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Enhancing Power and Reducing Harmonics in Grid-Connected Inverters Using AI-Based Predictive Control and Optimization Techniques

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The increasing integration of renewable energy sources has led to a surge in grid-connected inverters (GIs), potentially affecting power quality and grid stability. To address these challenges, AI-based predictive control and optimization techniques are employed to enhance power delivery while minimizing harmonic distortions. This study evaluates the effectiveness of proportional integral (PI) and proportional resonant (PR) controllers, both with and without harmonic compensators (HC), in the synchronous reference frame. The analysis demonstrates that AI-driven predictive control significantly improves harmonic mitigation and overall system performance. Among the tested control strategies, the PR+HC controller exhibits superior current quality. Additionally, this research benchmarks the performance of the proposed AI-based approach against the IEEE 1547 standard and commercial inverters from different manufacturers.

1. Introduction

In recent years, the number of new fossil-fuel-based conventional power plants has significantly declined due to environmental regulations and policies. As a result, distributed generation (DG) using renewable energy sources (RES) has gained popularity as a cleaner alternative. Maintaining regulated frequency and voltage in renewable energy systems and DG relies on power electronic converters. The industrial, commercial, and residential sectors increasingly adopt power electronics to reduce costs and size while improving performance and power quality. However, power electronic converters introduce harmonic emissions at both low and high frequencies (below and above 2 kHz), which pose challenges to power quality. Every DG system requires at least one inverter to convert DC power to AC. Pulse Width Modulation (PWM) is the most common technique for achieving this conversion, with the Fourier-based model being widely accepted for PWM analysis. To mitigate ripples and harmonics at the inverter terminals, LCL filters are commonly employed. Additionally, a current controller is essential for grid-connected inverters to regulate grid current accuracy.

Recent research has explored more efficient current control strategies for grid-tied inverters using LCL filters. For instance, a Five-Level Packed U-Cell inverter employs a Linear Quadratic Regulator with integral action to control the current. This approach minimizes the impact of grid voltage distortion on grid current and effectively reduces specific harmonics in the system. A standard grid-connected inverter setup typically includes an LCL filter, as shown in Figure 1. In such configurations, a Thévenin equivalent circuit, consisting of an AC voltage source in series with a resistance, is often used to model the external grid. Ensuring inverter stability requires achieving the desired output in terms of magnitude and phase. The middle branch of the LCL filter is usually stabilized by incorporating a large passive damping resistor. However, while this method enhances stability, it also modifies the output waveform, introducing a major drawback. Historically, harmonic emissions in electrical grids were primarily limited to lower frequencies (below 2 kHz). However, advancements in active front-end power electronics have expanded the harmonic spectrum to include frequencies up to 150 kHz. Studies have demonstrated the presence of significant harmonics in the 2–150 kHz range, particularly in residential, commercial, and industrial networks, where modern power electronic devices operate at switching frequencies above 2 kHz. Despite their detrimental effects on equipment lifespan and power grid quality, high-frequency harmonics remain underexplored and are not adequately addressed in existing standardization efforts. Recent investigations highlight the urgent need for comprehensive standards to regulate harmonics in this frequency range effectively.

