

Second-Order Odd Repetitive Control for Three-Phase Four-Wire Active Power Filter to Mitigation Current Harmonics, Unbalance and Neutral Current of Nonlinear Loads

Bisrat Gezahegn Lemma¹, Minfu Laio^{2*}

Duan Xiongying³

^{1,2,3}, Institute of Electrical and electronics;

School of electrical engineering, Dalian University of Technology,
Dalian 116024, China

Abstract:-This paper describes a three-phase four-wire (3P4W) active power filter (APF) for current harmonic, unbalance and neutral current compensation. The three-phase four-wire system distribution system has been used for residential, industrial and commercial centers of single/ three-phase loads. The single-phase nonlinear loads have been increasing into the low voltage distribution system. It causes a current harmonic, imbalance and excessive neutral current in the local grids. The shunt active power filter takes the upper hand among the other type of harmonics compensation techniques. The odd periodic frequencies nature of the power electronics harmonic makes suitable for repetitive control. Thus, the authors proposed a second-order odd repetitive control for 3p4w APF for compensating current harmonics, unbalance and neutral current with generating high gain only at odd harmonic frequencies. The sensitivity magnitude response of second-order odd RC has deeper and wider notches at the odd fundamental frequencies. It compensated the total current harmonic distortion THDi from 87.42 % to about 3.52% and neutral current of unbalanced single-phase nonlinear loads, it reduced a total current harmonic from 49.45% to 3.43% for balanced and from 50.55% to 3.24% for unbalanced three-phase nonlinear loads.

Keywords: Repetitive control (RC), second-order repetitive control; three-phase four-wire (3p4w), Active power filter (APF), neutral current, current harmonic.

Introduction

Three-phase four-wire (3P4W) distribution feeders have been used for residential, industrial and commercial centers of single/ three-phase loads. The single-phase power electronics-based devices have been increasing into the low voltage distribution systems [1]. This is due to its customer attraction features for house appliances, information technology [2] and electric traction [3], [4] [5]. However, the single-phase nonlinear loads contribute a current harmonic, imbalance and excessive neutral current in the local distribution system. The third (dominant zero-sequence) current harmonic contributed by each single-phase nonlinear loads summed up together and results in three times the zero-sequence current of phase line [6]. Moreover, the single-phasing and abnormal phase change in

the industry aggravates the situation. The current harmonics and unbalances cause economical losses on the 3p4w distribution system. It increases the neutral current, circulation of current in the delta winding of star- delta Δ/Y distribution transformer. An excessive neutral-line current causes overloading of distribution transformer and feeder, rise common mode noise, flat topping voltage waveform [7]. The excessive neutral-line current may raise the potential of the neutral and may causes a safety concerns for customers [8]. Its flat-topping voltage waveform also affects the normal function of precision devices. On the other hand, the harmonic effects on the phase line(s) increase harmonic distortion and power losses.

Starting from the time of 1989 [9] there have been investigating different techniques such as passive filter [10], zig-zag transformer [6], series APF [8], a combination of APF with zig-zag transformer [11] ... etc for mitigating the excessive neutral current. The shunt APF are the most promising for mitigating current harmonics, reactive and unbalanced loads [8], [12],[13],[14],[15],[16] ,[17]. The authors in [12] introduced the concept of the 3p4w APF and made simulation compared with split capacitor 3p4w APF topology. In the following year, the same authors [13] demonstrates its prototype for the practical test.

The instantaneous reactive power theory ($P - Q$) method proposed by Akagi [18], the synchronous reference frame ($i_d - i_q$) method [19], are the control strategy applied for the 3p4w APFs. In the PQ method, the source only demanded to supply the load dc power. All the remaining power of loads (ac power and zero sequences components power) must compensate by the active power filter. The ($i_d - i_q$) method, works to accomplish the source only supplies the mean value of the direct axes component current of the loads. The comparison of the 3p4w APF control indicates that perfect harmonic cancellation (PHC) eliminates the imbalance in the source currents [20]. The 3p4w APF can compensate harmonics and unbalance caused by single-phase nonlinear loads [16]. The performance of the APF control depends on the accuracy of signal conditioning, the accuracy of the reference generation method and gating signal stages. Among these three stages, the reference generation stage is

the most important and has a diversified approach for APF application. So far different inner control approaches have been investigated for APF such as PI control, hysteresis control [21], repetitive control [22], [23],[24], predictive control [16], deadbeat control [25] ... etc. The conventional PI controller is unable to react frequency and phase angle variation at steady-state or under transient conditions. The hysteresis controls cause power loss and acoustic resonance [21].

Fortunately, the power electronic harmonics are odd periodic harmonic frequencies [26], i.e. the $6k \pm 1, k = 1, 2, 3, \dots$ of the fundamental frequencies for three-phase three-wire system and odd harmonics for the 3p4w system. An odd repetitive control (RC) has a promising control for tracking and disturbance rejection on the odd period harmonic without introducing high gain at even frequencies [27]. However, the gain of the repetitive control drastically fails for deviation from the center frequency. The higher-order RC (HORC) can be achieved a higher robustness for frequency variation and uncertainties in the design of active power filter [28]. The second-order repetitive control (RC) is used to compensate for the current harmonics and neutral current. The authors proposed the higher second-

order odd RC for compensation, current harmonics, reactive and neutral current in the 3p4w system. The second-order odd RC provides a wide and deep notch at the odd fundamental frequencies which are the targeted frequencies of the 3p4w system. The rest of the paper is organized as follows: Section 2 describes of 3p4w active power filter and its mathematical model, section 3 compares the different orders of odd harmonic repetitive control and its tracking performance, section 4 presents analysis the simulation results, and finally, the conclusion was drawn in section 5.

II. System description and mathematical model

Fig.1 presents a three-phase four-wire (3p4w) active power filter (APF) with a four-leg IGBTs based voltage source inverter (VSI) and a common capacitor for dc source. The loads are modeled with three single-phase diode rectifiers (*Single-phase type-1 and type-2*), three-phase diode rectifier RC diode (*three-phase type-3*) and a linear resistive load as shown in Table 1. Hereafter we call it by its load type for this paper. The conventional PI controllers are used to regulate the dc-bus voltage variation. The output of the PI regulator used for the magnitude reference of the source current.

