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An adaptive proportional resonant current controller for grid connected three phase voltage source inverter for unbalanced grid voltages

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Abstract—**A current control strategy for a grid connected three phase Voltage Source Inverter (VSI) under the sensitive load condition is proposed in this paper. In the proposed model, a PR controller is designed for a grid connected three phase Voltage Source Inverter (VSI) with an integrated LCL filter and compared to a conventionally designed PR controller for regulating the output current. Coordinates transformation, direct current control by introducing zero compensation method for better stability and a simplified damping method are used in the proposed technique in comparison to conventionally designed SVPWM technique. The comprehensive designing procedure is also mentioned for guaranteeing the stability of the system in worst case scenarios. A harmonic compensator is used for mitigating the unbalanced grid voltages. Simulation results validate the outstanding transient, steady-state and tracking performance of the proposed control scheme and presents a suitable comparison of the proposed PR controller with a conventional PR controller.**

Index Terms—**Three Phase VSI, grid connected inverter, PR current control, SVPWM, LCL filter, Harmonics compensation, Coordinates transformation, Unbalanced grid voltages**

I. Introduction

There are numerous reasons for continually growing consideration to renewable energy sources as well as distributed generation (DG) systems in power-driven industry, such as modification of energy sources, sustainable advancement and energy protection. The current developments, demonstrate the high potential of renewable energy sources as an alternative of the conventional electrical sources, especially in transfer of electricity to the far-flung areas or complex loads. Generally, the generated power is DC in these systems and it is connected to a load having a certain amplitude and frequency. Therefore, an inverter is used to regulate the generated energy, which acts as a controlled-voltage source in the stand-alone operation [1].

Normally, an inverter is coupled to the AC load through an LC smoothing filter in order to reduce the switching noises. In fact, this form of filters proposes enhanced performance and improved efficiency as compared to the simple L-type or LR-type filters for inverters. Up till now, various control techniques are presented for inverters in literature [2, 3].

Mostly it is employed to energy stowage devices and renewable energy sources i.e. wind turbines (WT), fuel cells and Photovoltaic cells (PV) for greenhouse gas emission and minimizing pollution. [1,4]. A three-phase voltage source inverter is utilized for interfacing the utility gird to the renewable energy sources for large scale installations. The control system associated to the inverter is the most essential technique used in energy conversion process to control harmonic distortion, current and active power supplied to the consumers [5]. Several current control strategies for grid connected inverter are proposed in order to attain enhanced performance power quality. However, on industrial scale, the proportional-integral (PI) controller is probably the finest, uncomplicated and frequently used controller. Though, whenever dealing with a three-phase system, the rotation dq synchronous reference frame approach is usually applied.

The rotating dq synchronous reference frame approach is based on the classical Park's transformation method [6]. Due to shortcomings of the PI controller, such as steady state errors, less capability to track reference signal and continuous need of tuning parameters [7], several substitute techniques for PI controller are employed by various researchers. Amongst these, the most popular strategy applied in the renewable energy applications is the PR control strategy. In [8], a technique for removing steady state errors is introduced for tracking AC signals at an acknowledged resonant frequency and a highly-reduced gain at harmonic frequencies. Additionally, in case of PR controller, Park's transformation is not compulsory, hence there exists a less cross coupling of control axis, therefore, no need to apply decoupling schemes [9]. The PR controller is employed remarkably in the stationary reference frame for a grid connected three-phase VSI in [10]. Consequently, substantial reduction in the harmonics of a current controller is possible. In [11], Harmonic compensation (HC) terms, in addition to main control exertion, are implemented for achieving extra eradication of the harmonic contents.

An abrupt droop in voltage leads to the deviation in the reference and controlled signal causing considerable error from its minimal value. The conventional PR controller cannot sustain with increased error, which leads to deteriorate its performance. In order to solve this problem, this paper proposes a novel PR current control strategy. The performance of the PR controller is verified and compared in case of normal and abnormal grid voltage conditions. Even during abnormal grid voltage conditions, the proposed technique offers low total harmonic distortion (THD). Moreover, low overshoot and settling time as well as capability to remove the steady state error are also achieved in the proposed technique. Additionally, this paper also offers a simplified technique to decompose the current and voltage into their positive and negative sequence components.

