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Control of Photovoltaic Inverters for Transient and Voltage stability Enhancement

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ABSTRACT:

The increasing number of megawatt-scale photovoltaic (PV) power plants and other large inverter-based power stations that are being added to the power system are leading to changes in the way the power grid is operated. In response to these changes, new grid code requirements establish that inverter based power stations should not only remain connected to the grid during faulty conditions but, also provide dynamic support. This feature is referred in the literature to as momentary cessation operation. The few published studies about momentary cessation operation for PV power plants have not shed much light on the impact of these systems on the overall power system stability problem. As an attempt to address this issue ,this paper proposes a control scheme for PV inverters that improves the transient stability of a synchronous generator connected to the grid. It is shown through the paper that the proposed control scheme makes the PV inverter's dc link capacitors absorb some of the kinetic energy stored in the synchronous machine during momentary cessation. Besides that, the proposed solution is also able to improve voltage stability through the injection of reactive power. Experimental and simulation results are presented in order to demonstrate the effectiveness of the proposed control scheme.

INDEX TERMS Photovoltaic generation, synchronous machine, transient stability, voltage stability.

INTRODUCTION:

In recent years, power systems have experienced a significant increase in the penetration of RE sources, which are usually connected to the power grid through power converters(such as inverters). The increase of PV generation implies some new technical challenges, such as transient stability [1],which makes the operation of power systems under severe disturbances an important issue. The overall system inertia and governor response are reduced for this new system configuration, which may negatively impact the transient response of the rotor angle of SMs. However, the inverters used in PV generation provide new opportunities, such as ancillary services to SMs. For instance, PV inverters may help maintain stability after a system disturbance, such as a short circuit caused by a lightning strike on a transmission line, which may trigger a FD signal that is responsible for opening the faulted line's circuit breakers [2].

The GCs of the past two decades did not anticipate the significant changes in the power system configuration regarding the operation of power inverters. Even today, it is difficult to comprehend and estimate future scenarios of RE generation. Because of that, during the last decade, GCs have required the RE sources to be disconnected as soon as a disturbance is detected [3]. This requirement is acceptable as long as the RE penetration level is not significant, which is done to prevent the loss of synchronism.

However, the GCs have changed to require FRT capacity from RE units during disturbances [4], which means that the generation unit must not only remain connected to the power system but, also, must give support in maintaining synchronism and voltage stability. Some countries have established standards that require additional capabilities from the PV inverters used in distributed generation units, and from PV plants connected to the medium voltage transmission grid. Some of these standards allow for a MC operating mode or temporarily stop transferring active power to the grid while giving priority to the reactive power support to improve voltage stability [5][7]. Some GCs establish APRRR for post fault operation, as can be seen in [5], [6] and [8].

In the literature, the FRT capacity of PV systems in compliance with the GCs has been largely investigated. For example, [9] proposes an FRT scheme to support the grid by injecting reactive power, as required in the German GC [6], and that enables the power quality to adjust based on a tradeoff between power ripple and current harmonics. In [10], the impact of the following PV systems' operating modes is investigated: disconnection from the grid; FRT in blocking mode; and FRT with dynamic voltage support on short term voltage stability, on post-fault recovery and, eventually, on transient stability. Another relevant research is presented in [11], which models the LVRT capacity in PV plants based on field test results performed by manufacturers in compliance with the Chinese GC [7]. Lastly, in [12] the control system of a PV plant is adapted to include current limiters and dc link voltage control, making the FRT capability able to face any type of fault. Even though the FRT implementation on PV systems and its benets on dynamic voltage support have been studied in the literature, a more thorough study about the impact that the GC's operating modes have on the system transient stability remains necessary. The Blue Cut Fire [13] and the Canyon 2 Fire [14] events showed how little are the studies on the impact of the MC operating mode of PV systems on power system stability during a transmission fault. The NERC/WECC joint task force [13], [14] recommends performing dynamic simulations to understand the impact of MC and post-fault APRRR on stability. These studies are necessary to determine the conditions under which the MC should be used, and if so, what type of power should be delivered (active or reactive) and, also, the sequence of the injected current (positive, negative, or zero). Recently, some research efforts have been made to assess the impact of the MC mode on transient stability [15], [16].