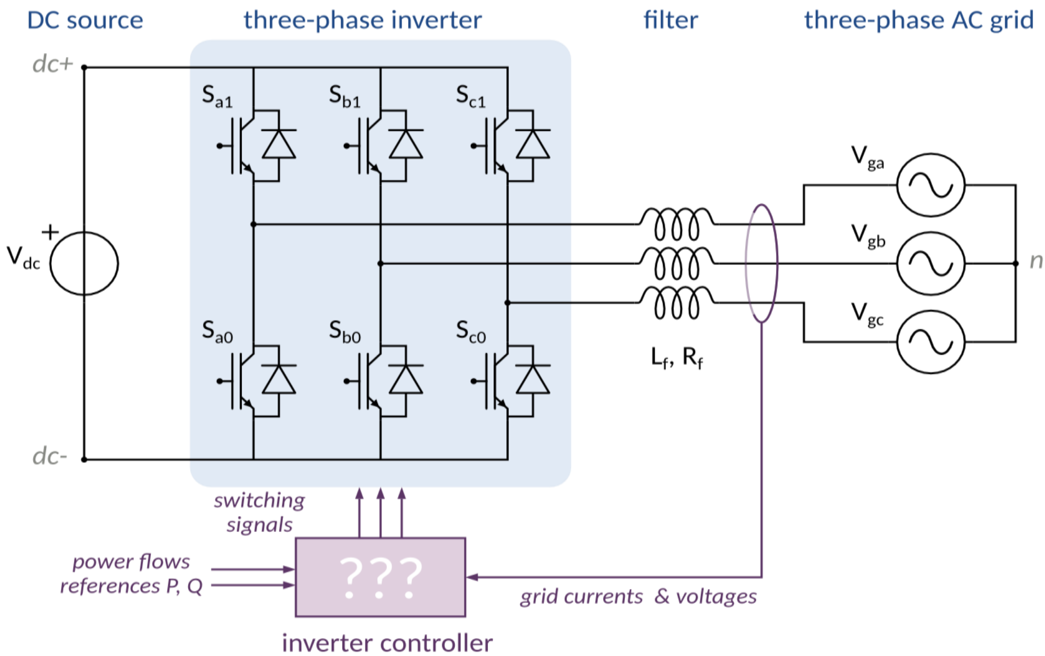

Figure 1: A grid-connected inverter in action

Nonlinearities inherent in PWM inverters may interact with harmonics introduced by the reference signal, the external grid, and the DC-link. Voltage harmonics of grid are the topic of a variety of useful publications, including those that examine critical harmonic circumstances and/or mitigation measures. An equivalent impedance-based model is used to investigate grid-connected inverter resonance in various situations of positive, negative, and complete resonance. This study defines full resonance as the sum of the grid and inverter output impedances being zero. Positive or negative incomplete resonance may be achieved by a zero sum of the grid or output impedance and resistance. This research also looks at the harmonic amplification in these three scenarios. When the stability margins are narrowest, there are more harmonics. In spite of this, the research doesn't take into consideration both the reference signal and the PWM harmonics. Increase the linear modulation range of an H-bridge single-phase grid inverter by employing a better third harmonic correction technique. The suggested approach makes use of a positive third harmonic to compensate for the inserted harmonic by using the equal quantity of negative third hormonic. However, despite its ability to cancel the third harmonic, the method cannot be used to harmonic orders higher than three. A solution has not been identified for harmonics in the reference signal or PWM output of the system explored in this paper.

Several papers have explored the rejection of inverter switching harmonics. The ripples of a three-phase inverter connected to an unbalanced load were studied. The active switching strategy reduces DC-link capacitor harmonic current. For two-level voltage source inverters, an AC ripple may be used to anticipate the DC-link current. These converters are used to convert pulse amplitude modulation (PAM) to pulse width modulation (PMW).B sin $(\omega_O(t) + \varphi_i)$

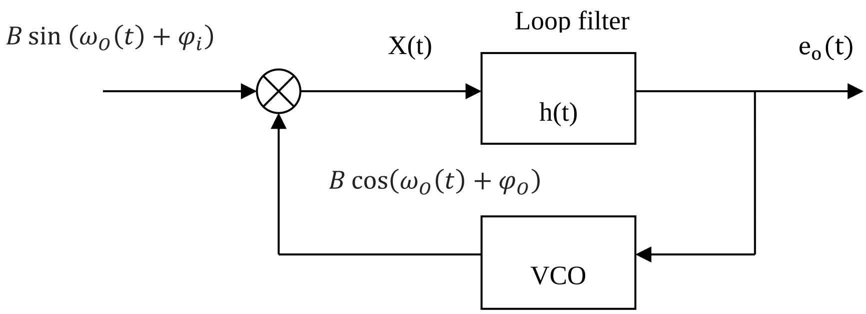

Figure 2: Diagram of a typical PLL's components

Furthermore, harmonics from the reference signal, external grid, and DC-link, as well as their own non-linarite harmonics, may impact PWM inverters. To learn more about harmonic grid voltage circumstances and/or mitigation measures, check out the many useful materials available. Assumptions of positive, negative, and complete grid-connected inverter resonance are tested via the use of a model based on equivalent impedance. A complete resonance is one in which the grid and inverter output impedances are equal to zero, according to this experiment. A positive or negative incomplete resonance is achieved when the grid and output impedances and resistances are equal to 0 (zero). An additional focus of this project is on the sonic amplification of each of these three possible scenarios when the stability margins are thinnest, there are more harmonics to consider. In spite of this, the research doesn't take into consideration both the PWM harmonics and the reference signal. H-bridge single-phase grid-connected inverters may benefit from an enhanced third harmonic correction approach that increases the linear modulation range. By substituting a positive third harmonic for the inserted harmonic, a similar quantity of negative third harmonic may be used to make up for the missing third harmonic. Despite its efficacy in cancelling the third harmonic, the method cannot be used to harmonic orders larger than three. As far as we know, no solution has been identified for harmonics generated by the reference signal or PWM output.

The rejection of harmonics by inverter switching has been the subject of a few papers. A three-phase inverter connected to an imbalanced load was studied for ripples in DC-link current and voltage. A method for lowering DC-link capacitor harmonic currents has been presented using an active switching technique. Inverters with two-level voltage sources may benefit from a prediction method that accounts for an AC ripple when estimating the DC-link current. Reduced current ripples are achieved by using a pulse-amplitude-to-pulse-width-modulation converter (PAM-PWM).