The performance of the proposed controller is substantiated by the simulation results. A grid connected three-phase VSI is modeled and controlled by using PR control strategy with a passive damping technique and a harmonic compensator is introduced for restraining the grid current's distortion. A phase locked loop (PLL) is implemented for detection of the transformation angle and improving the synchronization of achieved grid voltages with inverter output current. Two PR controllers are employed in current controller. The proposed control scheme doesn't show any coupling between active and reactive components. Moreover, simulation results show the excellent static and dynamic response. The recommendations of IEEE standards 519 and 1547 for international harmonic and power quality are correspondingly considered and specifically 5% current THD limitation is also executed [12].

II. SYSTEM MODELING

In Fig. 1, the topology of a grid connected three phase VSI is shown through an LCL filter having Six IGBT switches. The LCL filter is designed according to [13]. However, the system parameters are mentioned in Table 1. However, the parasitic resistances are neglected in this case.

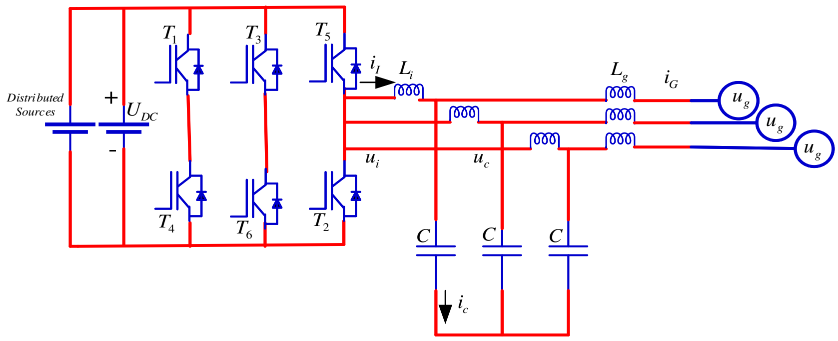

Fig. 1. Grid connected three phase VSI with LCL filter

The switching frequency is taken considerably high. The PWM technique implemented is SVPWM and it is also assumed that the dc capacitance is large enough that it can act as a dc source. Considering all these assumptions the model of the inverter is represented by the following equations

$$L_i \frac{di_{it}}{dt} = u_{it} - u_{ct} \tag{1}$$

$$L_g \frac{di_{gt}}{dt} = u_{ct} - u_{gt} \tag{2}$$

$$C \frac{du_{ct}}{dt} = i_{it} - i_{gt} \tag{3}$$

Where u_{gr} is the grid side voltage, u_{ct} is the voltage across capacitors, u_{it} is inverter side voltage, i_{it} and i_{gt} represents the inverter side current and grid side current respectively. However, L_i and L_g are the inverter side inductor and grid side inductor respectively. In the above equations t represents the coordinates, in case of static uvw coordinates, $t = a, b, c$, whereas, in $\alpha\beta$ coordinates, $t = \alpha, \beta$. After coordinates conversion from uvw to $\alpha\beta$ the system is converted into single phase system, as shown in Fig. 2. As the controller of a three-phase VSI system is always designed in two coordinates system. Therefore, if $\alpha\beta$ coordinates are converted into dq coordinates, the equations will become:

$$u_d = u_{di} - \omega L_i i_q - L_i \omega C u_{cq} s - L_i \omega C L_g i_{gq} s^2 \tag{4}$$

$$u_q = u_{qi} + \omega L_i i_d + L_i \omega C u_{cd} s + L_i \omega C L_g i_{gd} s^2 \tag{5}$$

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As, Eq. (4) and (5) shows that there is strong decoupling in the dq coordinates, therefore, it can be noted that there are differential terms and three coupled terms are also included, so it's not appropriate for decoupling. In case, the coupling is ignored, then PI controller in synchronous rotating frame is considered to be equivalent to PR controller in static coordinates [14]. To avoid the inconvenient decoupling, the control strategy applied in this paper is discussed in $\alpha\beta$ coordinates.

