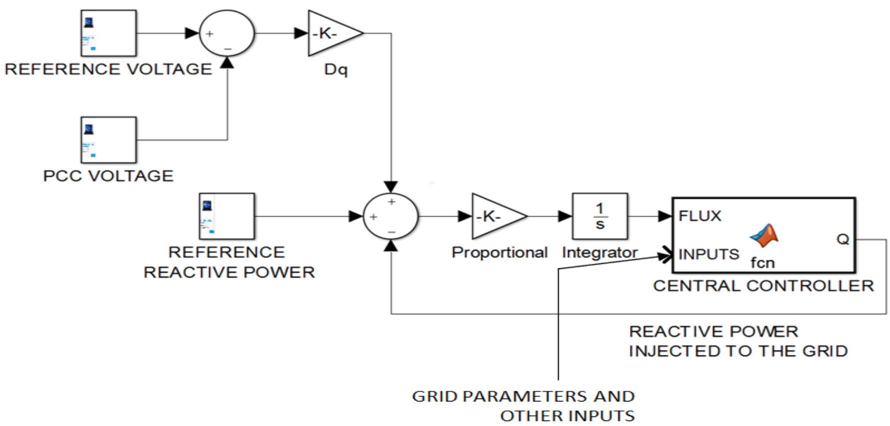

Fig. 2. Voltage control loop

As shown in Fig. 2, block diagram consists of two nested loops for the voltage control. Outer one controls the amplitude of voltage whereas reactive power control is processed through the inner one. Reference voltage is set at the normal value of the amplitude of grid phase voltage, taken to be 326.5 V in this work (line-to-line 400 V RMS). It is compared with the actual magnitude of PCC voltage at each time step of simulation. The amplitude of PCC voltage, v_m is calculated as

$$v_a v_b + v_b v_c + v_c v_a = -\frac{3}{4} v_m{}^2 \quad (1)$$

Where, v_a, v_b and v_c are the instantaneous magnitudes of the grid phase voltages measured at the PCC. Any change in this voltage results in an error signal which is multiplied with the voltage-drooping coefficient D_q which is expressed as

$$D_q = -\frac{\Delta Q}{\Delta v} \quad (2)$$

Where, Q→ reactive power, v→ voltage. The output signal, multiplied by D_q is added to the set point of the reactive power control loop as shown. It implies that any change in the PCC voltage magnitude from its set point would lead to a change in the set point for reactive power. Thus this mechanism supports the voltage stability of the grid by controlling the reactive power injection as and when needed, depending upon the voltage magnitude.

B. Frequency Droop Control

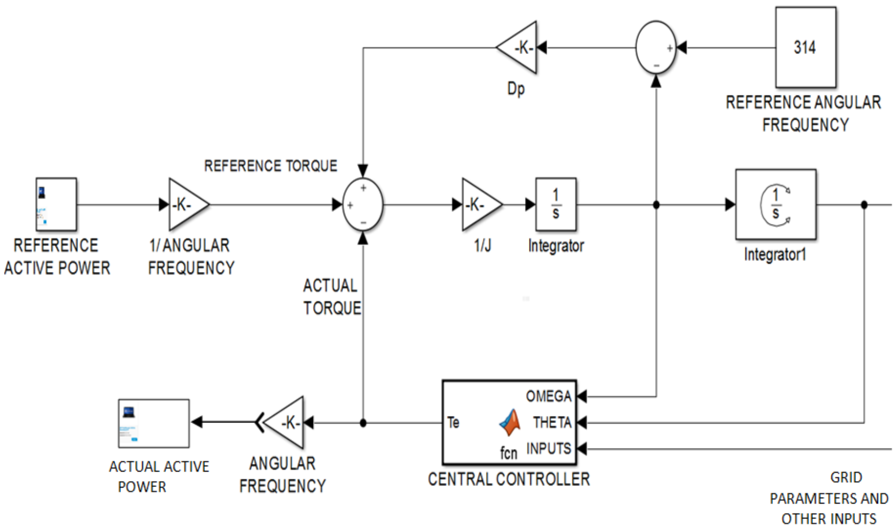

Fig. 3. Frequency control loop

As shown in Fig. 3, functioning of the frequency control loop is similar to that of voltage control loop. It is a nested feedback loop with the outer loop consisting of angular frequency control loop and the inner loop consisting of active power control loop. The mechanical torque T_m is compared with the electromagnetic torque T_e which is obtained from electrical power output P_e, of the synchroconverter. The frequency control mechanism is governed by the following equations where it should be noted that the actual system does not have any structural similarity with a synchronous generator rather bears a functional similarity.