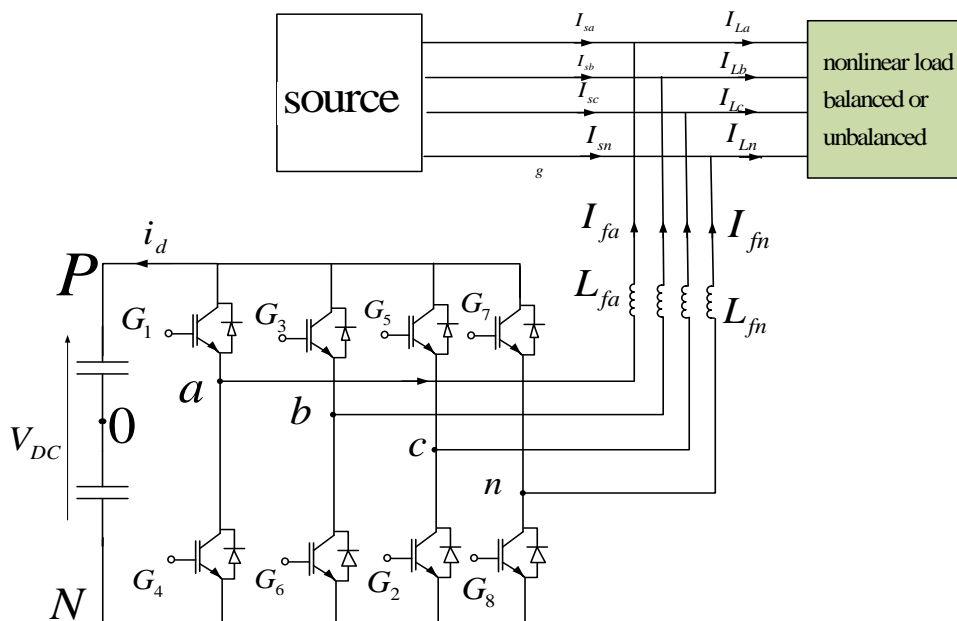


Fig. 1 Circuit diagram of the three-phase four-wire active power filter.

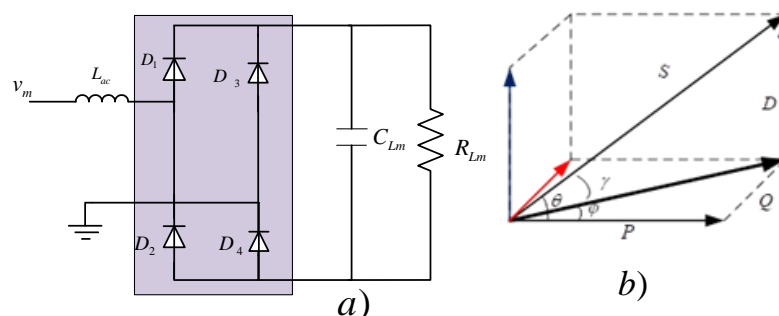


Fig. 2 Diode rectifier with RC loads a) circuit diagram b) power triangle of the load.

The power capacity of the loads is also indicated in a three dimensional (3-D) power triangle diagram [29] using the load parameters given in Table 1. The design system has a voltage rating of voltage is 230 V and a capacity of 5 kVA.

The zero-sequence current of the load was varied by adjusting the load resistor and the load fundamental current [29].

Table 1 The load parameters for single-phase and three-phase loads.

Load types	$L_{ac}(5\%)$	C_L	R_L
Single-phase type-1	3.2 mH	1100 μ F	75 Ω
Single-phase type-2	3.2 mH	1100 μ F	100 Ω
Three-phase type-3	3.2 mH	1100 μ F	100 Ω
Resistive Linear load			50 Ω

Decreasing the load resistor causes an increase in the fundamental current or system load power (i.e. the system is overloaded) and vice-versa. This provides a variable zero-sequence current without affecting other power variables.

The 3p4w APF is connected in parallel to the nonlinear load as seen from the PCC. The first order output ripple filters connected at the PCC with the 4-leg VSI. The governing dynamic equation of the active power filter following the current direction given in Fig. 1 can be written as [29], [16]:

$$v_{gm} = v_{mn} - L_{fm} \frac{di_{fm}}{dt} - i_{fm} r_{fm} - v_{g0} \quad (1)$$

Where $m = a, b, c$ for the phases and the voltage from source ground to point n of the 4L-VSI is given as $v_{g0} = \frac{v_{a0} + v_{b0} + v_{c0} + v_{n0}}{4}$. Thus, taking the source voltage as

$$i_f = \frac{1}{sL_f + r_f} V_f \quad (2)$$

disturbance the final first-order model of the inner plant can be obtained as (2):

III. COMPARISON OF THE FIRST-, SECOND-, AND THIRD-ORDER REPETITIVE CONTROL

According to the internal model principle [30], zero error signal tracking and the disturbance rejection for a periodic signal can be achieved if a representative signal generator is included in the stable closed-loop system. The full-RC system has an infinite loop gain at the integer multiple of the fundamental frequencies of the disturbance. Fortunately, the harmonic of the power electronics are the odd periodic signal. The repetitive control is effective for perfect asymptotic tracking and rejection of periodic signals. However, the convention first order repetitive control loses its gain drastically when the frequency deviates from the harmonic frequency. This due to the structure of the periodic signal generator. Steinbuch [31] proposed a general way of the periodic signal generator to achieve higher gain around the targeted frequency and its neighborhood.

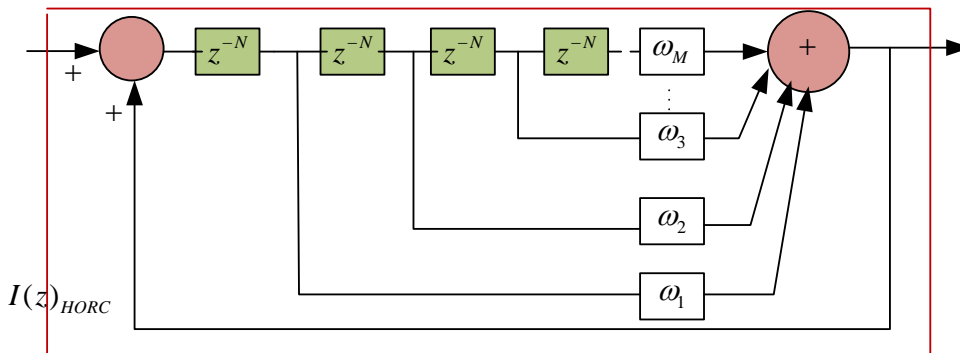


Fig. 3 Structure of a general M-order periodic signal generator [31].