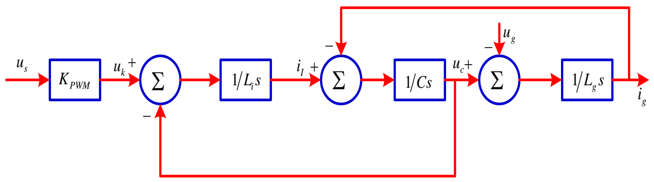

Fig. 2. Block diagram of three phase VSI in $\alpha\beta$ coordinates.

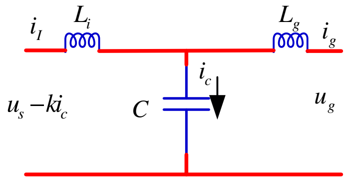

Fig. 3. LCL circuit in $\alpha\beta$ frame under output of controller and grid voltage.

In the Fig. 2, u_g represents the output from the controller. However, Fig. 3 represents the equivalent circuit of an LCL filter, where output of the controller is fed into the LCL filter, where k is the proportional element for PWM considered as unity.

III. Controller Implementation

A. Control Model implementation

In the figure 4, the three phase VSI is connected to the grid through a LCL filter. However, the reference current signal is provided in dq rotating coordinates, then these dq coordinates are transformed into the $\alpha\beta$ coordinates for simplifying the decoupling problem that exists in the dq coordinates. Then modulation reference is generated and the SVPWM technique is implemented. However, in the proposed method, direct power control strategy by implementing the zero-compensation method is executed and then adaption of PR controller is planted. The PLL is used for synchronizing the phase of controlled current with grid current. In Fig. 5, the grid connected LCL filter is controlled by introducing a damping resistance, R_d . A phase locked loop is introduced to maintain the synchronization between grid current and controlled inverter output current. Drive signal generator performs the function of generating drive signals to control duty cycles.

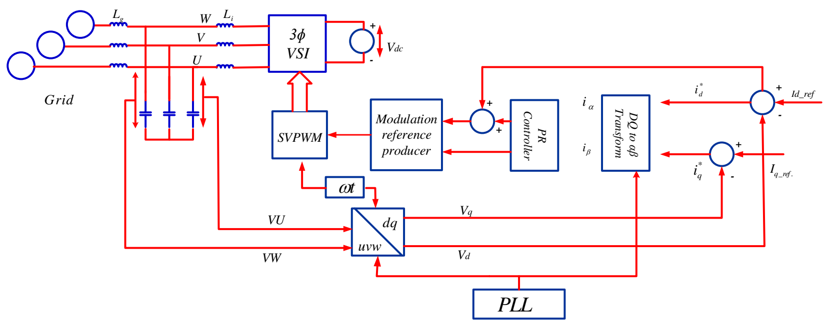

Fig. 4. Conventional PR control technique applied over three phase VSI.

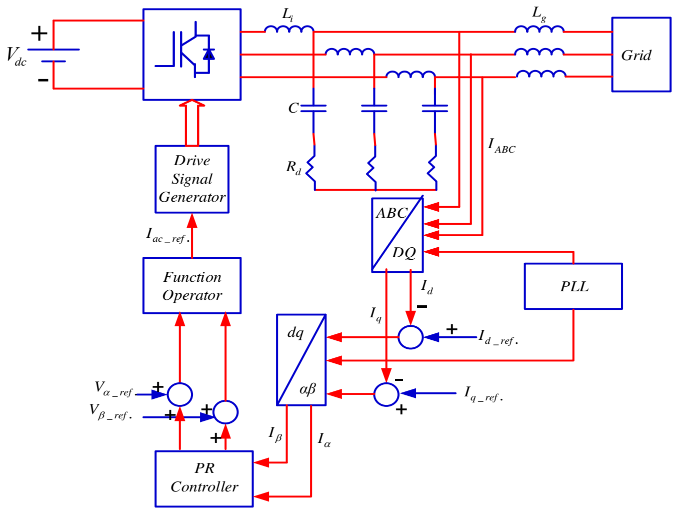

Fig. 5. Proposed PR control technique applied over three phase VSI.