$$J\frac{d^2\theta}{dt^2} = T_a = T_m - T_e - D_p\Delta\dot{\theta} \quad (3)$$

$$\theta = \iint \frac{1}{J}\left(T_m - T_e - D_p\Delta\dot{\theta}\right) \quad (4)$$

$$D_p = -\frac{\Delta T}{\Delta\dot{\theta}} \quad (5)$$

Where, J → rotor inertia, D_p → virtual coefficient of frequency droop and θ → virtual rotor position. $\Delta\dot{\theta}$ is calculated by comparing the actual angular frequency at the synchroconverter output with the reference angular frequency taken as 314 radian/s. The error is multiplied by the frequency droop coefficient D_p, that gives the droop of the power vs frequency curve. Any perturbation in frequency would lead to a non-zero output from the frequency control loop and thus T_e and P_e follows this new value which is the sum of reference value and the output of the outer loop.

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C. Central Controller

The central controller is a MATLAB function block which is a Multiple Input Multiple Output (MIMO) system having the following inputs and outputs:

Inputs → theta $\boldsymbol{\theta}$, theta_dot $\dot{\boldsymbol{\theta}}$, vector of grid currents **i** and imaginary flux linkage $\mathbf{M_f I_f}$

Outputs → **P**, $\mathbf{T_e}$, **Q** and **E** (magnitude of phase voltage to be obtained at output of the inverter)

The target output voltage at the inverter output is calculated using the equation:

$$E=326.5+theta\_dot*MfIf \quad (6)$$

The inverter switches should be operated in such a way that the amplitude of the sinusoidal output voltage in each phase is in accordance with the equation (6). Then the equation for electromagnetic torque is first given as (7) which can be modified as expressed in (8).

$$T_e = \frac{E*i}{theta\_dot} \quad (7)$$

$$T_e = M_f I_f < i.\sin\theta > \quad (8)$$

Where, < > represents the dot product in 3-D coordinates. The reactive power and active power is given as in the equation (9) and (10) respectively.

$$Q = theta\_dot * M_f I_f < i.\cos\theta > \quad (9)$$

$$P = T_e * theta\_dot \quad (10)$$

The implementation of central controller coded in MATLAB is shown in the Fig. 4. It calculates the values of all four output parameters defined above at each time step of simulation and passes them on to the PWM generator. The space vector PWM (SVPWM) scheme has been employed in this work to get desired magnitude and phase of output voltage at the inverter terminals. The carrier frequency is taken to be 15 kHz. It produces six series of output pulses for the three inverter switches.