Fig. 3 is generalized M-HORC controller having M delay function weighted by ω_M to form M-memory loops. Thus HORC offers an enlargement of the interval around the harmonic at which IM provides a peak gain. This provides to HORC to have better performance robustness under a varying or uncertain frequency of the disturbance/reference signals. The general internal model (IM) for first-, second- and third-order odd repetitive control can be defined as [28]:

$$I_{HORC}(z) = \frac{-W_{HORC}(z)H(z)}{1+W_{HORC}(z)H(z)} \quad (3)$$

where

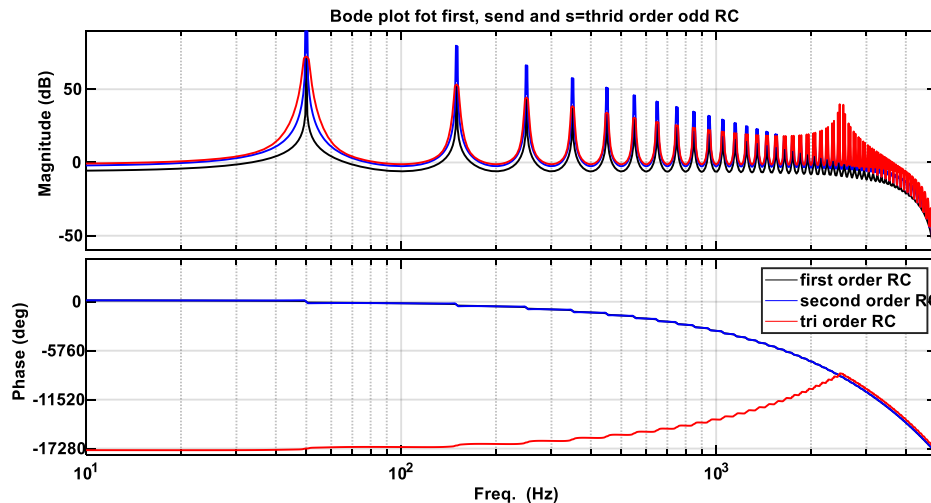


Fig. 4 Magnitude response of the internal model of odd repetitive control with $H(z) = 1$ for order 1,2 and 3.

$z^{-N/2}$, for first order RC
 $W_{HORC}(z) = -1 + (1 + z^{-N/2})^2$, for first order RC
 $-1 + (1 + z^{-N/2})^3$, for first order RC

and $H(z)$ is the FIR filter. Assuming that $H(z) = 1$, the poles of (3) are generated infinite gain at frequencies of $\omega_k = 2(2k-1)\pi/N$, for $k = 1, 2, \dots, N/2-1$ for first order odd repetitive control at frequencies of $\omega_k = 2k\pi/N$, for $k = 0, 1, 2, \dots, N/2-1$. These poles are evenly distributed at the circle at a point of $z = \exp(2k\pi j/N)$ for the first order and $\sqrt[N]{1}$ mthe ultiplicity of the higher order, m

a) Bode plot for first-, second-, and third-order Repetitive control

The bode plot in **Fig. 4** showed that the second-order odd RC has a higher magnitude followed by the third order and first-order RC. The numerical value of the maximum magnitude in dB for the first, second and third-order odd RCs are 4052.18, 261931.72 and 4114.20 respectively. This implies that the second-order odd RC the most robust than the first and third order odd RCs. Of course, it is not only evaluated at a single point but also for other points in the graph showed that second-order RC has a higher magnitude for all fundamental frequencies. The third order followed the second-order in magnitude response. The first order odd RC has the smallest magnitude response. Therefore, the second-order odd RC is the most robust RC than the third and the first order odd RC. This implies that the first-order RC is unsuitable for frequency variations around the fundamental frequencies. Moreover, for higher frequencies, the third-order RC has some magnitude variation. Its practical implementation needs a conservation filter design for higher frequencies.

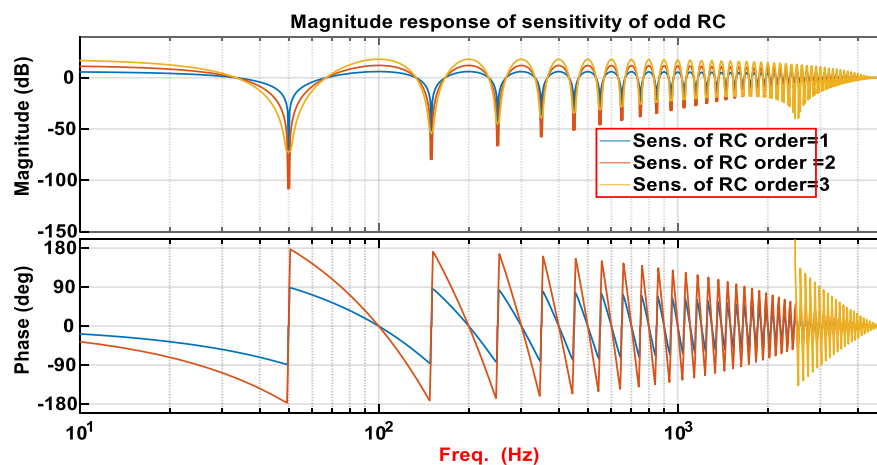


Fig. 5 Sensitivity magnitude response of first, second and third-order odd RC.

b) Sensitivity for first-, second-, and third-order Repetitive control

The sensitive magnitude response of the first-, second-, and third-order odd RC are depicted in **Fig. 5**. The third-order odd RC has higher magnitude between the fundamental frequencies. This indicates that the third-order RC amplifies the inter-harmonic between two fundamental harmonics. In this regard, the first-order RC has the smallest magnitude response between two fundamental frequencies. However, the first-order sensitivity magnitude response has a shallow and narrow notch at the fundamental frequencies. This characteristic also indicates

that the first-order odd RC may not effective for frequency deviation or uncertainties. On the other hand, the second-order odd RC has moderate magnitude between two fundamental frequencies. Moreover, the second-order odd RC has deeper and wider notch at the harmonic frequencies. The third-order follows the second-order odd RC as shown in the magnified plot of **Fig. 5**. The more the deeper notch means the more attenuate the error signals. In this aspect, the second-order odd RC has better characteristics for frequencies variation and inter-harmonic frequency. The sensitivity function is computed as (4):

$$S_{HORC}(z) = \frac{1 - W_{HORC}(z)H(z)}{1 - W_{HORC}(z)H(z)(G_x(z) * G_{cl}(z) - 1)} \quad (4)$$

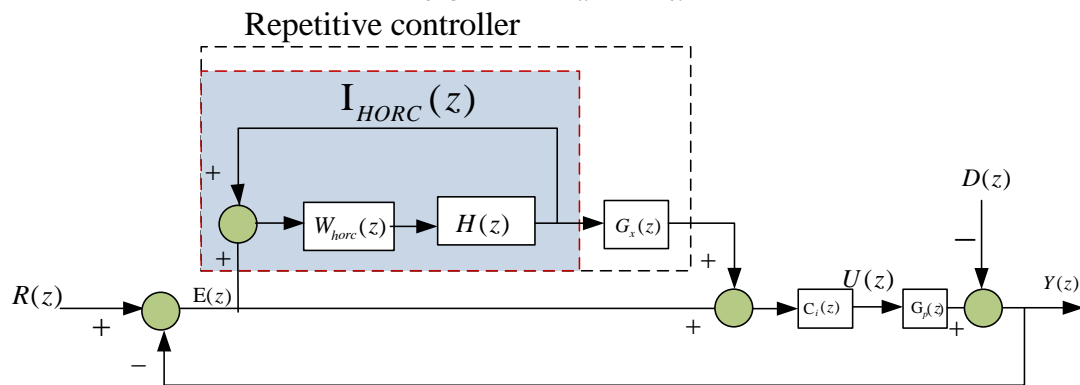


Fig. 6 plugin in High-order Repetitive controller

Fig. 6 is the control diagram of the plugin high order RC consists of the internal model of the, $I_{HORC}(z)$, low-pass filter $H(z)$ and the stabilizing controller $G_x(z)$. The low-pass filter guarantees the stability of the control by the attention of high order signals beyond the targeted frequency. A constant gain low than unity can be used instead of the low-pass filter. But it provides a lowers gain at the required points and will not suppress effectively at

