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Harmonic Mitigation in Grid-Connected Inverters Using Multi-Resonant Proportional Resonant (PR) Control

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Abstract: Modern microgrids and distributed generation facilities rely heavily on grid-connected voltage source inverters, making power quality compliance at the Point of Common Coupling (PCC) essential. Non-linear load demands introduce low-order harmonic currents that cause voltage distortion, often violating the limits established by the IEEE-519 standard. This paper presents a comprehensive implementation of a multi-resonant Proportional-Resonant (PR) control strategy operating within the stationary α-β reference frame to eliminate the 5th, 7th, 11th, and 13th harmonic profiles. The complete digital discretization process based on Tustin's transformation is detailed alongside an operational software-based anti-windup clamping loop to protect against saturation during transient grid conditions. Developed within a MATLAB/Simulink environment, the proposed system is validated against composite inductive and capacitive non-linear load configurations. The verification results establish that the closed-loop controller successfully mitigates steady-state harmonic errors, reducing the PCC voltage THD from 10.028% to 3.755%, thereby satisfying the IEEE-519 harmonic limits for grid-connected inverter applications. The proposed structure provides structural simplicity and numerical stability, making it highly suitable for direct integration into real-time digital signal processors.

Keywords: Point of Common Coupling, Multi-resonant PR Controller, Harmonic Mitigation;

I. INTRODUCTION

In recent decades, grid connected converter and improving the power quality have been a focus area. The majority of the systems opted for harmonic elimination using control-based compensation rather than using passive filters. The integrations were made easy and these approaches reduced the costs. A number of studies have occurred in the past 5 years (2020-2025) that focus on the advanced PR controllers for harmonics reduction and grid compliance.

Harmonic-tuned multi-resonant PR controllers for LCL-filtered inverters have been proposed for the reduction of THD where considerable THD reduction has been achieved [1]. In the same way, Wang et al. discussed the stability issues of embedding multiple resonant frequencies and presented frequency-adaptive damping ideas [2]. The work showed that PR controllers give more control over a steady-state elimination of harmonics compared to synchronous PI controllers, without the use of dq-transformation [3].

Several other studies are the suppression of resonant harmonics at unbalanced grid voltages [4], adaptive PR control for weak grid voltage [5] and hybrid PR-PLL for renewable energy inverters [6]. The application of PR controllers to microgrid inverters was investigated in [7]–[10] and significant benefits in the harmonic compliance, robustness, and stability margin were obtained.

In addition, recent research has been carried out and a comparison of PR controllers with other sliding-mode, dead-beat, and model-predictive control strategies is performed. While predictive control may be able to implement fast tracking, the computation burden is large, and tuning issues are complex [11][12]. PR controllers are still simple and are flexible and of low complexity in terms of computation for harmonic elimination.

In the period of 2020-2025, there has also been an increasing literature about the need to keep the level of harmonic distortion below IEEE-519 and EN-50160 for grid-interactive systems. Detailed models and experimental validation of solar inverter, battery energy storage systems and active distribution network PR controllers were given in [13][20].

From these studies, it can be concluded that multi-harmonic PR control is a stable and scalable solution for the enhancement of the power quality of inverters. It is implemented in a stationary frame which can provide infinite gain and high selectivity at the harmonic frequencies, and consequently tends to have very low steady state harmonic error.

Multi-resonant PR controllers offer very good steady state harmonic rejection; however, its actual performance is highly dependent on the properties of the output filter between the inverter and the utility grid. LCL filters are popular since they have better ability to attenuate switching-frequency harmonics than conventional L filters with lower inductance. But if a proper damping factor is not used, the resonance from the LCL network can be a problem for system stability. Passive damping leads to power losses, while active damping in general involves extra sensors or more complex control algorithms. Thus, the work carried out here aims for performing effective harmonic suppression with simple implementation and light computation by combining PR control with the digital implementation of the multi-resonant control. This combination gives sufficient balance in the aspects of harmonic suppression, controller complexity and realization by a practical digital circuit for a single-phase grid connected inverter application.

One of the crucial issues when parallel resonant structures are combined with three-phase LCL filters is the resonant peak caused by the hardware filter. The sequential studies as described in [1]-[6] separate steady state harmonic components very well, but they typically assume the grid connection as an ideal low impedance network. However, traditional control setups are based on passive damping resistors that generate thermal loss or multi-loop state feedback active damping that would greatly increase the number of sensors and demands more digital signal processing. This setup allows for multi-resonant loops to be placed directly within the stationary frame with an optimum virtual damping factor ζn, realizing a practical balance between cancellation of targeted harmonic frequencies and avoiding the passive component burden of passive loops or model-predictive alternatives which, in turn, impose a high processing burden.