Given the importance of making the PV plant have a positive impact on the system stability while operating in the MC mode, this paper proposes an FRT control scheme based on the absorption of the kinetic energy stored in the SM's rotating mass to ensure transient stability. The proposed control scheme also improves voltage stability and its post fault recovery through the delivery of reactive power into the grid. When using the proposed scheme, the SM active power output is increased close to its pre-fault value, recovering the balance between the SM electrical power and mechanical power, what decelerates the rotor angular speed that, in turn, reduces the rotor angle excursions and ensures transient stability within the first cycles of the disturbance. The proposed control scheme doesn't require any other additional equipment on the power system (as in [17]) or in the inverters' dc link (as in [18]). When comparing with the solutions proposed in [18] and [19], the control scheme presented in this paper also shows better performance ensuring the transient stability in the first cycles after the FD.

The proposed control scheme requires no additional hardware to be added to the existing equipment of a PV plant, and hence no additional costs are expected. However, it relays on a PMU and a PDC, which may need to be installed. Even though this is a large investment, there is an increasing trend to operate power systems in an economical and synchronized way, using smart grid technologies. PMUs and PDCs may thus become commodities in this environment, as they provide other functionalities for metering, monitoring and control.

The paper is organized as follows. In Section II, the proposed control scheme to be implemented in the PV inverter is explained. The experimental verification in Section III and the simulation of a utility-scale PV system in Section IV compare the performance of the proposed control scheme with other FRTstrategies. Finally, conclusions are presented in Section V.

PROPOSED CONTROL SCHEME OF THE PV INVERTER

The power system configuration shown in Fig. 1 is used for the transient stability analysis presented below. This hybrid power system consists of an SM operating in parallel with a PV system, both power plants are connected to the grid through two transmission lines. The PV system is composed of n PV units as shown in Fig. 2, these units are controlled according to a MPPT strategy under normal operation. However, during a fault in one of the transmission lines, the PV inverters can enable FRT in MC mode and perform the proposed control action to minimize the SM load angle (δ_r) . It is well known that in an APF the grid currents can be indirectly controlled by making the APF inject the harmonic components and reactive parts of the load currents. Similarly, the SM current components responsible for regulating the torque (or active power) and magnetic flux (or reactive power) can be imposed by controlling the currents injected into the grid by the PV inverters. This can be done because these inverters can act within the fault time frame, whereas the SM governor usually acts after the fault has ended. The disequilibrium caused by a disturbance can be reduced by maintaining the active power output of the SM as close as possible to its pre-fault condition. This means that, during the fault, the exceeding active power, that cannot be absorbed by the faulty grid must be delivered to the dc link capacitors of the PV units. Therefore, it should be noted that this strategy depends on the operational limits of the inverter, which must be considered. During the fault, the objective of the proposed control scheme becomes ensuring that the SM active power . $\left(P_{\mathrm{SM}}^{\mathrm{f}}\right)$ remains equal to its pre-fault value $\left(P_{\mathrm{SM}}^{\text{pre-f}}\right)$. To achieve this objective, the PV plant reference active power should be:

$$P_{\mathrm{PV}}^{*}=\bar{P}_{\mathrm{g}}^{\mathrm{f}}-P_{\mathrm{SM}}^{\text{pre-f}}, \qquad (1)$$

where $\bar{P}_{\mathrm{g}}^{\mathrm{f}}$ is the average active power injected into the grid during the fault. As determined by (1), the PV plant will require real-time measurements of the SM and of the grid. For this, as shown in Fig. 1, a PMU is installed in the SM substation to measure the voltage phasor at the PCC and the current phasors of the transmission lines. Current PMU technology can transmit synchro phasor data at up to 120 samples per second [20], [21] to a PDC, which is located at the PV plant substation for the following analysis.