higher frequencies as well. Finally, the learning controller, $C_i(z)$ and the plant model $G_i(z)$ are connected inseries to the HORC. The design procedure of HORC follows the same procedure as the other RC. The controller $C_i(z)$ must meet a sufficient margin for the loop without RC. The transform function of the system without HORC can be written as

$$G_{cl}(z) = \frac{C_i(z)G_i(z)}{1 + C_i(z)G_i(z)} \quad (5)$$

c) Tracking capacity of the first-, second-, and third-order Repetitive control

The performance of the tracking ability if the three odd RCs were evaluated using a mixed harmonic signal composed of the fundamental, third, fifth and seventh order harmonic frequencies

$$v(s) = v_1(s) + v_3(s) + v_5(s) + v_7(s) \quad (6)$$

The numerical value of the harmonic signal where $v_1(s) = 10 \sin(\omega t + \varphi_1) + 3.33 \sin(3\omega t + \varphi_3) + 0.2 \sin(5\omega t + \varphi_5) + 1.43 \sin(7\omega t + \varphi_7)$.

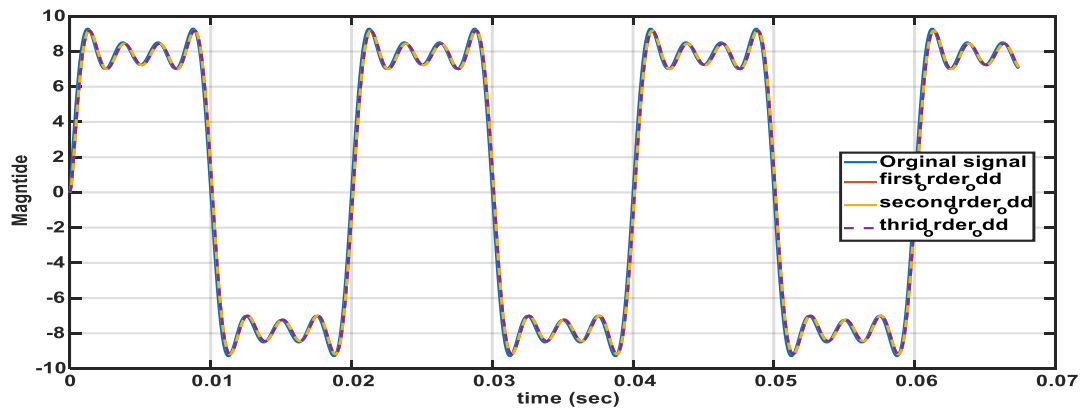


Fig. 7 Comparisons of tracking capacity of first-, second-, and third-order odd RCs.

The tracking performance of the three odd RC harmonic are good as shown in Fig. 7 and Fig. 8. Both odd RCs have shown a good tracking performance for a typical high distorted harmonic input signal.

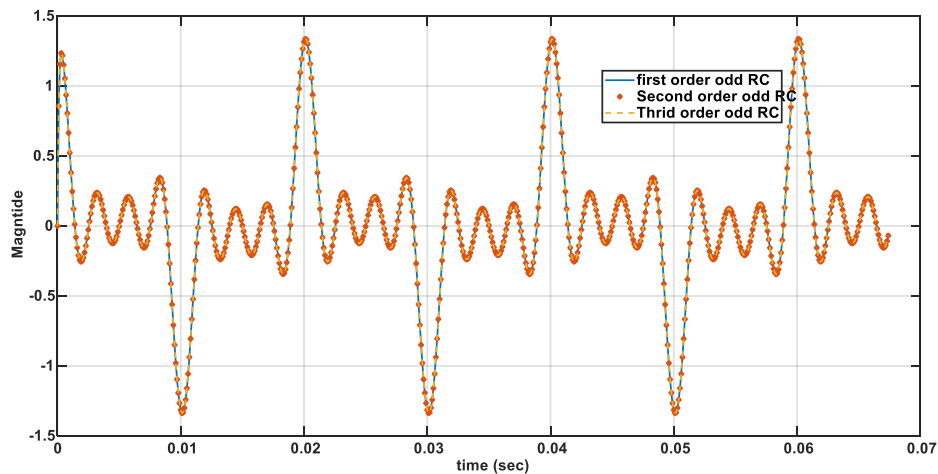


Fig. 8 Comparisons of error for tracking capacity of first-, second- and third-order odd RCs.

TABLE 2. SYSTEM DATA FOR SIMULATION

Description	Symbol	unit
Total capacity	S	5090 VA
Source voltage	V_{LL}	400 V
System frequency	f	50Hz
source resistance	r_s	0.1 Ω (0.4%)
Source inductance	L_s	0.3 mH (0.5%)
Feeder reactance	L_{AC}	3.2 mH (5%)
Load Power Factor	Pf	0.77
Dc bus voltage	V_{dc}	680V
Load capacitance	C_{dc}	2660 μ F
Filter reactance	L_f	3 mH

APF Rating = 2.4kVA,

IV. SIMULATION RESULTS AND DISCUSSION

The three-phase four-wire system was modeled in MATLAB/Simulink toolboxes with three single-phase nonlinear loads, three-phase nonlinear load and a linear resistive load. Two single-phase diode rectifiers with RC were used to simulate and design the proposed system. The two single-phase diode rectifiers with RC nonlinear loads

are differed only by load resistor (i.e. 75 Ω and 100 Ω and keeping the other parameter of the load constant) to modifying only the fundamental current without changing the active and reactive power for both loads. This helps to take in to account the performance of the proposed control for the zero-sequence harmonics only [29].

A four-leg IGBT based three-phase converter was used for circuits modeling with a common capacitor at the dc side. The simulation incorporates balanced and unbalanced loads of three-phase and/or single-phase nonlinear loads.

a) *Balanced three single-phase nonlinear loads without compensation*

A balanced three single-phase nonlinear RC loads are connected to the three-phase source system to collect the

harmonic spectrum of the RCs loads. The waveforms in Fig. 9 showed that the source current is highly distorted for single-phase type-1. Moreover, the current magnitude of the neutral current is the same as the current of the phase lines but the neutral line with zero-sequence harmonic distortion. The total source current harmonic distortion THD_i was found to be 80.32 %. Fig. 9 demonstrates that the system current harmonic for single-phase type-1 before the proposed control has been connected to the system.