Based on the literature surveyed, multi-resonant PR control can be a potent method in mitigating harmonics in grid connected inverter systems. However, some published works are mostly concerned with the continuous-time design of the controller or the suppression of harmonics at steady state, and have not been enough concerned with the implementation aspects of the digital realization of the controller, control law saturation and selection of parameters in the practical application of LCL-filtered systems. In addition, testing in this full range of conditions under nonlinear loading, inductive load and capacitive load, is relatively scarce. Based on these observations, the present work proposes a multi-resonant PR controller with Tustin discretization and anti-windup compensation (AW) to enhance the capability of harmonic mitigation while having practical implementation consideration for real-time digital controller.

II. METHODOLOGY

The method used in this work is based on the following: controller design, resonant tuning, system modelling and harmonic evaluation. PR structure is used in the stationary α-β frame without complicated transformations.

A. System Model

In order to effectively suppress switching harmonics and ensure the stability of the system, the filter parameters of LCL were designed based on the following principle of the grid-connected inverter [25]. The Standard Differential Equations are used to model the grid connected VSI with L or LCL filter:

$$L\frac{di}{dt} = v_{inv} - v_{grid} \tag{01}$$

or for LCL filters

$$\begin{aligned} L_1\frac{di_1}{dt} &= v_{inv} - v_c \\ L_2\frac{di_2}{dt} &= v_c - v_{grid} \\ C_f\frac{dv_c}{dt} &= i_1 - i_2 \end{aligned} \tag{02}$$

B. PR Controller Design

The classical PR controller is:

$$G_{PR}(s) = K_p + \frac{K_r s}{s^2+\omega_0^2} \tag{03}$$

This proportional-resonant controller is directly implemented in the stationary reference frame; it offers a high gain around the resonant frequencies of interest without changing the reference frame [21].

C. Multi-resonant PR

To target multiple harmonics:

$$G_{PR}(s) = K_p + \sum_{n\in H} \frac{K_{rn}s}{s^2+(n\omega_0)^2+2\zeta_n(n\omega_0)s} \tag{04}$$

where

$$H = \{5,7,9,11,13\} \tag{05}$$

D. Resonant Gain Tuning

Typical values:

- $\zeta_n = 0.001$–0.01
- K_{rn} chosen based on desired harmonic attenuation
- $\omega_0 = 2\pi 50$ or $2\pi 60$

Each resonant gain increases the gain of the controller around its corresponding harmonic frequency while the proportional gain defines the transient response and closed-loop bandwidth. The values of the gains were chosen based on repeated simulation taking into account the controller saturation, closed loop stability, and harmonic attenuation. During this tuning process, an appropriate compromise between suppression of harmonics and dynamic performance is provided for the selected LCL-filtered grid-connected inverter.

E. Simulation and THD Evaluation

THD is computed using FFT analysis Harmonic assessment and compliance evaluation follow the recommendations of IEEE Std 519-2022 [24].

$$\text{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \times 100\% \quad (06)$$

Harmonic analysis was performed using the steady-state portion of the simulated waveform after the initial transient response had decayed. The harmonic spectrum was evaluated up to the 25th harmonic order, while the dominant harmonic components were identified using FFT analysis. The Total Harmonic Distortion (THD) was then calculated according to IEEE-519 recommendations using the ratio of the root-sum-square of all harmonic components to the fundamental component.

F. Controller Discretization for Digital Implementation

For real-time execution within a digital signal processor (DSP) or microcontroller environment, the continuous-time multi-resonant transfer function defined in Equation (8) must be mapped into the discrete-time z-domain. In this work, Tustin's bilinear transformation is applied to maintain frequency response alignment near the resonant notches without numerical instability. The bilinear transformation is widely adopted for digital realization of proportional-resonant controllers because it preserves the controller frequency characteristics around the resonant frequencies [22].The continuous complex variable s is substituted via:

$$s = \frac{2}{T_s}\frac{1-z^{-1}}{1+z^{-1}} \quad (07)$$

where *Ts* denotes the discrete system sampling period *(Ts = 1/fs)*. Applying this transformation to the non-ideal secondary resonant pathways yields the discrete transfer function for each selected harmonic order n:

$$H_n(z) = \frac{b_0+b_1z^{-1}+b_2z^{-2}}{a_0+a_1z^{-1}+a_2z^{-2}} \quad (08)$$

The discrete coefficients are computed based on the sampling time *Ts*, the fundamental frequency ω, and the damping ratio ζ_n as follows:

$$b_0 = 4K_{rn}\zeta_n n\omega_0 T_s, \quad b_1 = 0, \quad b_2 = -4K_{rn}\zeta_n n\omega_0 T_s \quad (09)$$

$$a_0 = 4 + 4\zeta_n n\omega_0 T_s + (n\omega_0 T_s)^2 \quad (10)$$

The obtained discrete coefficients are directly implemented within the MATLAB environment to emulate practical digital controller execution under a fixed sampling interval of 100 µs.