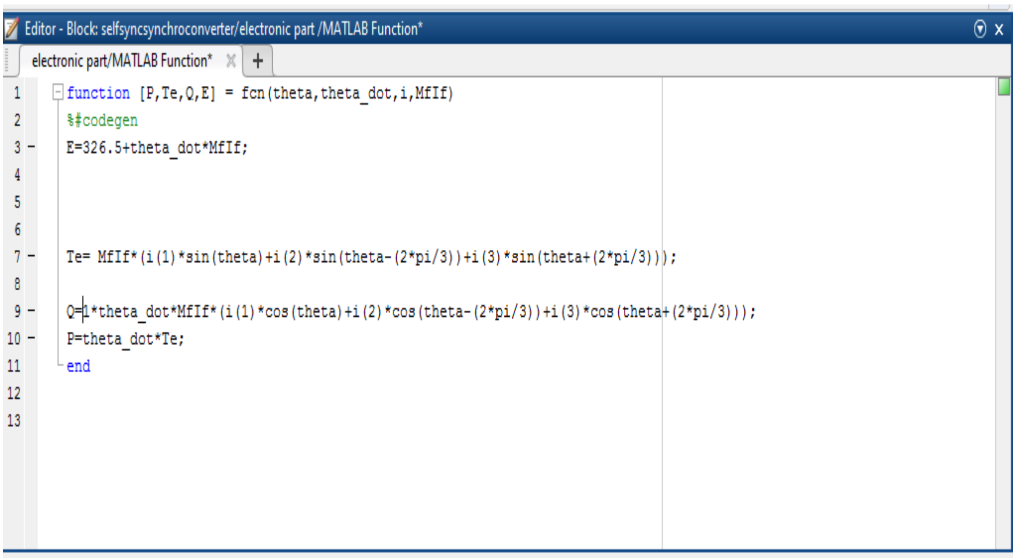

Fig. 4. Central controller coded in MATLAB

III. RESULTS AND DISCUSSIONS

This section presents the detailed analysis of the proposed control algorithm for the PV inverter. A large number of results have been shown for the complete evaluation of the proposed algorithm under all sorts of possible varied conditions in order to demonstrate both the qualitative and quantitative effectiveness. The simulation circuit and its control mechanism have been shown in Fig.5 and Fig. 6 respectively.