2. Literature Survey

Various novel dampening algorithms have been devised to stabilize the DPGS and improve its waveform. Here, inverter- and grid-sideamping measurements are categorized according on these parameters and their categorizations. Changing the inverter's effective output impedance or the grid impedance may ensure system stability using any dampening approach. The impedance-based stability analysis underpins this. Traditional damping strategies for industrial applications will be evaluated and compared in this study. Impedance-based stability analysis and prospective damping techniques will be shown to have a bright future [1].

In an unstable system, at around the intersection frequency, harmonic resonances are generated when the steadiness boundary is reduced to a negative value. To decrease harmonics, the inverter's admittance and the grid's must have a phase mismatch of less than 120 degrees at their crossing. This notion led to the development of an inverter admittance phase reshaping method that does not need real-time grid impedance or resonance frequency information. At the common coupling point, voltage feedforward is used to apply the strategy (PCC). An adjustable proportional element in a second-order notch filter corrects the feedforward lag network for the admittance amplitude of the fundamental frequency. Using the recommended approach, harmonics at or near the junction frequency may be efficiently reduced with a system phase margin of more than 60 degrees. It is clear from the results of the experiments that the proposed method is effective. [2]

A virtual harmonic impedance technique may be used to rectify harmonic distortion and generate sinusoidal voltages. Changes in filter inductance have a compensatory impact on virtual harmonic impedances. Consequently, inductance fluctuations must be viewed as real-world physical disturbances because of this Voltage control may be made more robust using linear active disturbance rejection control (LADRC) by reducing virtual harmonic impedance sensitivity and decoupling the model. Because it uses fewer acquisition modules than the traditional dual-loop PI control, the proposed control strategy is more suited to engineering applications. Virtual harmonic impedance design and stability research are also presented. Both simulations and testing demonstrated the effectiveness of the proposed approach [3].

By proposing a modified exponential reaching rule, the SMC strategy's shaking shock effect may be successfully mitigated. The proposed SMC approach's analysis and design procedures are explained in detail. Using Matlab/Simulink and RT-LAB, an experimental platform on a 50kW three-phase LCL grid inverter is needed to compare the suggested SMC technique with the conventional control strategy. According to modelling and experimental results, constant and transient grid current performance may be improved by using the SMC approach [4].

Solar grid-connected inverters are dealt with in this thesis by using Repetitive and PI control to reduce harmonics. For better system damping, this technique has included repeated and PI control to the current controller as well as capacitive-current feedback to the LCL photovoltaic grid-connected inverter. As a further benefit of using PI control, harmonic suppression is achieved by repeatedly controlling the outer control loop. Moreover, the THD of grid-connected current in simulations is 19.65% lower than the THD of a PI controller, which is a significant improvement in the system's dynamic response capabilities [5].

Interactions between inverters, weak grids, and their paralleled counterparts might jeopardies' the stability of the system. In addition to the LCL filter resonance peak, there are two more forms of interactions that might disrupt grid currents as well. This page covers every facet of the LCL inverter's modelling and stability investigation. The filter's weight and size may be reduced using magnetic integration methods for filter inductors, which increases the system's power density. Finally, the different damping techniques for improving the internal stability and the associated application issues are thoroughly examined. An focus is given on different models of inverter output impedance and on-line impedance measuring methods when looking at impedance-based strategies for assessing system interaction stability at the system-level. Future studies on grid-connected LCL-type inverters' modelling and stability analysis are also highlighted. [6]

An SG is the next generation of a modern power system since it exchanges power and data in both ways. Customers and utility companies must be able to communicate with one other in order to have a smart grid. All of its components and settings must work correctly and effectively for it to execute appropriately. An important aspect of the modern power system is Power Quality (PQ). In this study, the micro grid (a component of the SG) system's power quality (PQ) is improved using shunt hybrid filters (SHF). Use of adaptive fuzzy neural network control is used to test the SHF's performance under varied situations of loads and supply voltage. ' (AFNN). Fuzzy sliding and fuzzy back stepping are two possible replacements for the current controller design (AFBS). Analyses are performed using MATLAB/Simulink software [7].

To maintain system stability, the BW of this new control loop must be lower than the BW of the existing control loop. The IARC method (i.e., a 0.02 switching frequency) has the greatest DCL-BW when comparing the other control systems. When the controller design leaves so much leeway for human mistake, there should be a standard approach for picking DCL-BW. The nominal inverter rating, output current harmonic distortion, and low-order harmonics on the DC link voltage all have an effect on the DCL-BW selection. The output current's harmonic distortion led to the selection of DCL-BW. The proposed technique improves power quality indices for grid-connected inverters with less than a kVA output. The findings of the study are supported by experiments and computer simulations. [8]

Since live measurements of the power grid impedance aren't necessary and control parameters are unaffected by changes in the power grid impedance, an adaptive robust H control strategy is presented. It is then explained how to calculate reference quantities and how to create control parameters. Experiments are conducted to test the theoretical analysis offered in this paper as well as a control strategy that is evaluated in the lab. When the power grid impedance swings over a wide range of values, various control systems claim that the adaptive robust H system delivers the most stable and accurate grid-connected current quality [9].