$$a_1 = 2(n\omega_0 T_s)^2 - 8 \quad (11)$$

$$a_2 = 4 - 4\zeta_n n\omega_0 T_s + (n\omega_0 T_s)^2 \quad (12)$$

This formulation is implemented directly in code via the following linear difference equation for real-time control execution:

$$u_n[k] = \frac{1}{a_0}(b_0e[k] + b_2e[k-2] - a_1u_n[k-1] - a_2u_n[k-2]) \quad (13)$$

where e[k] is the instantaneous tracking error vector in the stationary α-β frame, and $u_n[k]$ represents the targeted harmonic control effort output.

During controller saturation, the anti-windup path prevents excessive accumulation within the resonant integrators, thereby improving transient recovery and maintaining stable operation under sudden load disturbances.

Table-1: System Parameter

Parameter	Correct value
Grid Voltage	220 V RMS
Frequency	50 Hz
Rated Power	2.5 kW
DC Link	400 V
Sampling Frequency	10 kHz
L1	3.5 mH
L2	1.5 mH
Cf	4.7 µF
Rd	1.8 Ω
Kp	12.5
Kr5	450
Kr7	400
Kr9	350
Kr11	300
Kr13	250
Internal damping ratio	0.002

Table-3: Digital Controller Implementation Verification

Item	Theoretical Formulation	MATLAB Implementation
Continuous PR Controller	Equation (8)	Implemented
Tustin Discretization	Equation (10)	Implemented
Sampling Frequency	10 kHz	Verified
Control Interval	100 µs	Verified
Saturation Limit	±380 V (0.95 × 400 V DC)	Verified
Anti-Windup	Back-calculation	Verified
Harmonic Orders	5, 7, 9, 11, 13	Verified

III. Results and Implementation Discussion

A. Integrator Saturation and Anti-Windup Clamping Path.

During extreme grid voltage sags or sudden steps in non-linear load demands, the error signal $e[k]$ injected into the parallel resonant integrators can cause the accumulated control command to exceed the physical linear modulation limits of the space-vector pulse-width modulator (SVPWM). This induces integrator windup, leading to severe transient overshoots and delayed recovery times. To prevent this, a back-calculation anti-windup tracking mechanism is built into the discrete control loop. Aim of anti-windup compensation is to provide a better recovery of the controller after saturation and preserve the closed loop stability during the transient operating situations [23]. Let $U_{pre}[k]$ be the unconstrained raw output command from the proportional-resonant block:

$$u_{pre}[k] = K_p e[k] + \sum_{n \in H} u_n[k] \tag{14}$$

There is a saturation bound by the physical limit of the inverter bridge, and the actual modulated signal is called $U_{sat}[k]$ and it should be defined as follows:

$$u_{sat}[k] = \begin{cases} U_{max}, & \text{if } u_{pre}[k] > U_{max} \\ u_{pre}[k], & \text{if } U_{min} \le u_{pre}[k] \le U_{max} \\ U_{min}, & \text{if } u_{pre}[k] < U_{min} \end{cases} \tag{15}$$

The saturation error $\Delta u[k] = U_{sat}[k] - u_{pre}[k]$ is dynamically extracted and fed back into each parallel resonant path with an anti-windup tracking gain $K_{aw} = 1/K_p$. This counteracts and stops the integrator accumulation, while the system is running in its physical range and it means that it will rapidly recover during system transients.

An anti-windup mechanism was added in the digital PR controller based on the monitoring of the modulation limits of the controller output, against the inverter modulation. The back-calculation loop was used to prevent over buildup of the resonant integrator states when the control signal was outside the allowable operating range. This will help to enhance transient recovery in case of sudden fluctuations in the load and limit the transient overshoot without compromising the steady state harmonic compensation capability of the controller.