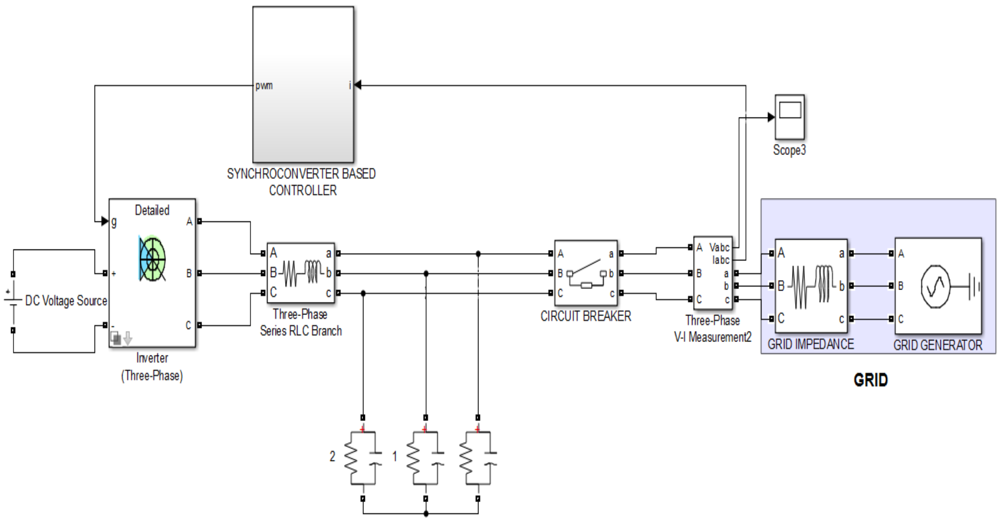

Fig. 5. Inverter working as synchroconverter

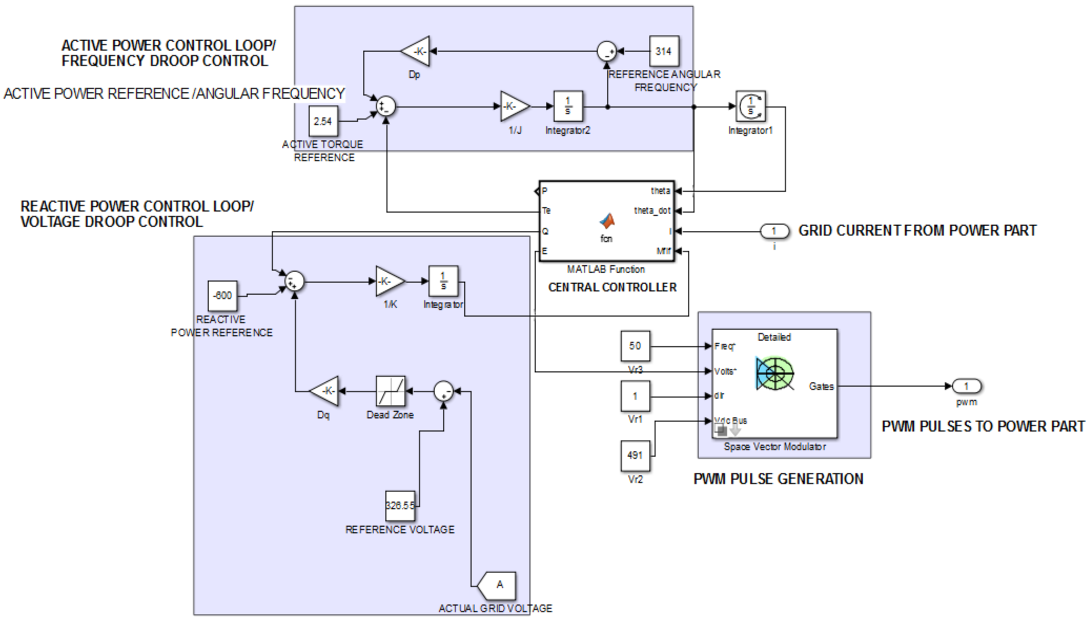

Fig. 6. Control mechanism of synchroconverter

Depending on the grid frequency and voltage conditions, system is designed to operate in different modes and to switch automatically from one mode to another as per the need. One or more modes may be active at any given instant of time. The circuit has been simulated with a step size of 2 µs, using 'Simulation Type' discrete. The simulation is run for different time spans depending on the parameter to be traced.

A. Operating Under Normal Grid Voltage and Frequency but With Varying Environmental Conditions:

Maximum power is tracked by the PV panels under any given environmental conditions by MB algorithm as described in the next section. The reference value of active power is same as the maximum power calculated by the applied MB algorithm. The tracked value of the active power varies throughout the day and falls to zero during the night. The synchroconverter is found to adjust its power output according to the tracked value of active power so that maximum active power injection is ensured. System has been operated by varying the reference value of active power for a period of 24 hours and it has been observed that the actual value tracks the reference value with reasonable accuracy as shown in Fig. 7. The nominal value of the active power at 50 Hz is taken as 800 W.

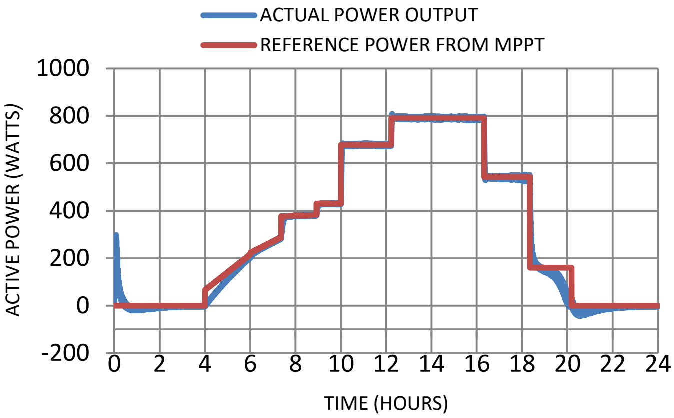

Fig. 7. Active power tracking for varying temperature & insolation

B. Operating Under Grid Frequency Variation:

As discussed earlier, the system has been equipped with the capabilities of active power control in condition of fluctuating grid frequency. Under the low frequency conditions due to high loading on grid, the synchroconverter attempts to recover it by injecting increased active power. Whereas, under the high frequency condition, the injection of active power is curtailed by lowering the reference value of 800 W, in proportion to the disturbance in frequency. Fig. 8 and 9, shows the frequency regulation by synchroconverter for low and high conditions respectively. Thus it is observed that the synchroconverter is highly sensitive to the grid frequency variations and responses quickly by controlling the value of active power injected into the grid.