A PDC is employed to aggregate and time-synchronize the phasor data collected from a PMU or multiple PMUs, and from other PDCs. The PDC is a critical link between PMUs and the synchrophasor software application to which the time-synchronized data is fed, for control decision action [21].

An important aspect regarding the data transmission is the communication delay involving sampling, data filtering and processing, communication system I/O, and communication distance. During the delay, since no variation in the SM active power output measurement reaches the PDC, the PV inverters won't be able to act properly. Thus, the communication system must be designed to avoid delays that are longer than acertain threshold, which is determined as the maximum delay that doesn't compromise the effectiveness of the proposed control scheme in ensuring transient stability. In this study, it was veried that the PMU delay shouldn't be longer than 20% of the total fault duration. The simulation in Section IV sets a maximum delay of 28 ms, which is well within the range of 20 ms to 50 ms for a typical system, as described in [20].

The proposed FRT scheme to be implemented on the PV inverters is shown in Fig. 3. The power references for each PV unit (Fig. 2) can be computed once the PMU measurements are transmitted to the PV plant substation's PDC. Based on (1), the pre-fault SM active power must be computed during the disturbance. For that, it can be obtained through the use of a very slow LPF, having a time constant of some seconds, which is much longer than the typical duration of a fault. On the other hand, the reduction of the active power consumed by the grid must be considered by the control. A MAF is used to attenuate the power oscillations caused by the negative-sequence and harmonic components of voltages and currents during the fault. The same applies to the PV reactive power reference computation.

Since the reference values calculated through (1) are for the PV plant, the power references of each PV unit are calculated dividing those values by the number of PV units (n). The reference P* inv value must be limited within the maximum active power P inv max that can be absorbed during the disturbance for safety purposes, which can be determined by:

$$P_{\max}^{\text{inv}} = \frac{C}{2\Delta t}\left(v_{\text{dc}}^{\max^2} - v_{\text{dc}}^2\right), \quad (2)$$

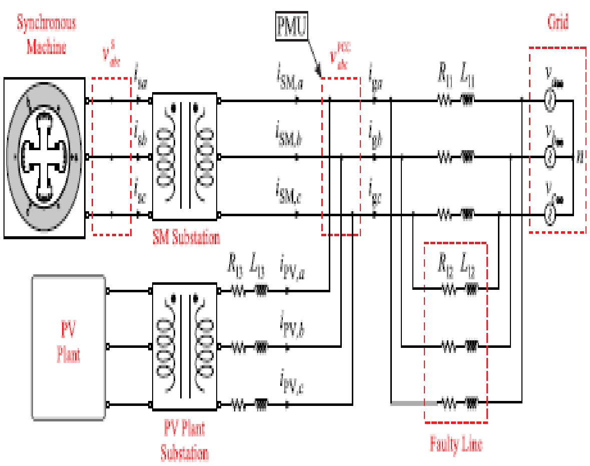


FIGURE 1. Three-phase diagram of a utility-scale hybrid power system.

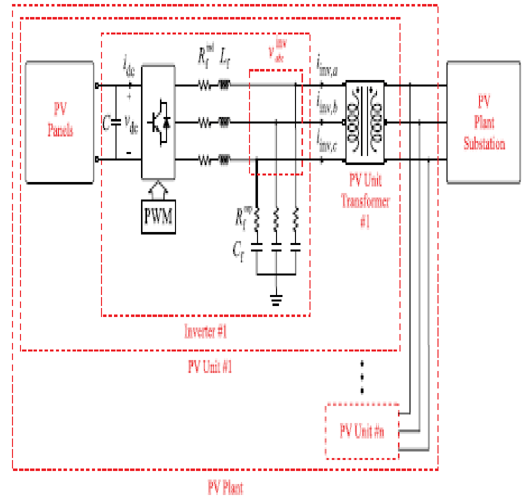


FIGURE 2. Three-phase diagram of each PV unit.