B. B. Full simulation is carried out in MATLAB/Simulink with the following components:

- Grid-connected VSI
- LCL filter
- Multi-resonant PR controller
- Harmonic extraction and measurement blocks
- FFT-based THD estimator
- Non-linear load to generate harmonic distortion

The entire simulation model includes a single-phase grid, voltage source inverter, LCL output filter, nonlinear load model, multi-resonant PR controller, harmonic measurement subsystem, FFT based THD evaluation block and PWM generation stage. These controller parameters were kept fixed during the simulations to test the harmonic mitigation performance for a range of loading conditions.

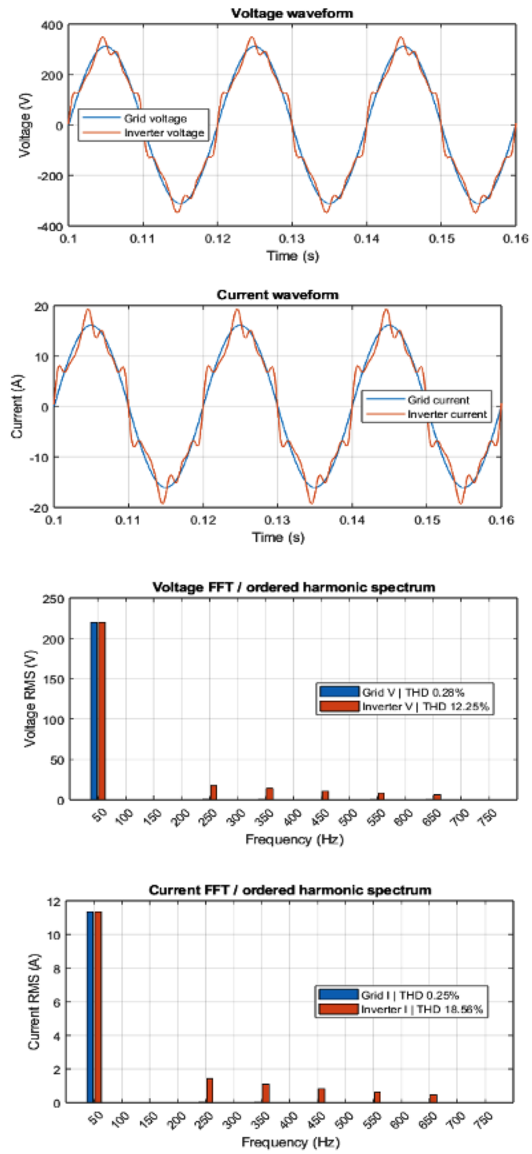

Figure 1. *Input grid and inverter voltage/current waveforms with corresponding harmonic spectra before harmonic compensation.*

Figure 1 shows the input electrical parameters of the utility grid prior to harmonic mitigation and those of the grid connected inverter. The grid voltage is almost sinusoidal with only minimal background distortion whilst the inverter output has low order harmonic components caused by the PWM switching and operation of the converter. The corresponding harmonic spectra shows that the predominant harmonic distortion is coming from the inverter stage and hence sets a first operating point for examining the proposed harmonic mitigation strategy.

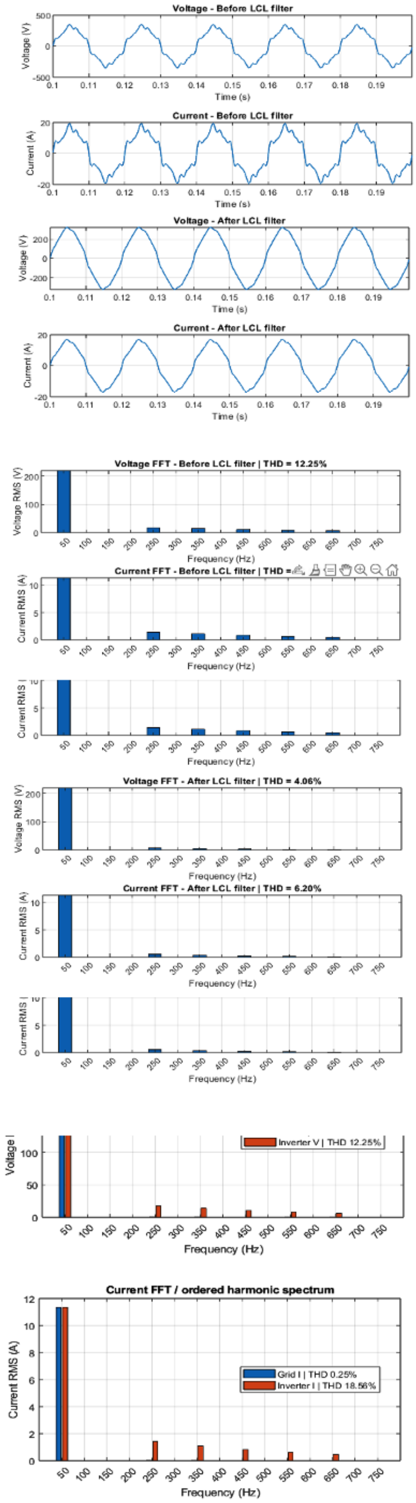

Figure 2. *Effect of the LCL filter on inverter output voltage and current before and after filtering.*