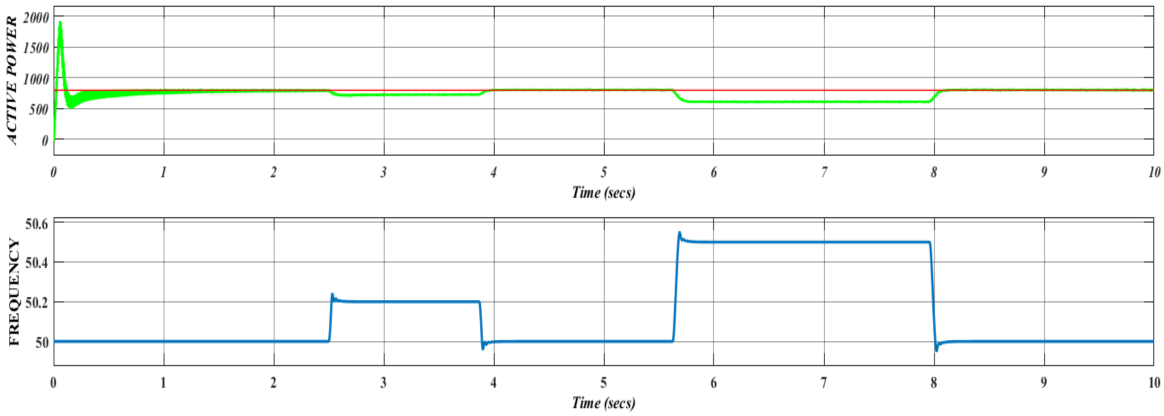

Fig. 8. Injected active power for low frequency

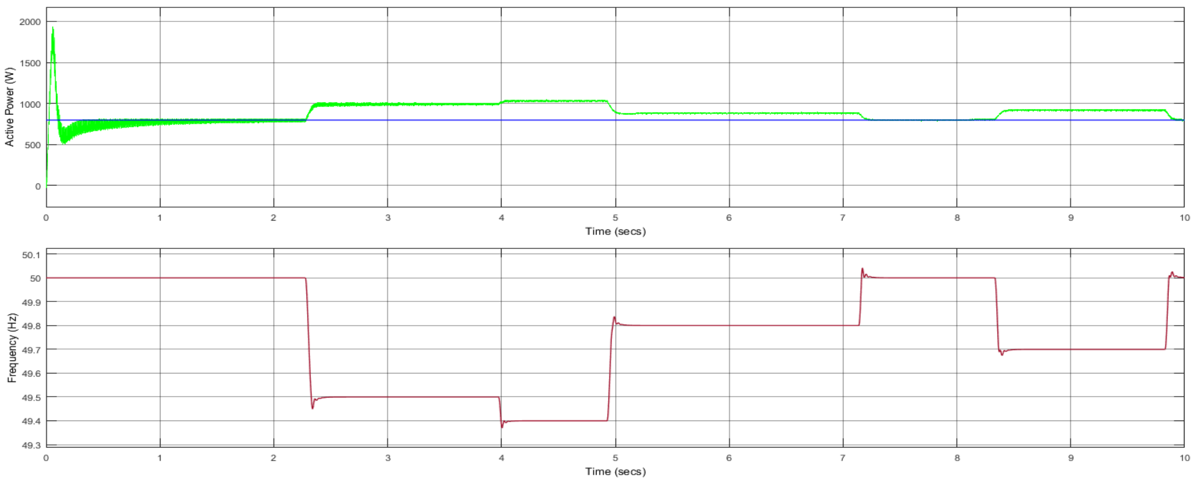

Fig. 9. Injected active power for high frequency

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C. Operating Under Grid Voltage Variation:

For the low voltage conditions on the grid, synchroconverter regulates the voltage at the PCC by injecting additional amount of reactive power which is proportional to the voltage magnitude at the PCC or the grid. Whereas, when the voltage at the PCC is higher than its nominal value, it takes part in voltage regulation by curtailing the amount of reactive power injected into the grid. When PCC voltage normalizes, reactive power also tracks its reference value of 600 VAR and hence the control mechanism enables quick changes in the value of reactive power with respect to PCC voltage; as shown in Fig. 10. and Fig. 11.