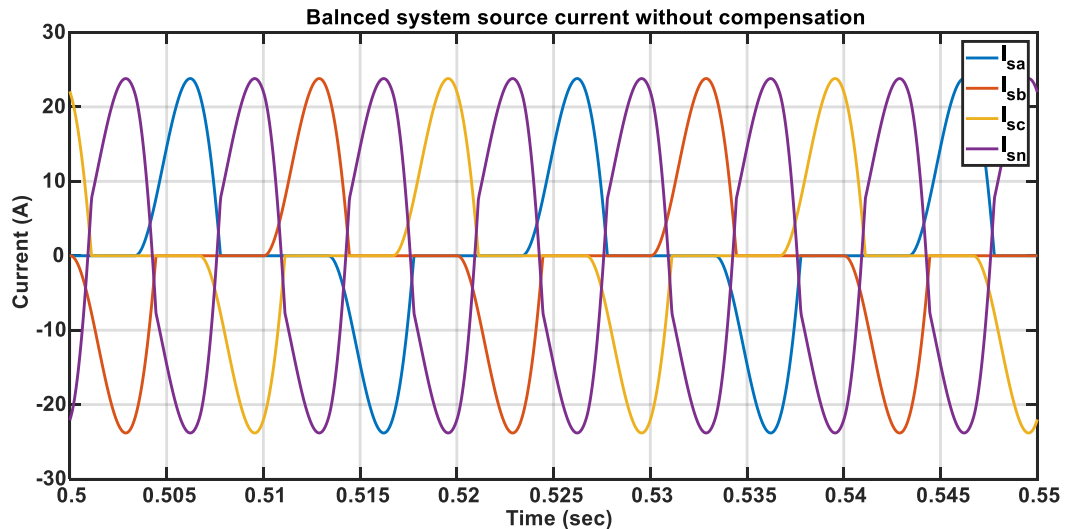


Fig. 9 Waveform of the source phase and neutral current with balanced three single-phase type-1 loads.

The neutral and phase current have the same magnitude of 7.52 A as demonstrated in Fig. 9. However, the phase lines have distorted with odd harmonics (i.e. 3rd = 71.53% 5th = 33.63% 7th = 9.71% and 9th = 7.99%) and a total current harmonic distortion of 80.32% as shown in Fig. 10. The neutral line only distorted with the zero-sequence current. Unfortunately, all the zero sequence

currents of the phase lines were not canceled out at the junction of neutral line instead they summed up and create burden for the system. Notice that the well-known theory of a balanced three-phase system has zero neutral current works only for linear loads. Therefore, balancing the three-phase loads will not guarantee zero neutral currents.

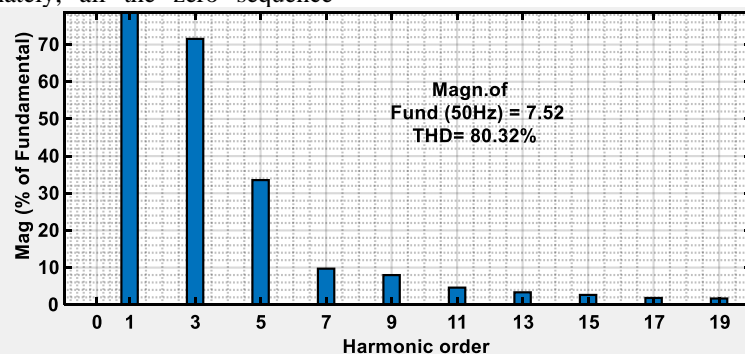


Fig. 10 Harmonic spectrum for the balanced three Single-phase type-1 type nonlinear loads.

b) *Balanced three single-phase nonlinear loads with compensation*

Fig. 11 depicted that a proposed control connected to the system with balanced three Single-phase type-1. The waveforms in Fig. 11 showed that the source current is composed from the current distortion caused by the

nonlinear load of single-phase type-1. Moreover, the current magnitude of the phases was reduced from 7.52 to 7.49 A and that of the neutral current reduced to almost zero current. The total source current harmonic distortion THD_i was reduced from 80.32 % to 4.20% as shown in Fig. 12.

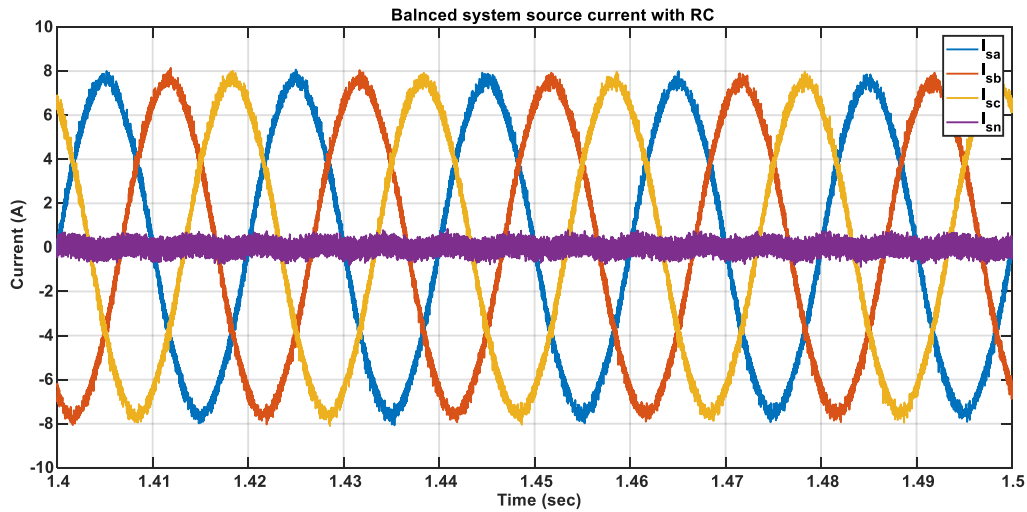


Fig. 11 The waveform of the source current with a balanced three Single-phase type-1 type nonlinear loads with RC compensation.

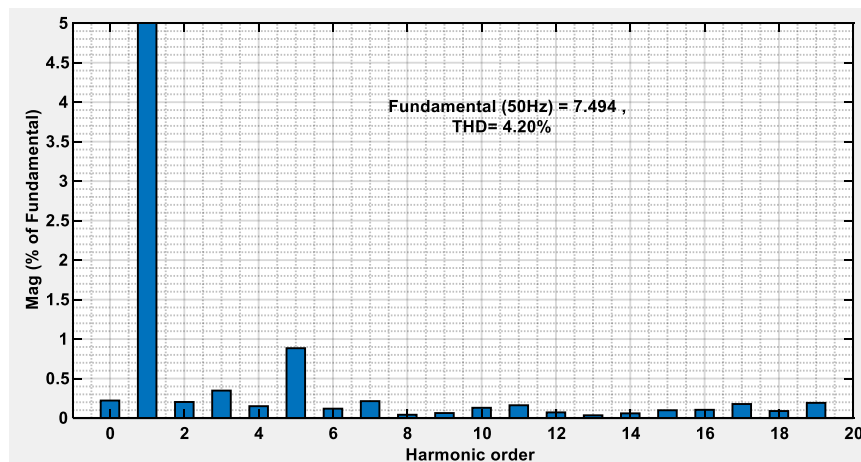


Fig. 12 Harmonic spectrum of the balanced three Single-phase type-1 type nonlinear loads with RC compensator.