According to (1), no oscillatory power should be part of the calculation of the PV plant reference power. For this to happen during major grid disturbances, MAFs and LPFs are used. The MAFs' cutoff frequency is higher, in order to allow the proposed control scheme to keep tracking the real-time changes of the average power that is being transferred through the grid. On the other hand, the LPFs with lower cutoff frequency are used to retain the SM pre-fault active power output, which is used as a reference signal in the proposed control scheme.

where C is the dc link capacitance,1t is the fault's maximum duration, vdc is the steady state dc link voltage, and $v_{\text{dc}}^{\max}$ is the maximum dc voltage during a disturbance. This imposed limit on the controller prevents the dc link voltage from rising beyond the maximum inverter's dc input voltage, as specified in [22], which is a more restrictive limit than the capacitor's surge voltage of two times its nominal voltage, as in [23].The reference Q_{inv}^{*} must also be limited within the maximumreactive power $Q_{\max}^{\text{inv}}$, which can be calculated as:

$$Q_{\max}^{\text{inv}} = \sqrt{\left(S_{\max}^{\text{inv}}\right)^2 - \left(P_{\text{inv}}^*\right)^2}. \tag{3}$$

It should be noted that the proposed control scheme gives priority to the computation of the active power reference necessary to be absorbed by the PV units. However, the limit imposed by (2) provides a power margin that can be dispatched as reactive power support to improve voltage stability as required by some GCs [5][7].

As presented in [9], the FRT scheme computes the inverter current references in order to achieve constant power injection (which demands to synthesize all odd harmonic current components) or oscillatory power injection of frequency 2! (which only demands to synthesize fundamental-frequency positive sequence (FFPS) currents). When applied to the proposed control scheme, the oscillatory power injection does not impact the average SM active power output because its mean value is zero, thus, it has no influence in the variation of. It should also be noted that, when compared to the injection of only FFPS currents, injection of all odd harmonic currents can exceed the maximum shortcircuit withstand capacity of the inverter. For these reasons, in this research, the inverter current references contain only FFPS component. The ``power to current" block determines the current references using the instantaneous power theory [24]:

$$\begin{bmatrix} i_{+1,\alpha}^{\text{inv}^*} \\ i_{+1,\beta}^{\text{inv}^*} \end{bmatrix} = M_{\alpha\beta}^{+1} \begin{bmatrix} P_{\text{inv}}^* \\ Q_{\text{inv}}^* \end{bmatrix}, \tag{4}$$

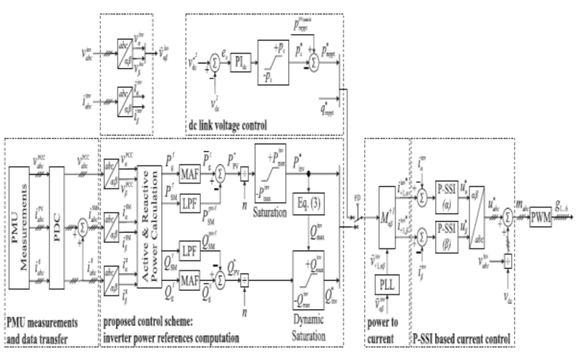
where $M_{\alpha\beta}^{+1}$ is given by:

$$M_{\alpha\beta}^{+1} = \frac{1}{\left|\vec{v}_{+1,\alpha\beta}^{\text{inv}}\right|^2} \begin{bmatrix} v_{+1,\alpha}^{\text{inv}} & v_{+1,\beta}^{\text{inv}} \\ v_{+1,\beta}^{\text{inv}} & -v_{+1,\alpha}^{\text{inv}} \end{bmatrix}. \tag{5}$$

In (5), the FFPS component of the voltage at PV unit's terminals $\left(\vec{v}_{+1,\alpha\beta}^{\text{inv}}\right)$ is obtained using a PLL (a GDSC-PLL was used for obtaining the results presented in this paper due to its better performance characteristics [25]). The resulting three-phase current .. $\left(i_{inv}^{abc}\right)$ ..should not exceed the short-circuit withstand capacity specified in the datasheet of the inverter unit [22].