The major problem in PI controller is the errorless tracking of reference signals under static coordinates. Therefore, this PI controller is changed for VSI with a PR controller. Moreover, the proposed PR controller has larger high frequency band and on fundamental frequency it has larger magnitude, therefore, tracking the reference signal becomes convenient. In order to verify the above-mentioned analysis, simulation results are verified and the tracking ability is observed critically. Moreover, the grid current is accurate in tracking the reference current when used with a PR controller. Moreover, mutation and dynamic response of the two controllers is almost similar with the better performance of the proposed PR controller in tracking the reference AC signal.

B. Discretized PR Controller

In order to implement the algorithm digitally, the proposed controller is required to transform to z-domain from s-domain. The classical PR controller with a couple of integral components as shown in Fig. 6 is relatively convenient for transformation. The backward difference method is applied for transformation of the feedback integer and forward difference method is applied for discretization of feed-forward integer in order to simplify the system without complexity of algebraic loop as described in Eq. 6 and 7. After discretization, PR controller structure is obtained in Fig. 7. It is described by the Eq. 8:

$$F_{bd} = s = \frac{1-z^{-1}}{T_s} \tag{6}$$

$$F_{fd} = s = \frac{z-1}{T_s} \tag{7}$$

$$G_{PR}(z) = K_r \frac{T_{sp}z^{-1} - T_{sp}z^{-2}}{1+T_{sp}^2\omega^2 z^{-1} - 2z^{-1} + z^{-2}} + K_P \tag{8}$$

Where, K_r is the resonant coefficient, T_{sp} is the sampling period, ω is the grid angular frequency and K_P is the proportional coefficient. For the harmonic compensation, the discretization technique is same as in the resonant component of the PR controller. The

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phase-locked loop (PLL), and zero compensation control strategy are realized by backward difference method and the structure of PLL is shown in Fig. 7. The optimum response of PR controller is achieved through SISO tool in Matlab, where integral gain, K_i at grid frequency, f_g should be kept large enough to accommodate the steady state error and K_p should be tuned to get sufficient bandwidth for accepting harmonic compensator so that system may not get unstable. For this purpose, the value of K_p becomes equal to 8.21 and the value of K_i gets equal to 1486.24 at f_g equals to 50 Hz. and verified through root locus and bode plot response of the controller.

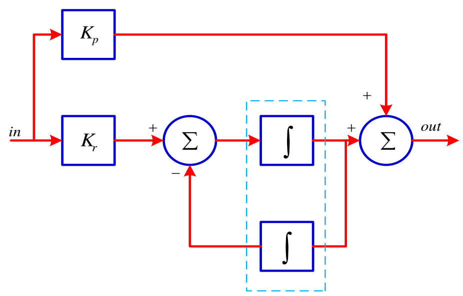

Fig. 6. Structure of a conventional PR controller.

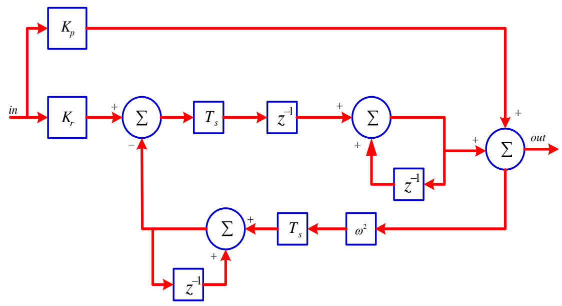

Fig. 7. Structure of a discrete PR controller.

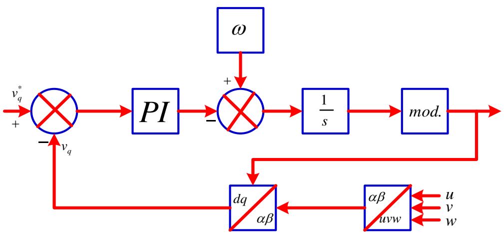

Fig. 8. Three Phase PLL structure.