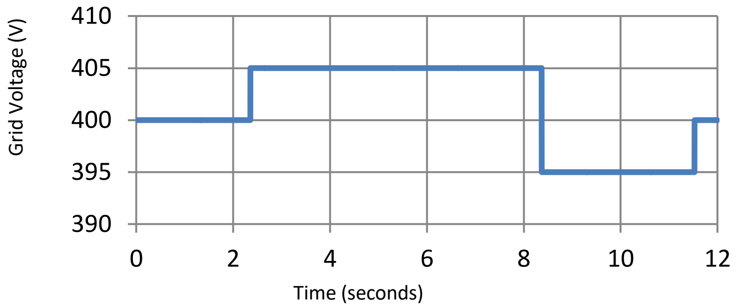


Fig. 10. Voltage fluctuations both low and high

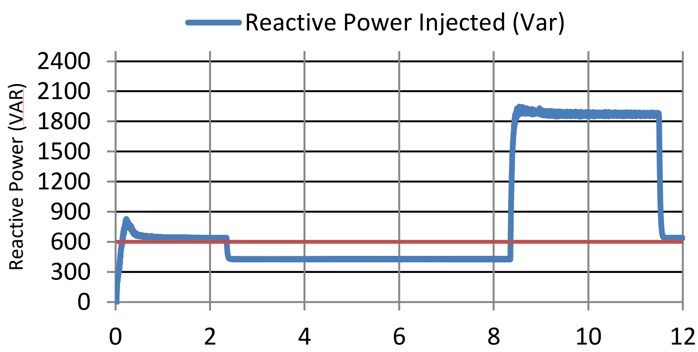
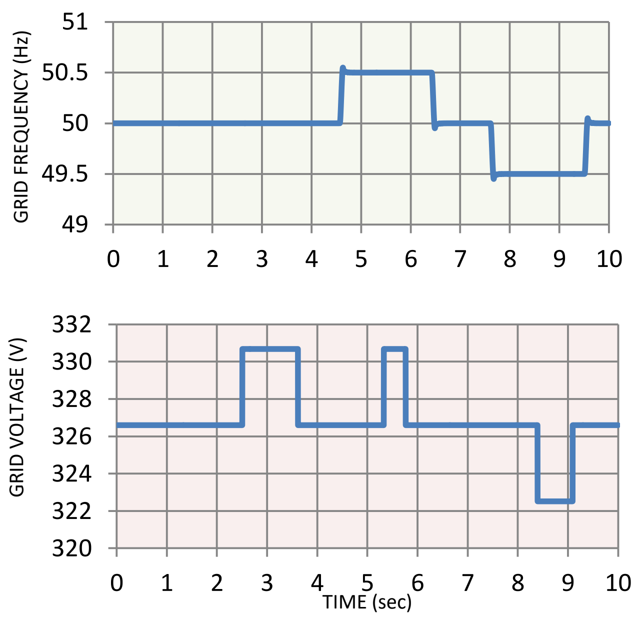


Fig. 11. Injected reactive power for voltage fluctuations

D. Operating Under Simultaneous Variations of Grid Frequency and Voltage:



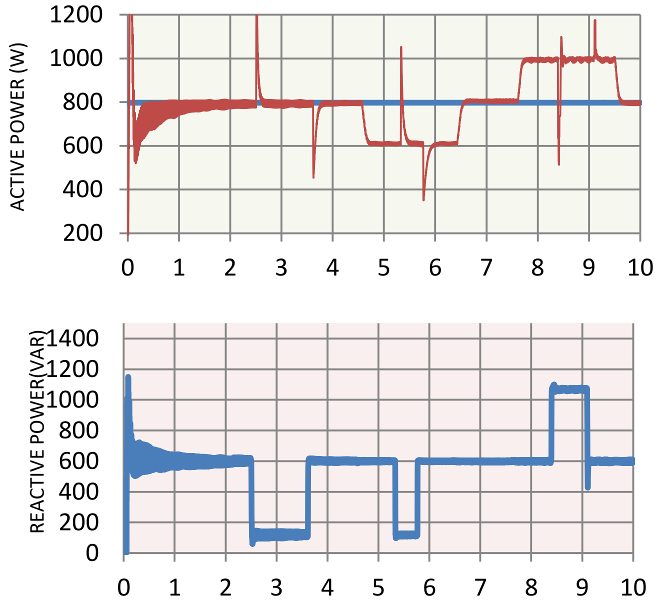


Fig. 12. Simultaneous operation of synchroconverter in all modes.

Finally the control algorithm is tested for both frequency and voltage perturbations above and below the nominal value. As shown in Fig. 12, control mechanism efficiently stabilizes the grid under these disturbances by regulating both active and reactive power injection and curtailment simultaneously.

IV. CONCLUSION

The power grid is being continuously subjected to voltage and frequency perturbations as a consequence of growing demand for large scale penetration of PV power in the distribution system. A feasible solution has been proposed in this work by designing novel control mechanism for inverter operation. The control strategy for grid connected inverter is based on synchroconverter concept that enables the inverter to participate in grid stabilization under fluctuations. Simulated results for inverter are analyzed where system is found to automatically and smoothly switch from one mode to another without transients and the settling time is also found to be reasonably small. Also, the active and reactive power is seen to track their reference value under any given condition with great precision and without any oscillations.

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