A. VOLTAGE AND CURRENT CONTROLLERS

The overall control scheme is presented in Fig. 3. In steady state operation, the dc link voltage control block makes the power that comes from the PV panels to be transferred to the grid [26]. The dc link voltage controller shown in Fig. 4 calculates the active power reference $\left(p_c^*\right)$ to be delivered to the capacitor to reduce the voltage control error $\left(e_v\right)$. This value corresponds to the amount of power necessary to keep constant the dc link voltage. The power extracted from the PV panels at MPPT $\left(p_{\text{mppt}}^{\text{PV-panels}}\right)$ is added to p_c^* as can be seen in Fig. 4. By doing so, the becomes part of the active power reference. The inferior and superior limits of the anti-windup saturation block (Fig. 4) are selected to determine the maximum power variation the controller can compensate. The block "==" makes zero the input of the integral controller in case p0c and pc values are different. When the FD signal is activated, the ``dc link voltage control" block is disabled, which means that the transfer of active power from the PV panels to the grid enters in MC mode. Under these conditions, the dc capacitors can absorb the SM kinetic energy, thus, mitigating the impact of the fault on the SM transient stability. The ``P-SSI based current control" block will act to track the current references $i_{+1,\alpha}^{\text{inv}*}$ and $i_{+1,\beta}^{\text{inv}*}$, which are obtained.



Proposed FRT scheme including: PMU measurements and data transfer, FRT inverter power references computation, dc link voltage control, and P-SSI based current control.

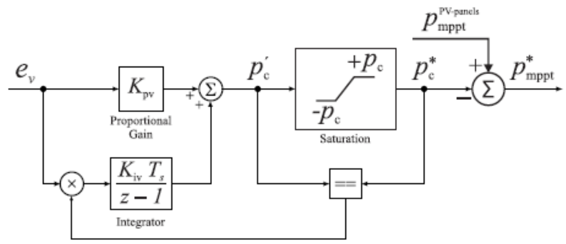


Diagram of the dc link v oltage controller with anti-windup action.

from the ``dc link voltage control" block in steady-state operation or from the ``proposed control scheme" block during the disturbance. For this purpose, two controllers, one for and the other for components, based on sinusoidal-signal integrators (SSIs) are used [27], [28]. A proportional action was also used for defining the controller's bandwidth .The P-SSI based current control scheme has been selected because it is widely used in systems with sinusoidal references and/or disturbances. This motivated by the fact that its transfer function is equivalent to that of a sinusoidal signal ,eliminating the steady-state error for sinusoidal reference signals (according to the internal model principle). A feed forward value of $\frac{v_{abc}^{\text{inv}}}{v_{\text{dc}}}$ is added to the controllers' output to obtain the modulation signals m abc, and a PWM converts these signals into commands g1. . . 6 for the inverters' IGBTs. The current control must be significantly faster than the dc voltage control.

PI controller:

INTRODUCTION

PI control is becoming more popular because of its ability to maintain exact set point. This chapter aims at establishing the design and implementation of the conventional PI controllers at various operating points of the buck and boost converter. Simulation is done by using MATLAB 7.1 and the controller is subjected to various disturbances of input voltage and load changes**.**

PI CONTROL MODE

Proportional-Integral controller mode results from the combination of the proportional and the integral mode. Certain advantages of both control actions can be obtained from this mode. This mode is also called as the proportional plus reset action controller. Equations for the proportional mode and integral mode are combined, to have an analytic expression for this mode, which is given below:

$$P = K_p e_p + K_p K_t \int e_p \, dt + p_{t(0)} \ldots\ldots \quad (3.1)$$

where

$p_{t(0)}$ = Integral term value at t = 0 (initial value)

The proportional gain, by design, also changes the net integration mode gain, but the integration gain, can be independently adjusted. It is understood that the proportional offset occurred, when a load change required a new nominal controller output, and this could not be provided except by a

fixed error from the set point. In the present mode, the integral function provides the required new controller output, thereby allowing the error to be zero after a load change. The integral feature effectively provides a 'reset' of the zero error output, after the load change occurs. At time t1 a load change occurs, that produces the error. The accommodation of the new load condition requires a new controller output. The controller output is provided through a sum of proportional plus integral action that finally leaves the error at zero. The proportional part is obviously just an image of the error.