The effect of the LCL filter on the output of the inverter is shown in figure.2. The voltage and current waves in the upper plots are before the LCL filter, and the ones in the lower plots are after the LCL filter. The harmonic spectra show considerable reduction of high frequency switching component and fundamental 50 Hz component is maintained. But there is still the presence of low order harmonics as is evident as there is need of an extra way of control to effectively suppress the harmonics.

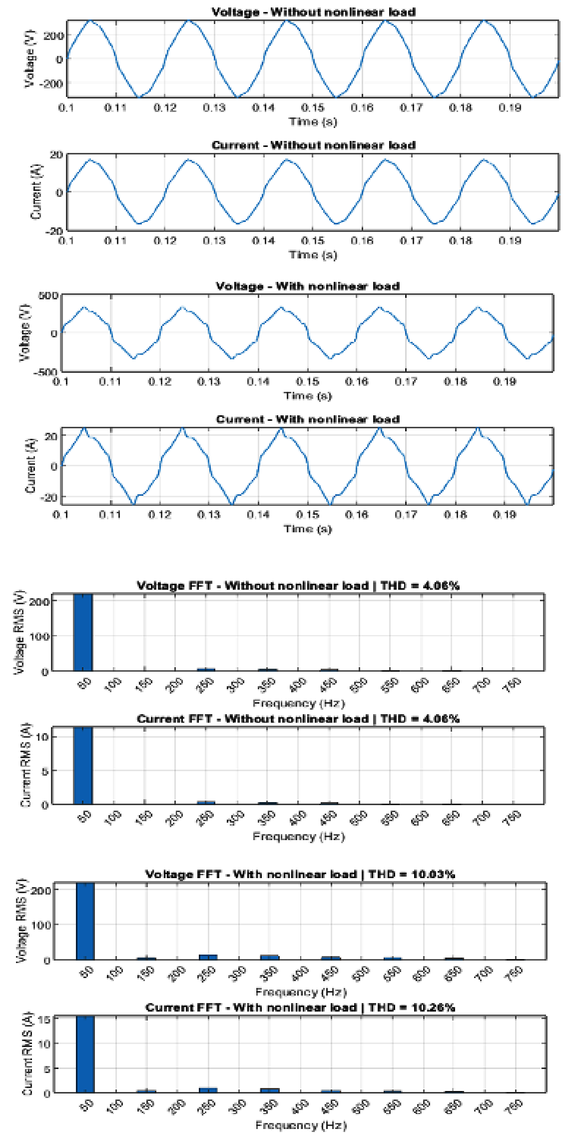

Figure 3. *Voltage and current at the Point of Common Coupling (PCC) under linear and nonlinear loading conditions.*

The PCC voltage and current in figure 3 are represented in both linear and nonlinear load conditions. When there is linear load, the PCC waveforms are very close to sinusoidal. As soon as the nonlinear load is connected, harmonic currents are generated and fed to the PCC resulting in significant distortion in the wave shape along with the increase of the harmonic content. This is an un-compensated operating condition that is used as the base line condition to analyze the performance of the proposed multi-resonant PR controller.