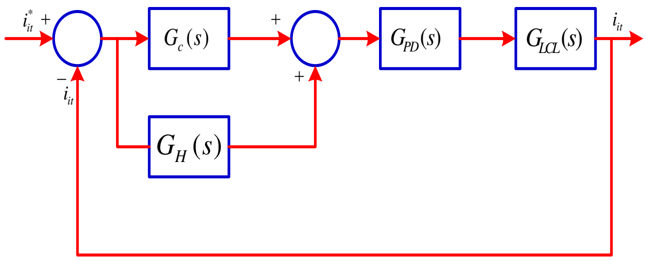

Fig. 9. The PR current controller with damping resistor and harmonic compensator

C. Accumulation of passive damping resistor with LCL filter

The system model of an LCL filter with a three phase VSI is described in Section-I. However, the transfer function of LCL filter in the case when R_d is neglected becomes:

$$G_{LCL}(s) = \frac{L_g C s^2 + 1}{L_i L_g C s^3 + (L_i + L_g) s} \tag{9}$$

The amalgamation of R_d in series with the capacitor C increases the stability of the system and lessen the resonance. In spite of advance methods of active damping and various other damping methods, the passive damping is chosen due to its uncomplicated calculation and user-friendly interface while implementing in Matlab Simulink. The transfer function of the LCL filter with integrated R_d is as follows:

$$G_{LCL}^{D}(s) = \frac{L_g s^2 + R_d C s + 1}{L_g C s^2 + \left(R_d + \left(\frac{L_g}{L_i} \right) R_d + \left(\frac{1}{L_i} \right) \right) s + \left(\frac{L_g}{L_i} + 1 \right)} \tag{10}$$

D. Harmonic compensation in PR Controller

A harmonic compensator is designed and unified with PR controller in order to control the harmonics and to smoothen the output of the controller. In fig. 9, a harmonic compensator is installed with the PR controller to stabilize the system and to overcome distortion in the output. The harmonic compensator is given by the equation

$$G_{HC}(s) = \sum_{h=3,5,7,...} R_h \frac{s}{s^2 + \left(\omega_R^h\right)^2} \tag{11}$$

Where, R_h is the resonance occurred at specific harmonic and ω_R^h describes the resonant frequency for a certain harmonic. The system described in Eq. 11 has infinite gain, so, it is limited for ideal case, when a fundamental PR controller is used and the harmonics have no bandwidth around it. It can lead to instability in the system. Therefore, considering a specific bandwidth around each harmonic, the transfer function of harmonic compensator becomes

$$G_{HC}(s) = \sum_{h=3,5,7,...} R_h \frac{\omega_b s}{s^2 + \omega_b + \left(\omega_R^h\right)^2} \tag{12}$$

Where, ω_b represents the twofold bandwidth round the harmonic frequency ω_R^h . This results in the finite gain for provide compensation easily. Siso tool in Matlab is used for finding out the harmonics compensation.

E. Zero compensation in PR Controller

It is noticed that due to high frequency gain damping rate and due to phase curve above than -180^o , system shows good stability. If the system is used with the transfer function mentioned in (8), stability of the system can be improved.

$$G(\text{s}) = K_p + \frac{K_r s}{\omega^2 + s^2} \tag{13}$$

$$G(s) = P \frac{(\mu \text{s} + 1)}{(T_s + 1)s^2} \tag{14}$$

Where, P is the proportional element, same as used with passive resistance. It is also found that Z_1 is zero compensation component, Z_2 is PI controller and Z represents the final grid current controller. The simulation is done in Matlab/Simulink environment and output results depict that there is lot of improvement in the outer current after implementation of zero compensation component. However, it can be noticed that at initial stage, when the system starts, the oscillations are more serious than with zero compensation, and hence it is verifying the correctness of aforesaid technique. Moreover, stability margin is also improved.