System stability might be jeopardized by parallel inverters that are connected to a weak grid. The usual grid-side inductance current feedback control technique plus a notch filter may be used to reduce high-frequency oscillations. Stability and even instability will be reduced as a result. As a result, we've developed a new notch filter for use with inverters linked in series rather than parallel. Harmonic current from parallel inverters may be effectively restricted with this method, avoiding the high-frequency oscillation of the impedance network. Additionally, it enhances the system's phase buffer, guaranteeing that the system is stable in weak grids. Based on the upgraded notch filter's notch depth and dynamic performance, control parameters are calculated. As a final note, these tests support the validity of the aforementioned control mechanism. [10]

A grid-connected inverter with locally imbalanced and distorting loads may make use of these technologies to decouple imbalance and harmonic correction in phase sequences and the frequency domain. Unbalanced and harmonic local voltages may be corrected using a sequence-asymmetric method rather than a standard grid-connected converter control system. A Norton similar model is used to demonstrate the strategy's functioning concept. For example, a frequency decoupling strategy may be used to manage each of the basic positive, harmonic symmetrical, basic zero, and the fundamental negative-sequence components individually. Studies have shown that the converter may be used to lower local voltage total harmonic distortion and unbalanced factor by using harmonic sinking and voltage imbalance correction [11].

3. Proposed Method

Output Current Control

It is possible to use a variety of controllers to regulate the inverter output current. To further enhance its performance, the same controller may be utilised with variables from various frames. While it is possible to use the natural dq frame for a basic proportional integral controller, this isn't always necessary. A PR controller may be used instead of a PI controller to prevent frame transformations.

A Synchronous frame's PI

Single-phase systems were the first to benefit from the dq synchronous frame in [8]. It is suggested that an imaginary circuit be used to provide two orthogonal sinusoidal values (for example, I and I). I and I are represented as dc values in a revolving frame at synchronous speed utilising this pair of values in a frame transformation matrix The direct and quadrature axes make form this rotating frame, which rotates at the same angular speed as the grid voltage. It is possible to obtain 0% steady-state error with a simple PI controller [5]. In addition, if the transformation phase angle () is identical to the grid voltage phase angle, the direct axis is in line with the grid voltage vector.

[14] Shows how this may be used to regulate both the active and reactive capabilities separately. For the purposes of this work, the control structure shown in Figure 1 has been selected as the block diagram. The power references are responsible for providing the reference currents that are utilised in the dq frame. To get the corresponding current in the dq frame, the output current is delayed by 90 degrees and then transformed into a frame representation. Once this is completed, the dq equivalent of output current is compared to its reference voltages, and the error is sent into the PWM control signal created by a PI controller to regulate the output current.

B Proportional resonant controller

Similar to the PI controller, the Proportional resonant controller (PRC) performs the same functions. However, the PR has a resonant part instead of an integrator. As a consequence, the infinite gain of the PI controller, with dc values, shifts to a set resonance frequency (fr) with the PR controller. For sinusoidal references, there is no need to do a frame translation to obtain zero steady state error. But it's possible that a system with unlimited gain would have stability issues. A cut-off frequency (fc) is then applied to restrict the gain at yhe fr (Resonance frequency).