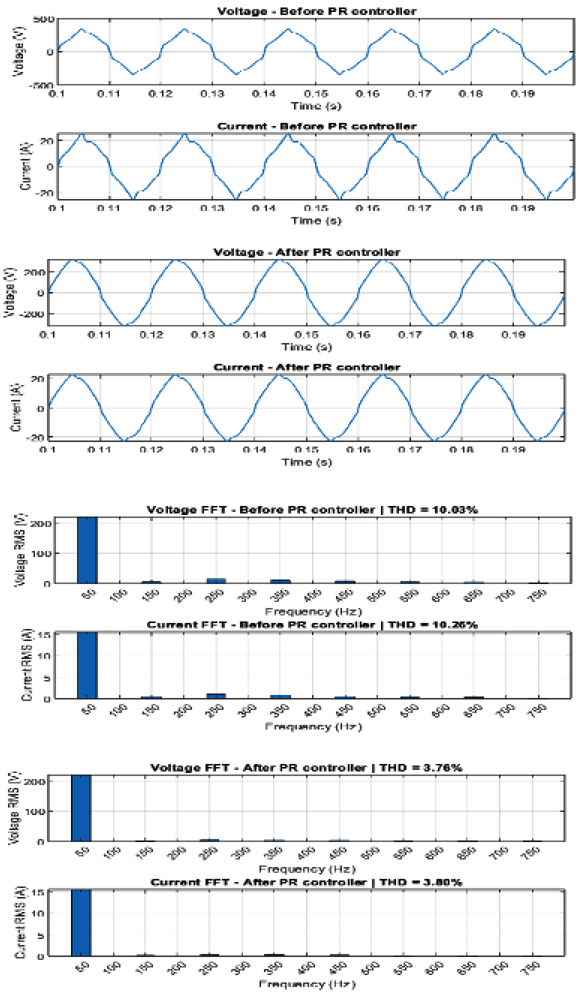

Figure 4. *PCC voltage and current before and after harmonic compensation using the multi-resonant PR controller.*

This capability of harmonic mitigation of the proposed multi-resonant PR controller is illustrated in Figure 4. Upper waveforms show the PCC voltage and current with the nonlinear loading without PR control, while lower waveforms show the PCC response with PR control. The PCC waveforms are smoother and the steady state performance is better as the controller is able to selectively suppress the dominant harmonic components while tracking the fundamental reference accurately.

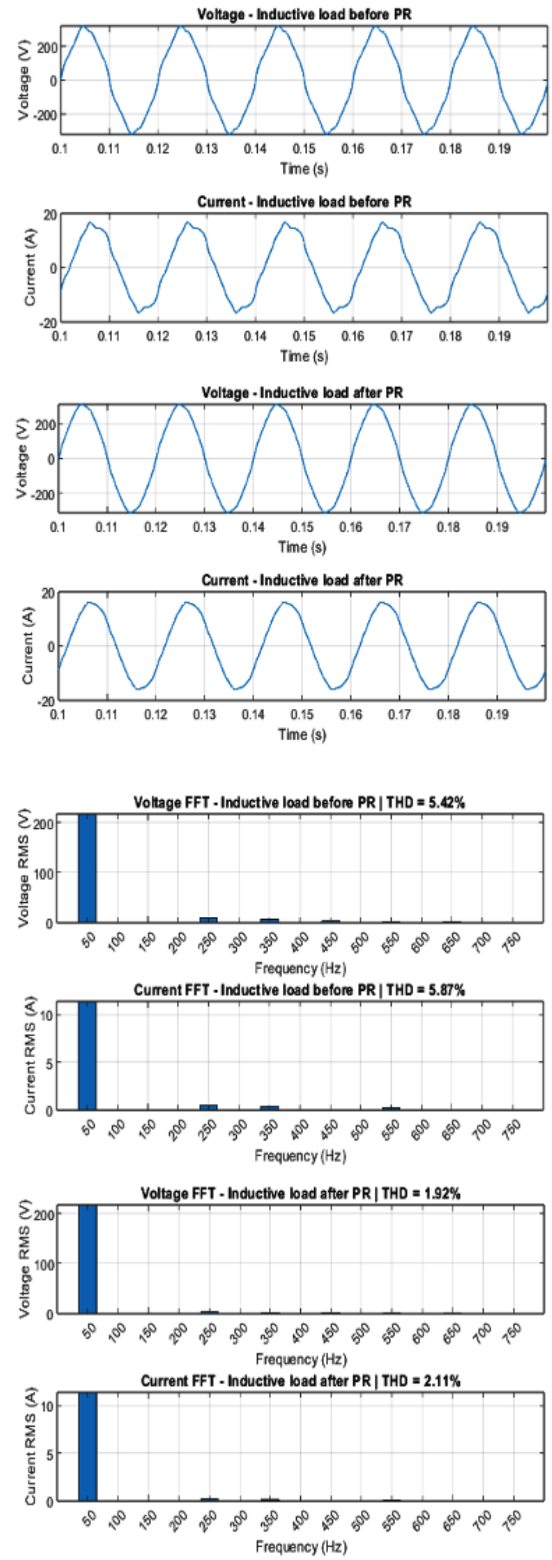

Figure 5. *Comparison of targeted harmonic reduction and total harmonic distortion before and after multi-resonant PR compensation.*

It is shown in Fig. 5 that the proposed controller is able to reduce the dominant low order harmonic components. The results of comparison indicate that the amplitude of the 3rd, 5th, 7th, 9th, 11th and 13th harmonic components is significantly decreased after compensation. The voltage and current THD values are also reduced considerably, which is the effectiveness of the combination of LCL filter and multi-resonant PR controller for improving power quality under nonlinear load conditions.