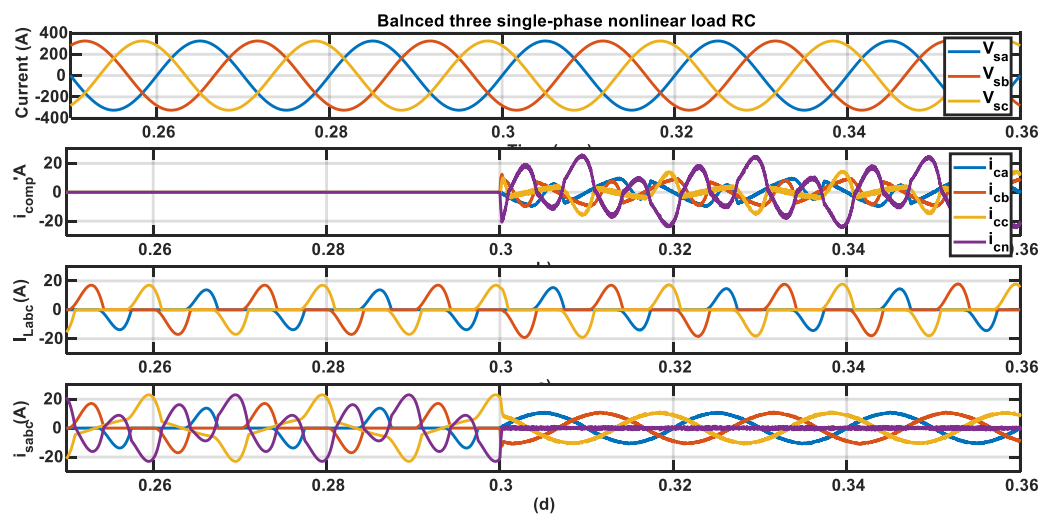


Fig. 13 The waveform of the source current with unbalanced three single-phase RCs nonlinear loads with second-order RC compensation connected to the system at 0.3 seconds. From top to down: (a) source voltage (V), (b) compensation current (A), (C) Load current (A) and (d) source current (A).

c) *Unbalanced load with three single-phase nonlinear and a resistive linear loads*

An unbalanced nonlinear system was formed by connecting phase-A with single-phase type-2, phase-B with Single-phase type-1 and phase-C with Single-phase type-1 with a resistive linear load at its ac side. The single-phase type-2 load changes the zero-sequence current of the phase-A and the linear resistive load changes the current of phase-C. The proposed RC compensator was connected to the system at 0.3 seconds as shown in Fig. 13. The waveform in Fig. 13 demonstrates from top to down that the source voltage (V), compensation current (A), the load current (A) and (d) source current (A). The unbalance and distortion of

the three-phase current was collected without the RC compensation (i.e. before 0.3 seconds). The total current harmonic distortion THDi were phase A, phase B and phase C 87.42%, 87.42%, and 47.91% respectively. However, after the RC compensator was connected (i.e. after 0.3 seconds) the system load become balanced and the total current harmonic THDi compensated phase A from 87.42% to 3.51%, phase B from 87.42% to 3.52% and phase C from 47.91% to 4.48% as shown in Table 3. These achieved a compensation of 83.89%, 83.9% and 43.43% in phase A, phase B, and phase C respectively. At the same time the neutral current reduced from 7.95 A (before compensation) and 0.03 A(after compensation).

Table 3 Current harmonic in an unbalance three single-phase nonlinear loads.

Unbalanced load with three single-phase nonlinear and a resistive linear loads									
	A			B			C		
	w/out	RC	Achieved	w/out	RC	Achieved	w/out	RC	Achieved
1	5.85	9.6	*	7.707	9.6	*	14.01	9.72	*
3	78.16	0.59	77.57	75.41	0.69	74.72	41.33	0.72	40.61
5	46.67	1.01	45.66	40.38	1.12	39.26	22.13	0.68	21.45
7	27.86	0.42	27.44	13.50	0.41	13.09	7.40	0.48	6.92
8.	7.43	0.18	7.25	7.96	0.13	7.83	4.37	0.06	4.31
11	6.28	0.18	6.10	6.28	0.07	6.21	3.44	0.12	3.32
THD	87.42%	3.51	83.89%	87.42%	3.52	83.9%	47.91%	4.48	43.43%
Neutral current reduce from 7.95A 0.03 A									

d) *Balanced Three-phase nonlinear loads.*

A balanced three-phase system is created with a three-phase type-3 connecting with the three-phase source. The current harmonic spectrum of the system and the waveforms are shown in Fig. 14. The total source current harmonic distortion THDi was found to be 49.45% before the compensation is connected to the system. However, after

the compensator is connected to the system at 0.3 seconds the system total harmonic reduced from 49.45% to 3.435 for the three-phases. The individual nonzero-sequence odd current harmonics are presented in Table 3. However, the zero-sequence currents are almost zero in balanced three-phase nonlinear loads.

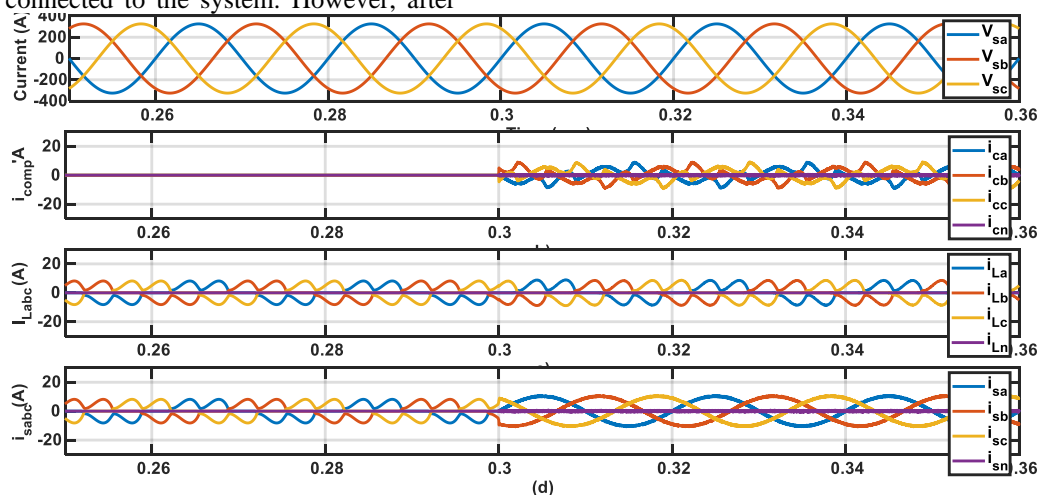


Fig. 14 The waveform of the source current with balanced Three-phase type-3 nonlinear loads with RC compensation connected to the system at 0.3 seconds. From top to down: (a) source voltage (V), (b) compensation current (A), (c) Load current (A) and (d) source current (A).