$$Z_1 = 1 + \frac{s}{\omega_{ref.}} \tag{15}$$

$$Z_2 = K_p + \frac{K_i}{s} \quad (16)$$

$$Z = Z_1 Z_2 \quad (17)$$

IV. Results

The simulation results of both the controllers are shown in Fig. 14. It is seen from the results that only when PR controller is used, there is obvious distortion in the grid current waveform and THD is observed as 8.35%. The harmonic component of the grid current is caused by the harmonic component of the grid disturbance voltage. When PR+HC controller is used, the grid current waveform is quite sinusoidal and THD is only 1.35%. It's illustrated that because of the new harmonic peaks, the harmonic impedance at typical grid voltage harmonic frequency is large enough to restrain the disturbance of the distorted grid voltage. The parameters of the system are mentioned in Table 1. The simulation results in Fig. 10 shows the response of a conventional PR controller. There are several harmonics and delay initially. However, the wave becomes smooth and the inverter current is controlled appropriately. The Fig. 10 shows the voltage, current, Voltage across phase A and current along Phase A respectively. The referred and the observed current is not exactly tracked initially by the conventional PR controller. The current remains to almost 19 A, as shown in the figure 10. Whereas the proposed technique of PR current controller with a harmonic compensator and zero compensation method implementation shows that the inverter is taking soft start with the proposed technique as compared to the conventional technique. Moreover, if current across phase A is observed critically, the tracking ability of the proposed PR controller with harmonic compensator is reliable and it can be used for industrial purpose. Moreover, the dynamic response of the controller is also checked, however, the results are not mentioned here. The proposed controller is verified through bode plot and root locus plots, which show that the proposed controller is having much rapid response, tracking ability, stability and stable error removing capability as compared to the conventional PR current controller. The zero-compensation method is used for stability and the improvement in margin and phase of the controller before and after the implementation of PR controller was remarkable.

TABLE 1. SYSTEM PARAMETERS

Parameter	Symbol	Value
Grid voltage	V_g	110 V
Switching frequency	f_{sw}	10 kHz.
Inverter side inductor	L_i	2.7 mH
Grid Side inductor	L_g	1 mH
DC link voltage	V_{dc}	360 V
Dc link capacitor	C	15 μF
Grid frequency	f_g	50 Hz.
Damping Resistor	R_d	12 Ω

The response of the grid side current in the proposed technique can be clearly observed through the comparison of the conventional PR current control technique with a harmonic compensator integrated proposed PR current control technique. The tracking of direct axis shows that the value becomes equal to 19 A. However, the value of current along quadrature axis was referred equal to zero, for reducing the effect of reactive power. The tracking ability of the proposed controller can be observed through outstanding output results. The proposed controller smoothens the current wave form through harmonic compensator. The harmonic compensator especially compensates the grid current harmonics at low operating power. The power factor of the grid current remained 0.989 which depicts that the quality of the grid current is good enough. The fundamental problem was to adjust the system when unbalanced grid voltage is fed into the system. However, the proposed controller shows a stable response against the unbalanced voltage.

V. Conclusion

The paper presents a technique for implementing PR controller with additional capability to control the current directly and to compensate the harmonics through harmonic compensator for a smooth and stable output response. The passive damping technique is implemented by introducing a damping resistance. In order to avoid the decoupling, the control system is considered in the $\alpha\beta$ stationary frame coordinates. The control technique is implemented and system is verified for providing qualitied grid current output, even if the voltage is unbalanced or distorted.

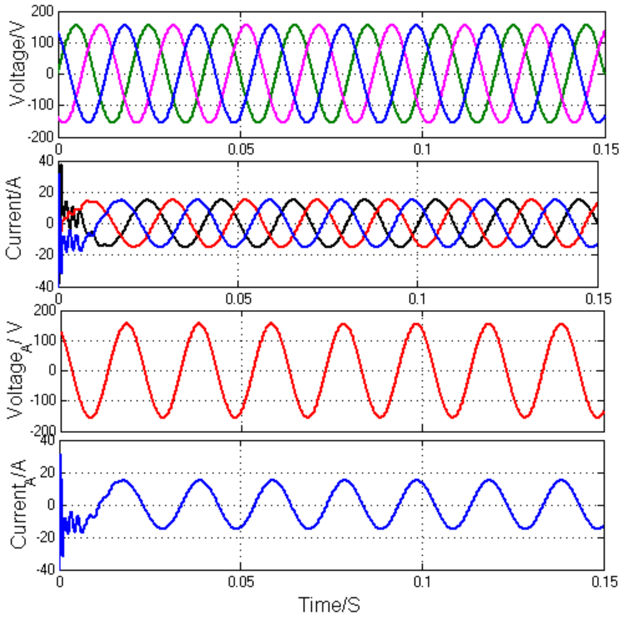

Fig. 10. The conventional PR current controller for inverter current control.