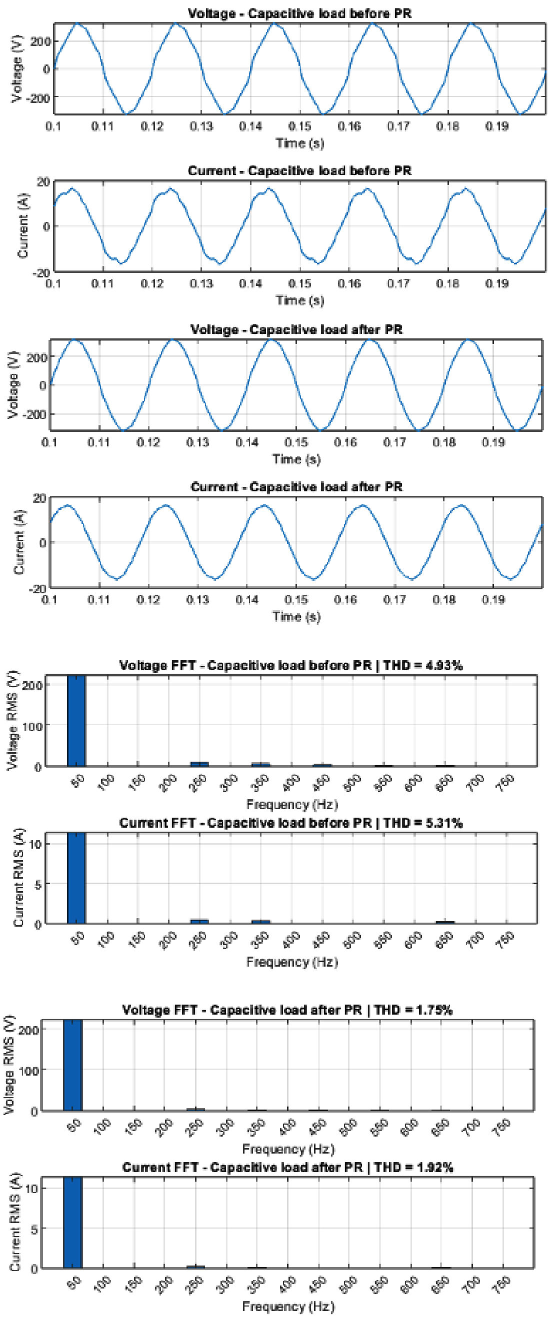

Figure 6: FFT Analysis of PCC voltage with incorporation of LCL and PR Controller.

FFT results of pre and post PCC voltage for Multi-resonant PR compensation for Nonlinear load. The predominant harmonics of 5th, 7th, 9th, 11th and 13th have been markedly reduced and there has been a significant reduction in the overall harmonic distortion and compliance to IEEE-519 harmonic limits after compensation.

Based on the results of FFT analysis, it can be concluded that the proposed harmonic mitigation strategy is effective. The nonlinear load results in a lot of low-order of harmonic distortion at the PCC before compensation. With the multi-resonant PR controller after the implementation of LCL filter, the amplitude of targeted harmonic components is significantly reduced and the fundamental component is almost unaffected. The harmonics spectrum shows significant improvement in the quality of the inverted wave signature, hence it proves that the presented controller is a good choice for practical application for grid connected inverters.