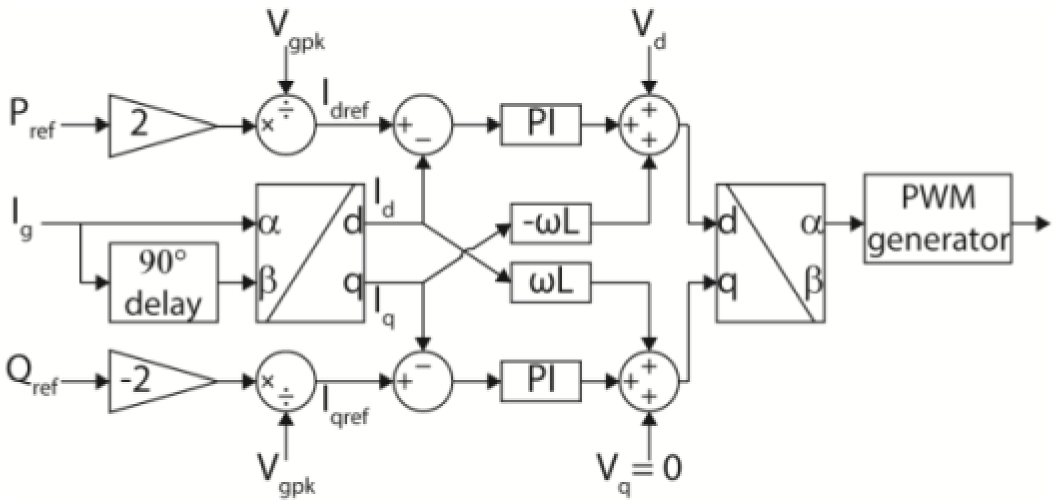

Figure. 3. Block diagram of synchronous frame with PI controller

As a consequence, the system is more reliable and has more bandwidth available. Thus, grid-connected inverters [10] benefit from better performance in situations where the frequency might fluctuate. The controller transfer function is shown in Equation (1) with cut-off frequency fc. The proportional and resonant gains are denoted by KP and KI, respectively.

$$G_{PR}(s) = K_{P\_PR} + \frac{\left(2.K_{1_{PR}}.\omega_C.S\right)}{(S^2 + 2.\omega_C.S + \omega^2)} \qquad (1)$$

The use of numerous resonant controllers, each set to a different resonant frequency, may be done in tandem. There is an option to compensate for harmonics that may be present in the monitored variable. For the purposes of this paper's PR controller testing, the control algorithm is shown in Figure 2. The power references are used to create the reference current in the dq frame. An inverter PWM duty cycle is generated by converting current to its natural frame and then using that frame as a reference to compare real output currents. The error is then sent to the PR controller for further processing.

Many control structure improvements have been proposed in order to improve system stability during frequency oscillations, including frequency adaptive techniques [15] [16] and the optimal tuning of controller gains. [17].

Proposed method impplementation

Unless otherwise stated, the results provided in this work are based on the same experimental design as those published in [18] [19]. This system, which is seen in Figure 3, makes use of dc-to-dc converters as well as complete bridge inverters to achieve its goals. Its use in V2G (vehicle-to-grid) and grid-to-vehicle communications are only two examples of how it might be put to use (G2V). When connecting the voltage source inverter to the grid from the battery bank's 8x12 V output, which was linked to the grid through a dc-link capacitor, an LC filter with values of 5.6 mH and 1 uF was used to filter the voltage source inverter's connection to the grid from the battery bank's 8x12 V output (1 mF). The Powerex PM75RLA120 intelligent power module acts as the system's fundamental building component throughout its entire lifecycle. Simulink® and ControlDesk® software packages were used to evaluate real-time control approaches. The dSPACE DS1103 real-time controller board was used to test the methods. As can be seen in Figure 4, the testing setup was easy and uncomplicated.

Using the PR controller, the HC gain (KI PR) is the same as the HC gain (KI PR), the resonant frequency () is 340 rad/s, and the cut-off frequency (c) is 1 rad/s in the dq frame, respectively.

Table 1. Controller gains for the tests.

K_{P_P1}	K_{1_P1}	K_{P_PR}	K_{1_PR}
20.00	1000.00	25.00	750.00

4. Results and Discussions

A wide range of injected power levels were tested extensively to determine the controller's performance. This controller was put through its paces in a dq frame (Fig. 5) and then again with compensation for 3rd, 5th, and 7th harmonics (Fig. 6). (Fig. 7). Despite the fact that all three controllers had a current in phase with the grid voltage, they all exhibited considerable frequency distortion. In both PR and DQ frame controllers, the third harmonic created severe distortion, which is alleviated by the HC.

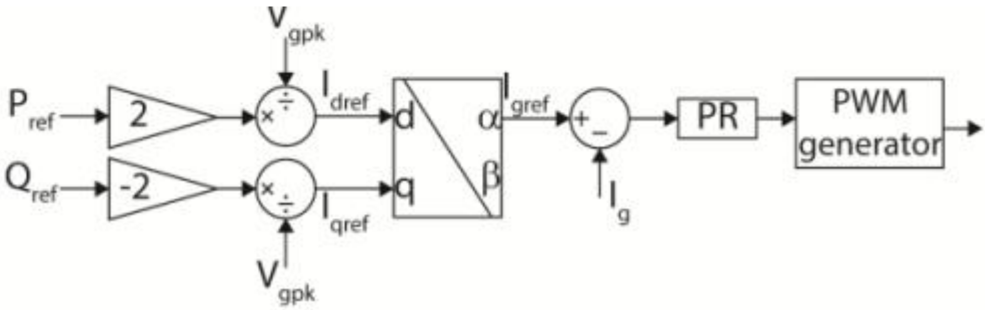

Figure. 4. PR controller block diagram

It is easier to see how controllers affect harmonics in the output current's harmonic spectrum, shown in fig 4. It displays the harmonics of the 3 controllers that were put to the test, as well as their respective IEEE 1547 restrictions. Now it's clear that the PR and dq controllers are overshooting their harmonic content limitations in the third, fifth, and seventh harmonics. These values were essentially lowered by the HC in order to meet the standards' tolerances.