CHARACTERISTICS OF THE PI MODE

When the error is zero, the controller output is fixed at the value that the integral term had, when the error reduced to zero. This output is given by pt(0) simply because we choose to define the time at which observation starts, as t = 0. If the error is not zero, the proportional term contributes a correction and the integral term begins to increase or decrease the accumulated value [initial pt(0)], depending on the sign of the error and its direct or reverse direction. The integral term cannot become negative; thus it will saturate at zero, if the error and the action try to drive the area to a net negative value.

The transfer function is given by

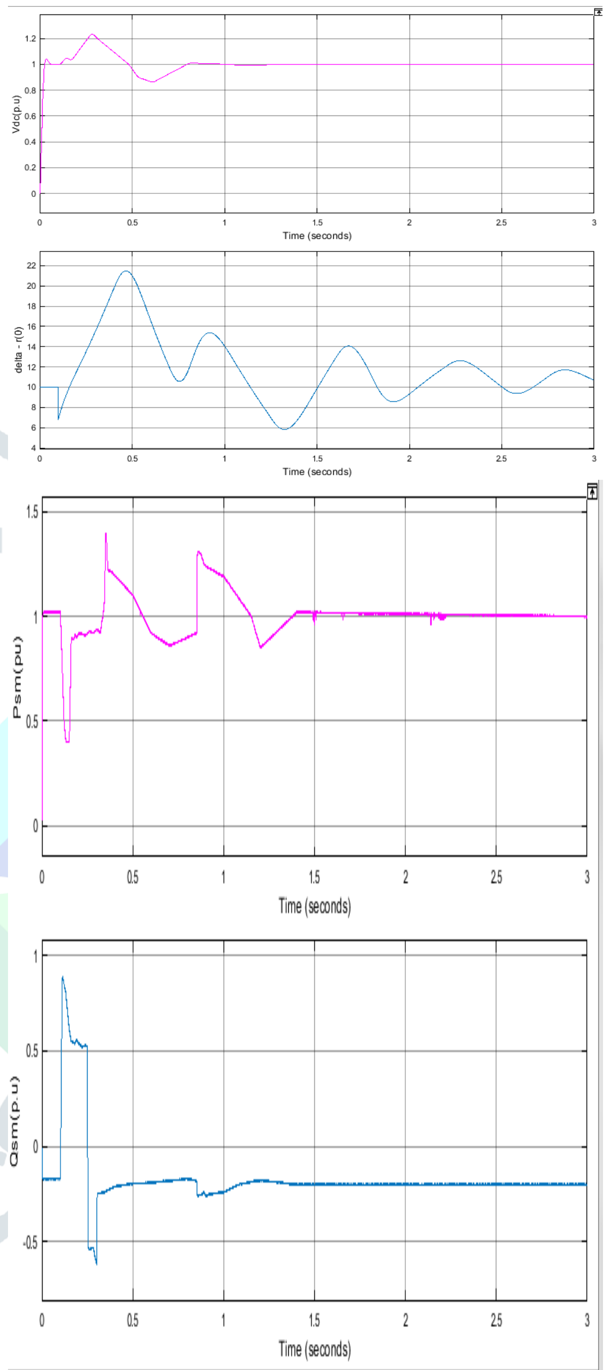
$$K_p + (K_I/s)$$

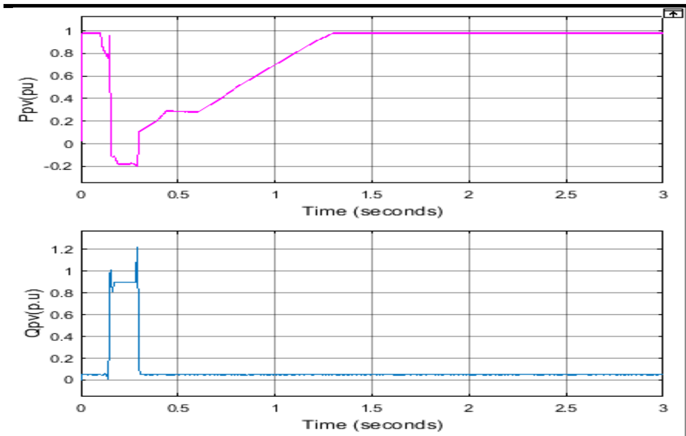
The integral action adjustment is the integral time T1 (=KI). For a step deviation 'e', the integral time or reset time is the time for proportional action. 'Reset rate' is defined as the number of times per minute that the proportional part of the response is duplicated. Reset Rate is therefore called 'repeats per minute', and is the inverse of integral type. During the design of the PI controller for the buck and boost converter, a closed loop operation is performed. The open loop operation is insensitive to load and line disturbances. So this operation is ineffective. Therefore the closed loop operation is selected. The closed loop control uses a feedback signal from the process, a desired value or set point (output voltage) and a control system that compares the two and derives an error signal. The error signal is then processed and used to control the converter to try to reduce