e) *unbalanced three-phase nonlinear loads.*

The unbalanced three-phase system is created with a three-phase type-3 and a linear load connecting with phase-C to the three-phase source. The unbalance nonlinear load creates an unbalance current of 5.64, 6.71, and 11.86 A for

phase-A, phase-B, and phase-C respectively. The zero-sequence current before the compensation connected to the system has a very neutral current of 6.48 A and reduced to 0.01A after compensation. The reduction of neutral current in the three-phase four-wire system has direct practical

implication in the lives of sensitive electronic devices, circulating current in Y- Δ distribution transformer ... etc. On the other hand, the current harmonic distortions before compensation in phase A, phase B and phase C were 50.55%, 49.46%, and 26.62 %. When the proposed compensator was connected to the system at 0.3 seconds,

the three-phase source current harmonic distortion reduced to from 50.55%, to 3.24% for phase A, from 49.46% to 3.17% for phase B and from 26.62% to 2.91 % for phase C. At the same time, the magnitude of the phase – C current reduce from 11.86 to 10.29 A after compensation.

Table 3 Current harmonic in a balance and unbalance three-phase rectifier loads.

Balanced three-phase nonlinear load			Unbalanced three-phase nonlinear loads					
	without APF	With APF	Without APF			With APF		
	A	A	A	B	C	A	B	C
1	5.95	10.27	5.64	6.71	11.86	10.28	10.29	10.29
3	*	*	14.97	5.26	8.26			
5	46.08	0.28	42.62	40.47	22.93	0.15	0.14	0.06
7	19.74	0.37	20.00	18.82	9.01	0.24	0.10	0.21
9	*	*	4.13	0.52	1.86			
11.	7.97	0.06	7.21	6.68	4.34	0.03	0.03	0.02
13	4.47	0.13	4.08	6.70	1.76	0.13	0.04	0.09
THD	49.45%	3.43%	50.55%	49.46	26.62%	3.24%	3.17%	2.91%
Neutral			The neutral current reduced from 6.48 to 0.01.					

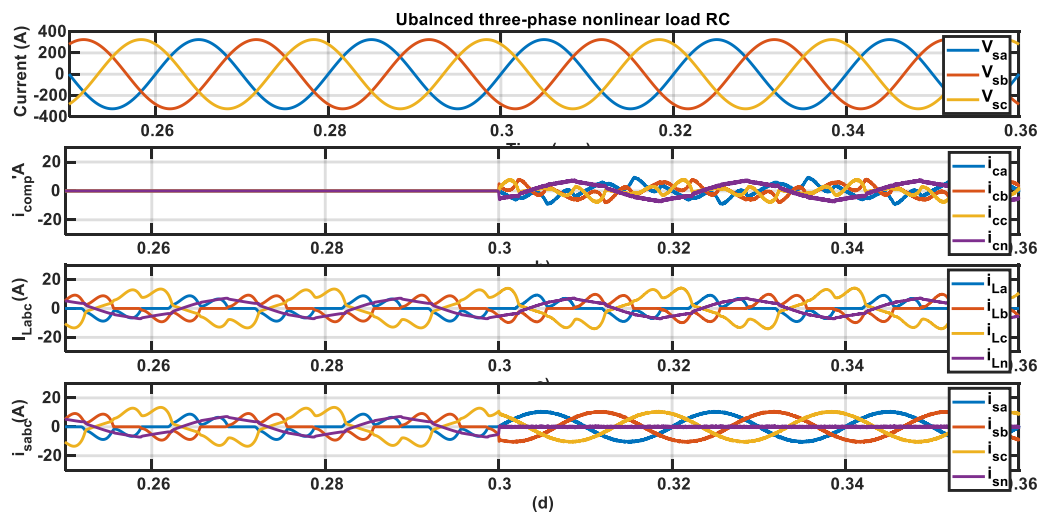


Fig. 15 The waveform of the source current with unbalanced three-phase RCs nonlinear loads with second-order RC compensation connected to the system at 0.3 seconds. From top to down: (a) source voltage (V), (b) compensation current (A), (C) Load current (A) and (d) source current (A).

CONCLUSION

The repetitive control can be implemented in the first-, second- and third-order harmonics. The first order odd repetitive drastically fails for any frequency variation from the center frequency. The third-order odd harmonics have wider and higher gains around the fundamental frequency. However, it is unsuitable at higher frequencies. The second-order fond to be the optimal odd repetitive control for odd harmonic frequencies. Its sensitivity magnitude response has deeper and wider notches at the fundament frequencies. Moreover, it has a high gain for lower dominant frequencies and decreases its gain evenly for unwanted higher odd fundamental frequencies. Therefore, the performance of the second-order odd RC was intensively investigated for a three-phase four-wire active power filter against the current harmonics, unbalanced and

neutral current compensation. The result indicates that the second-order odd RC compensates the total current harmonic distortion THDi from 87.42 % to about 3.52% for unbalanced single-phase nonlinear loads. At the same time, it also compensated the neutral current from the phase current level to a negligible current level. In the case of the balanced three-phase nonlinear loads, it achieved a total current harmonic compensation of 49.45% to 3.43% and from 50.55% to 3.24% for unbalanced three-phase nonlinear loads.

ACKNOWLEDGMENTS

The project is supported by the National Natural Science Foundation of China (No.51777025); and the Fundamental Research Funds for the Central Universities (No.DUT19ZD219).