Nonetheless, all three controllers failed to meet the constraints of the eleventh and thirteenth harmonics.

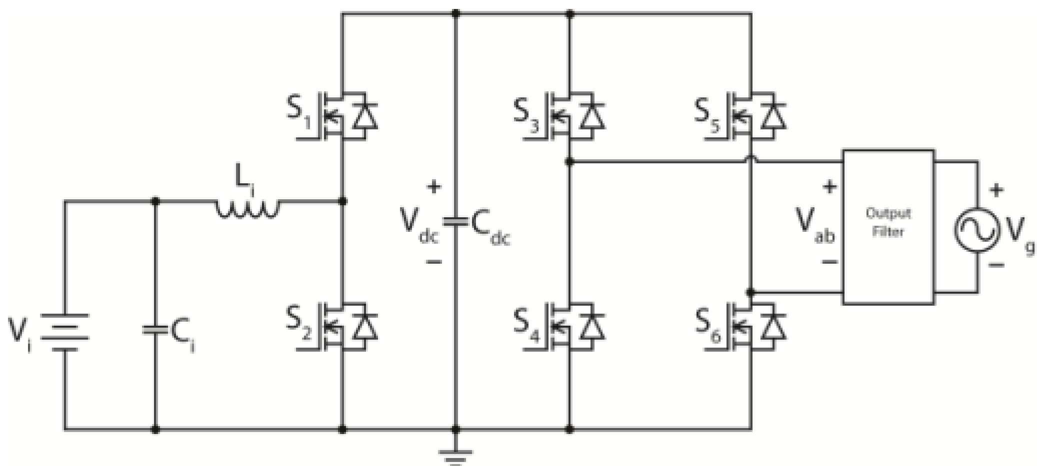

Figure. 5. Bidirectional topology used

As shown in the figures 9 to 11, the output current of the controllers is measured while injecting half of the rated power (500 W) in order to better understand how the controllers respond when the amount of injected power fluctuates.

Table II shows the results of the evaluation of three controllers for their inverter output current (Ig rms), output power (Po), and total harmonic distortion (THD).

In order to provide a point of reference, the output current of three commercial inverters from diverse manufacturers was also measured. The SMA Sunny Boy 1.5-1VL40, the Kostal PIKO MP Plus 1.5-1 (rated power: 1500 W), and the Ginlong Solis mini 700 were all put through their paces throughout the testing process (Rated power: 700 W). The harmonic spectra of the inverters is seen in Figure 12. According to the findings of the tests, the 5th and 7th harmonics of the SMA Sunny Boy surpassed the restrictions of the Kostal PIKO and Ginlong Solis. Three commercial inverters were put through their paces, and the results are reported in Table III. The output current rms, output power, and total harmonic distortion of each inverter are all shown.