the error. The error signal processing can be very complex because of delays in the system. The error signal is usually processed using a Proportional - Integral (PI) controller whose parameters can be adjusted to optimize the performance and stability of the system. Once a system is set up and is stable, very efficient and accurate control can be achieved. Input is the voltage error (reference voltage subtracted from the actual voltage) Output is the incremental duty ratio.

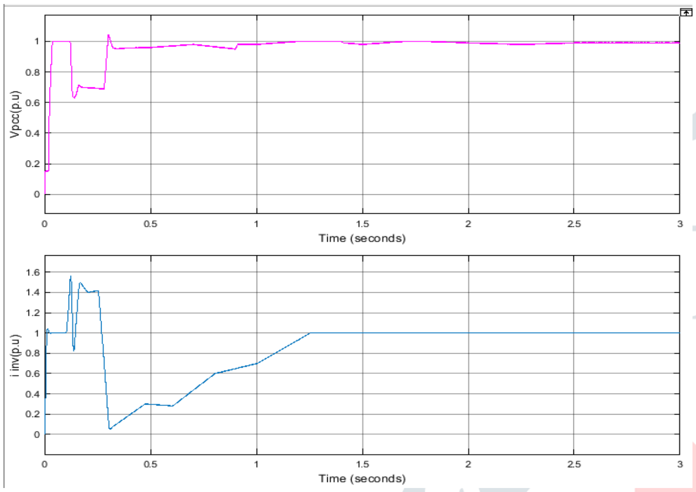
The controller specifications of a converter are

- Minimum steady state error.
- Less settling time.

SIMULATION RESULTS:







CONCLUSION

In this work, a control scheme for PV inverters is proposed toact during faults that could compromise the transient and voltagestability of a hybrid power system. The analysis demonstratedthat the proposed control scheme can act while thePV system is in MC operation, supporting the grid to recoverstability during and after a disturbance on the transmissiongrid. The proposed control scheme makes the SM kineticenergy to be absorbed into the dc link capacitors to ensuretransient stability. Besides that, it also enables the injectionof reactive power into the grid to support voltage stability.

Experimental and simulation results have shown thatthe proposed control scheme can reduce the rotor angleoscillations within the first few cycles of the fault, effectivelyensuring the SM's transient stability. It has also shownimprovements in the grid voltages during the fault period anda very fast post-fault voltage recovery in comparison withother FRT control schemes.

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