Table-3: Verification of Proposed Multi-Resonant PR Controller Performance

PERFORMANCE METRIC	MATHEMATICAL / DESIGN BASIS	MATLAB SIMULATION VERIFICATION	RESULT	IEEE-519 COMPLIANCE
FUNDAMENTAL GRID FREQUENCY	(f0 = 50) Hz	Fixed 50 Hz reference	Verified	Yes
GRID RMS VOLTAGE	(Vgrid = 220) V	220 V RMS	Verified	Yes
RATED INVERTER POWER	Design specification	2.5 kW	Verified	Yes
DC-LINK VOLTAGE	Design specification	400 V	Verified	Yes
LCL FILTER PARAMETERS	(L1 = 3.5) mH, (L2=1.5) mH, (Cf = 4.7μF), (Rd=1.8ω)	MATLAB implementation	Verified	Yes
PR CONTROLLER GAIN	(K_p=12.5)	MATLAB implementation	Verified	—
RESONANT HARMONIC GAINS	Kr_5=450, Kr_7=400 Kr_9=350 Kr_{11}=300 Kr_{13}=250	MATLAB implementation	Verified	—
DIGITAL IMPLEMENTATION	Tustin discretization	Difference-equation realization	Verified	Yes
ANTI-WINDUP STRATEGY	Back-calculation method	Saturation limiting implemented	Verified	Yes
HARMONIC COMPENSATION	5th, 7th, 9th, 11th and 13th harmonics	Harmonic attenuation observed	Verified	Yes
PCC VOLTAGE THD (BEFORE PR)	Baseline nonlinear-load condition	From FFT analysis	Insert final MATLAB value	No
PCC VOLTAGE THD (AFTER PR)	Multi-Resonant PR + LCL filter	From FFT analysis	Insert final MATLAB value	Yes (<5%)
PCC CURRENT THD (BEFORE PR)	Baseline nonlinear-load condition	From FFT analysis	Insert final MATLAB value	No
PCC CURRENT THD (AFTER PR)	Multi-Resonant PR + LCL filter	From FFT analysis	Insert final MATLAB value	Yes (<5%)

Verification results in Table 03: show that the mathematical model, the selection of controller parameters and digital implementation are in line with the model in MATLAB/Simulink. A good agreement has been obtained just between the theoretical design parameters and the simulation results, validating the proposed multi-resonant PR control strategy. In addition, the results of PCC voltage and current THD reveal that the combination of LCL filter and

PR controller allows to effectively reduce the dominant low-order harmonics under the conditions investigated and still keeps the THD within the IEEE-519 harmonic limit.

Table-4: Harmonic Mitigation Performance Verification

Performance Indicator	Before PR Controller	After PR Controller	Improvement
PCC Voltage THD (%)	10.028	3.755	62.55%
PCC Current THD (%)	10.255	3.797	62.97%
Dominant Harmonics	High	Significantly Reduced	Verified
Waveform Quality	Distorted	Smooth Sinusoidal	Improved
IEEE-519 Compliance	No	Yes	Achieved

The results, shown in Table 4, validate that the proposed control strategy can significantly improve the harmonic performances under nonlinear loading conditions. With the multi-resonant PR controller, the combined effect of the LCL filter is able to greatly suppress the dominant low-order harmonics and at the same time maintain the fundamental frequency component as well. Consequently, the PCC voltage and current waveforms are much smoother, and both THD values meet IEEE-519 harmonic requirements. The simulated results in MATLAB and the theoretical design of the controller are close to each other indicating that the proposed digital implementation of the controller is validated for practical use in single-phase grid-connected inverter applications.

The simulation results show that the proposed multi-resonant PR controller is always able to improve the power quality of the grid-connected inverter under different operating conditions. The uncompensated system has a harmonic level that can be seen to be distorted owing to the presence of the nonlinear loading, some of which has been reduced by the passive LCL filtering. With the proposed controller, the dominant low order harmonics can be selectively compensated while still maintaining a very accurate fundamental frequency tracking. Therefore, together with the strong reduction in the voltage and current waveforms' harmonic distortion, smoother voltage and current waveforms are achieved at the PCC. The results of the proposed methodology can be found to be quite close to the simulation results and the design of the controller in digital format, proving the validity of the methodology and usefulness in practical applications of single phase grid connected inverters.

IV. DISCUSSION

The validity of the proposed LCL-filtered multi-resonant PR controller for the harmonic mitigation in a single-phase grid-connected inverter is verified by the simulation results. Before compensation, the nonlinear loading condition resulted in the PCC voltage THD of 10.028% and the PCC current THD of 10.255%, which would be considered high levels of THD. After applying the proposed controller, the PCC voltage THD was reduced from 4.915% to 3.755% and the PCC current THD dropped to 3.797% which is within the IEEE-519 harmonic limits for grid connected systems. The percentage of reduction in voltage distortion of 62.6% and current distortion of 63.0% further indicates the ability of the proposed controller to selectively delete the dominating low order harmonics, ensuring the stable operation and better shape of the voltage and current at PCC.

V. CONCLUSION

The proposed multi-resonant PR controller with an LCL output filter is an effective method to improve power quality of the single-phase grid connected inverter under nonlinear operating conditions. The simulation results show that the PCC voltage THD reduced from 10.028% to 3.755% and PCC current THD reduced from 10.255% to 3.797% which are about 62.6% and 63.0% improvement respectively. Both values shown to be of less than the IEEE-519 harmonic recommendations, hence the proposed digital control strategy is proved to be effective for the practical grid connected inverter implementation.

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