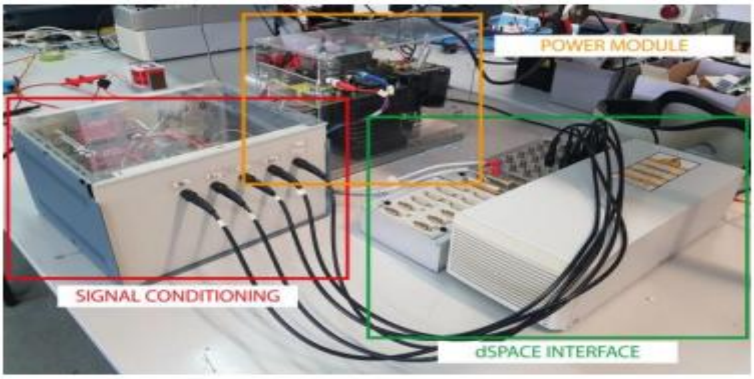

Figure. 6 – Laboratory used for the tests

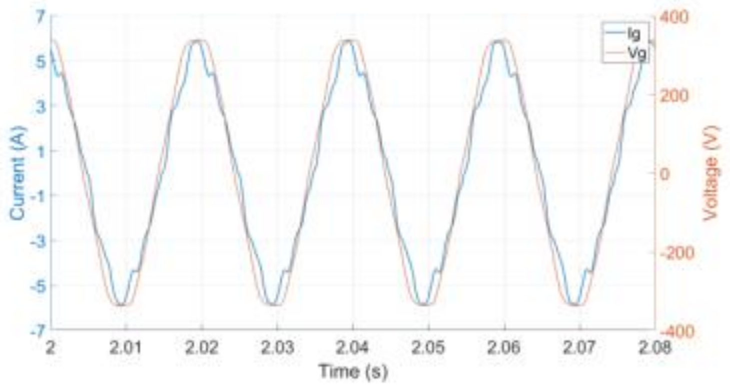

Figure. 7. PR controller output - Pref = 1000.00 W

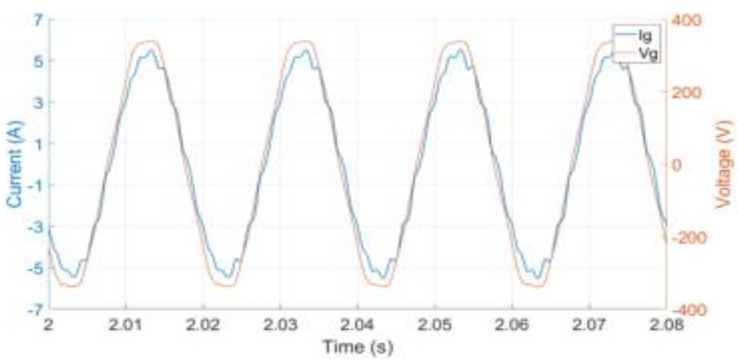

Figure. 8. PR+HC controller output - Pref = 1000 W

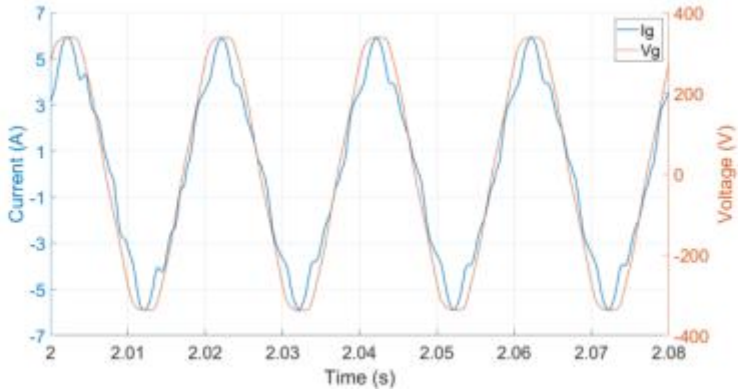

Figure. 9. Dq con troller output - Pref = 1000.00 W

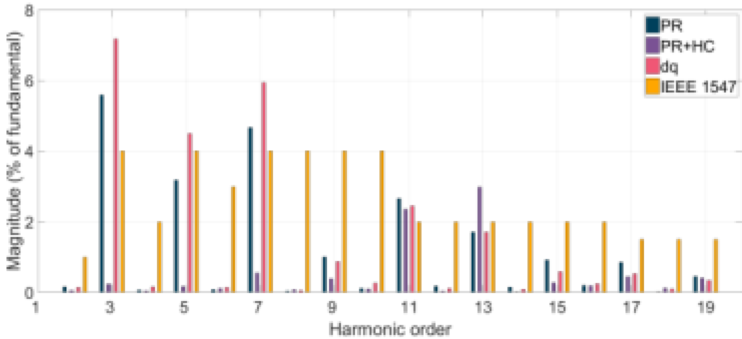

Figure. 10. Various controllers Hormonics

Table II. Various controllers output values$I_{g_{rms}}$ (A)

Controller	$I_{g_{rms}}$(A)	P_o(W)	THD (%)
PR	03.74	928.44	09.22
	01.77	418.58	16.99
PR+HC_1	03.77	915.66	04.88
	01.88	410.55	08.74
PI	03.77	905.88	11.88
	02.44	500.88	18.64

The PR with HC controller got the greatest performance out of the controllers evaluated. Each harmonic compensator, on the other hand, may raise the controller's computing cost, making it unworkable in certain cases. IEEE 1547 restrictions were not met by the PI in dq frame and PR controllers. To further minimise harmonics, it may be utilised in less complex systems with better output filters.