REFERENCE

- [1] S. Inoue, T. Shimizu, and K. Wada, "Control Methods and Compensation Characteristics of a Series Active Filter for a Neutral Conductor," *IEEE Transactions on Industrial Electronics*, vol. 54, pp. 433-440, 2007.
- [2] A. Javadi, A. Hamadi, L. Woodward, and K. Al-Haddad, "Experimental Investigation on a Hybrid Series Active Power Compensator to Improve Power Quality of Typical Households," *IEEE Trans. Industrial Electronics* vol. 63, Aug. 2016.
- [3] W. Song, S. Wang, C. Xiong, X. Ge, and X. Feng, "Single-phase three-level space vector pulse width modulation algorithm for grid-side railway traction converter and its relationship of carrier-based pulse width modulation," *IET Electrical Systems in Transportation*, vol. 4, pp. 78-87, 2014.
- [4] Y. Fu, Y. Li, Y. Huang, X. Lu, K. Zou, C. Chen, et al., "Imbalanced Load Regulation Based on Virtual Resistance of A Three-Phase Four-Wire Inverter for EV Vehicle-to-Home Applications," *IEEE Transactions on Transportation Electrification*, vol. 5, pp. 162-173, 2019.
- [5] A. Javadi and K. Al-Haddad, "A Single-Phase Active Device for Power Quality Improvement of Electrified Transportation," *IEEE Trans. Industrial Electronics*, vol. 62, pp. 3033-3041, 2015.
- [6] J. Hurng-Liahng, W. Jinn-Chang, W. Kuen-Der, C. Wen-Jung, and C. Yi-Hsun, "Analysis of zig-zag transformer applying in the three-phase four-wire distribution power system," *IEEE Transactions on Power Delivery*, vol. 20, pp. 1168-1173, 2005.
- [7] J. C. Balda, A. R. Oliva, D. W. McNabb, and R. D. Richardson, "Measurements of neutral currents and voltages on a distribution feeder," *IEEE Transactions on Power Delivery*, vol. 12, pp. 1799-1804, 1997.
- [8] F. H. M. Rafi, M. J. Hossain, and J. Lu, "Improved Neutral Current Compensation With a Four-Leg PV Smart VSI in a LV Residential Network," *IEEE Transactions on Power Delivery*, vol. 32, pp. 2291-2302, 2017.
- [9] A. Liew, "Excessive neutral currents in three-phase fluorescent lighting circuits," *IEEE Transactions on Industry Applications*, vol. 25, pp. 776-782, 1989.
- [10] P. Rodríguez, J. I. Candela, A. Luna, L. Asiminoaei, R. Teodorescu, and F. Blaabjerg, "Current Harmonics Cancellation in Three-Phase Four-Wire Systems by Using a Four-Branch Star Filtering Topology," *IEEE Transactions on Power Electronics*, vol. 24, pp. 1939-1950, 2009.
- [11] J. Wu, H. Jou, H. Hsiao, and S. Xiao, "A New Hybrid Power Conditioner for Suppressing Harmonics and Neutral-Line Current in Three-Phase Four-Wire Distribution Power Systems," *IEEE Transactions on Power Delivery*, vol. 29, pp. 1525-1532, 2014.
- [12] C. A. Quinn and N. Mohan, "Active filtering of harmonic currents in three-phase, four-wire systems with three-phase and single-phase nonlinear loads," in *[Proceedings] APEC '92 Seventh Annual Applied Power Electronics Conference and Exposition*, 1992, pp. 829-836.
- [13] C. A. Quinn, N. Mohan, and H. Mehta, "A four-wire, current-controlled converter provides harmonic neutralization in three-phase, four-wire systems," in *Proceedings Eighth Annual Applied Power Electronics Conference and Exposition*, 1993, pp. 841-846.
- [14] P. Fang Zheng, G. W. Ott, and D. J. Adams, "Harmonic and reactive power compensation based on the generalized instantaneous reactive power theory for three-phase four-wire systems," *IEEE Transactions on Power Electronics*, vol. 13, pp. 1174-1181, 1998.
- [15] S. J. Chiang, W. J. Ai, and F. J. Lin, "Parallel operation of capacity-limited three-phase four-wire active power filters," *IEE Proceedings - Electric Power Applications*, vol. 149, pp. 329-336, 2002.
- [16] P. Acuna, L. Moran, M. Rivera, J. Dixon, and J. Rodriguez, "Improved Active Power Filter Performance for Renewable Power Generation Systems," *Power Electronics, IEEE Transactions on*, vol. 29, pp. 687-694, 2014.
- [17] M. Aredes, J. Hafner, and K. Heumann, "Three-phase four-wire shunt active filter control strategies," *IEEE Transactions on Power Electronics*, vol. 12, pp. 311-318, 1997.
- [18] H. Akagi, Y. Kanazawa, and A. Nabae, "Instantaneous Reactive Power Compensators Comprising Switching Devices without Energy Storage Components," *IEEE Transactions on Industry Applications*, vol. IA-20, pp. 625-630, 1984.
- [19] V. Soares, P. Verdelho, and G. D. Marques, "An instantaneous active and reactive current component method for active filters," *IEEE Transactions on Power Electronics*, vol. 15, pp. 660-669, 2000.
- [20] M. I. M. Montero, E. R. Cadaval, and F. B. Gonzalez, "Comparison of Control Strategies for Shunt Active Power Filters in Three-Phase Four-Wire Systems," *IEEE Transactions on Power Electronics*, vol. 22, pp. 229-236, 2007.
- [21] Y. Suresh, A. K. Panda, and M. Suresh, "Real-time implementation of adaptive fuzzy hysteresis-band current control technique for shunt active power filter," *IET Power Electronics*, vol. 5, pp. 1188-1195, 2012.
- [22] R. Grino, R. Cardoner, R. Costa-Castello, and E. Fossas, "Digital Repetitive Control of a Three-Phase Four-Wire Shunt Active Filter," *IEEE Transactions on Industrial Electronics*, vol. 54, pp. 1495-1503, 2007.
- [23] G. Pandove and M. Singh, "Robust Repetitive Control Design for a Three-Phase Four Wire Shunt Active Power Filter," *IEEE Transactions on Industrial Informatics*, vol. 15, pp. 2810-2818, 2019.
- [24] B. G. Lemma, M. Laio, and Duan Xiongying, "A Three-Phase Three-Level T-Type Converter for Three-Phase Four-Wire (3P4W) Active Power Filter," *International Journal Of Engineering Research & Technology (IJERT)* vol. 09, pp. 493-498, 2020.
- [25] D. Shen and P. W. Lehn, "Fixed-frequency space-vector-modulation control for three-phase four-leg active power filters," *IEE Proceedings - Electric Power Applications*, vol. 149, pp. 268-274, 2002.
- [26] W. Lu, K. Zhou, D. Wang, and M. Cheng, "A Generic Digital $\sin k\pi m\pi$ -Order Harmonic Repetitive Control Scheme for PWM Converters," *IEEE Transactions on Industrial Electronics*, vol. 61, pp. 1516-1527, 2014.
- [27] R. Costa-Castello, R. Grino, and E. Fossas, "Odd-harmonic digital repetitive control of a single-phase current active filter," *IEEE Transactions on Power Electronics*, vol. 19, pp. 1060-1068, 2004.
- [28] G. A. Ramos, R. Costa-Castelló, J. M. Olm, and R. Cardoner, "Robust high-order repetitive control of an active filter using an odd-harmonic internal model," in *2010 IEEE International Symposium on Industrial Electronics*, 2010, pp. 1040-1045.
- [29] E. L. L. Fabricio, S. C. S. Júnior, C. B. Jacobina, and M. B. d. R. Corrêa, "Analysis of Main Topologies of Shunt Active Power Filters Applied to Four-Wire Systems," *IEEE Transactions on Power Electronics*, vol. 33, pp. 2100-2112, 2018.
- [30] B. A. Francis and W. M. Wonham, "The internal model principle for linear multivariable regulators," *Applied Mathematics & Optimization*, vol. 2, pp. 170-194, 1975.
- [31] M. Steinbuch, "Brief Paper Repetitive control for systems with uncertain period-time," *Automatica* 38, vol. 38, pp. 2103-2109, 2002.