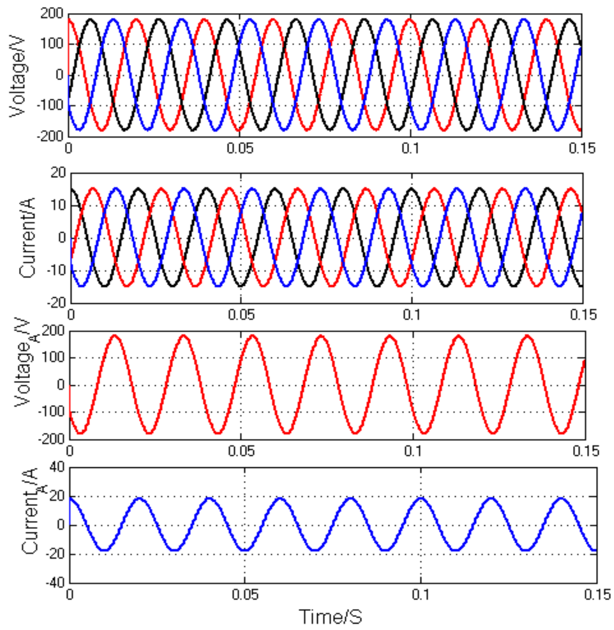

Fig. 11. The proposed PR current controller response for inverter current control.

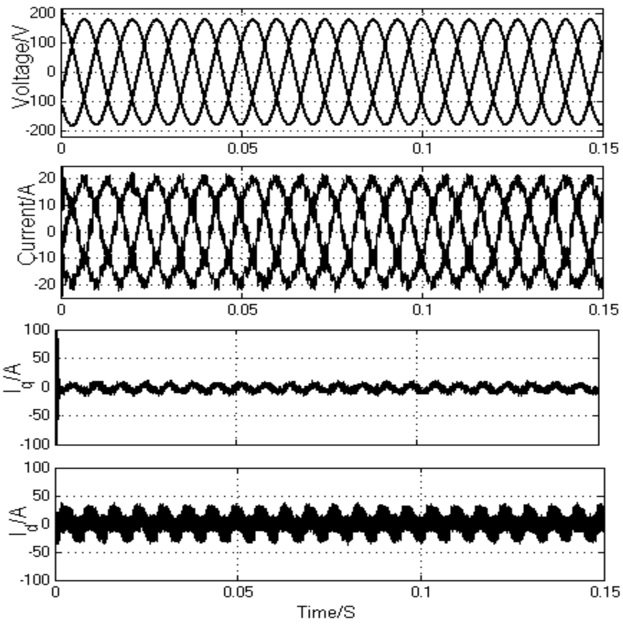

Fig. 12. The conventional PR current controller response for grid current control.

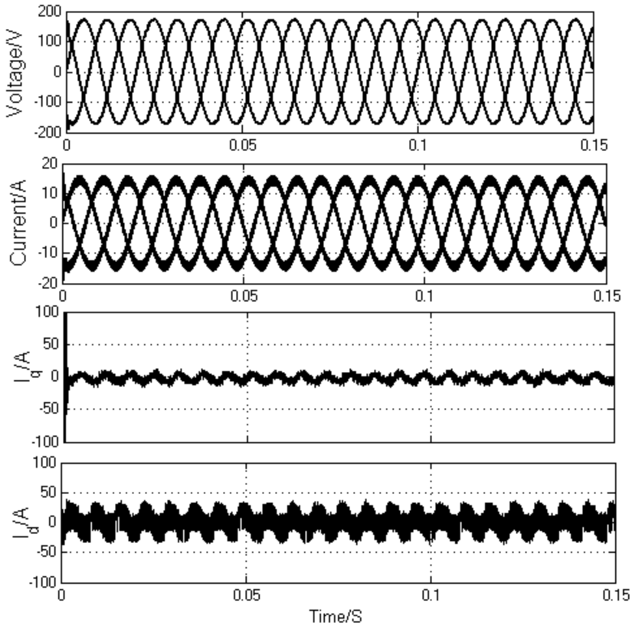

Fig. 13. The proposed PR current controller response for grid current control.

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