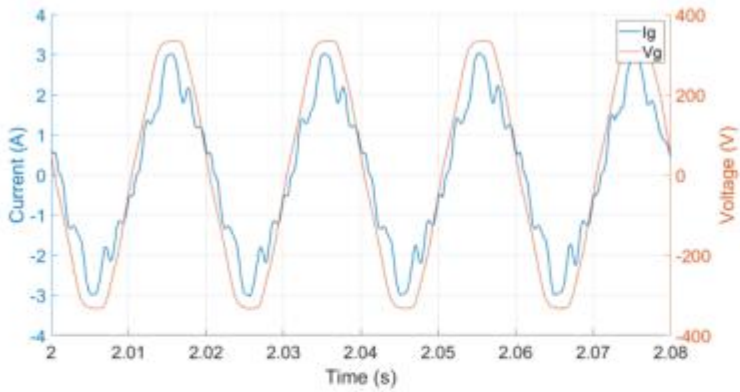

Figure. 11. Output of the PR controller with a preference of 500 W

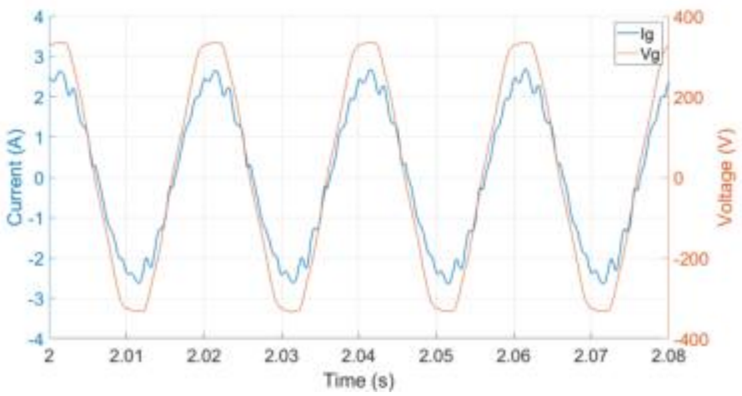

Figure. 12. Output of the PR+HC controller - Pref = 500 W

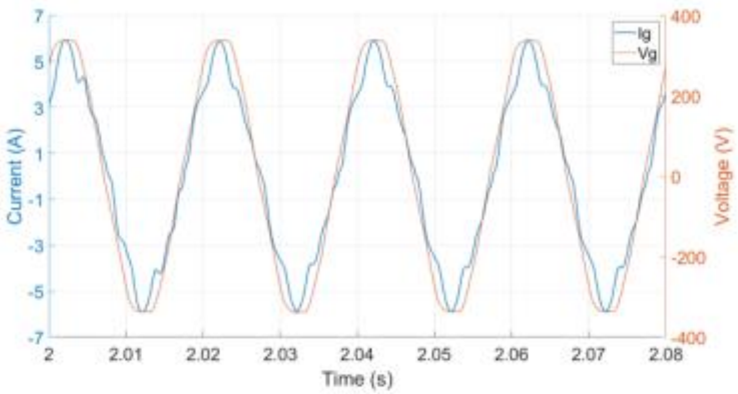

Figure. 13 dq controller output - Pref = 500 W

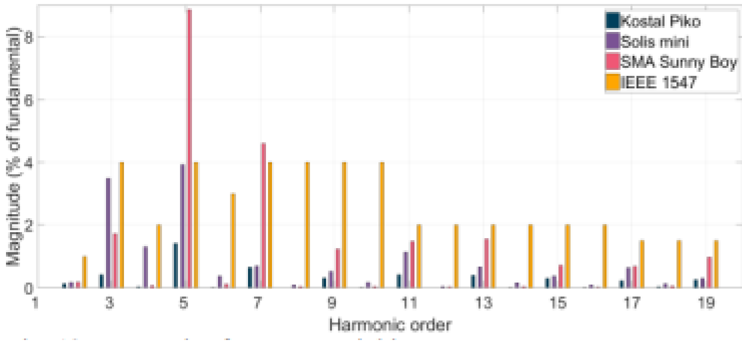

Figure. 14. Harmonics for commercial inverters

Table III. Commercial inverters output values

Controller	I_{grms}(A)	P_o(W)	THD (%)
Costal PIKO	04.66	1042.58	03.47
Ginlong $Solis_1$	03.47	754.28	05.48
SMA Sunny Boy	03.87	930.48	10.58

Both commercial inverters exceeded th THD restrictions when their output values were analysed. However, the rated power of the Sunny Boy was not put to the test. To be clear, all of the evaluated inverters are approved and available for purchase in the industry. Even though it wasn't tested at rated power, the Kostal PIKO complied with all of the IEEE 1547 limitations.

5. Conclusion

Increases in the number of inverters supplying electricity to the grid are necessary to ensure that the produced power is of a consistently high quality. In this circumstance, output current control methods are critical. Grid-connected inverters' output current is often controlled by one of two algorithms: the PI controller in the dq reference frame or the PR controller. Commercial inverter output current was compared to data from both controllers in this study.

When it came to THD and specific harmonics that were adjusted, the PR controller with harmonic compensation performed best. However, this controller requires a lot of processing, and this should be taken into consideration before using it. Auxiliary controllers or other output filters may enhance the outcomes of the PR controller and dq frame controller, which performed beyond the norms.

Because of the controller's improvements, the THD grew when the injected power was reduced. Gains must be adjusted to each power level in order for the inverter to perform optimally. However, putting this into practise isn't as straightforward as it seems.

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