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Integration of AI with reduced order generalized integrator controller for power system harmonic reduction

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Abstract

The increased use of electronics for control and use of nonlinear type loads by consumers in the present power system network are injecting harmonics into the power signal, due to which the power quality issue has become more challenge for the present researchers. In this work, the reduced order generalized integrator (ROGI) and fuzzy logic control (FLC) are collectively used to reduce the current harmonics in the power system. FLC-SVM technique is used to maintain the process of SAF—Shunt active filter with fixed switching frequency. This proposed control technique consists of control loop for current to have fast and effective control. The Proportional Resonant controller is used to have control on voltage for a slow and effective control process which is also used to compensate reactive power. The shunt active filter is designed with the help of ROGI by integrating PI controller for fuzzy-based SVM to reduce the current harmonics on the load side. The results are achieved in MATLAB/SIMULINK software.

KEYWORDS

fuzzy logic, harmonic distortion, proportional resonant, reduced order generalized integrator (ROGI), shunt active filter, space vector modulation

1 | INTRODUCTION

In the current power system network, various power electronic devices are widely used for different applications, such as inverter, rectifier, and so on.[1,2] These electronic devices inject harmonics into the power lines and result in distortion in supply voltage and current. This leads to the decrease in power quality. The distribution line becomes less efficient as the voltage and current distortions are increased and it ends in poor power factor. The compensation of harmonics is done by using the shunt active power filter (SAPF) and many structures exist for the SAPF in literature. Many control techniques exist for control of SAPF and P-Q method[3,4] proposed in 1984 provides the constant active power in demand and does not supply the zero sequence component. A hybrid -SAF filter was designed in Reference 3 to reduce harmonics in utility system. The circuit is designed using two SAF connected at point of common coupling, to reduce the harmonics. The positive inductance is used to tune the passive filter. A SAPF[4] was described to improve the power quality.

The synchronous reference frame (SRF) method[5,6] had the direct axis and quadrature axis which are found by using the angle θ of frame obtained from P-Q theory. Unified SAPF (USAPF)[5] was used to reduce the harmonics by interfacing and operating under both voltage source converter and current source converter simultaneously. Passive elements which are small in size and low in weight than conventional APF are used in converters to find frequency of switching in both the converters. The unity power factor (UPF) control technique[7,8] makes the source to view the load and compensator as a resistance. In this, the current from source and point of common coupling (pcc) should follow each and are to be in phase with each other. The P-Q, SRF, and UPF methods are used in perfect harmonic compensation method[9] for compensating the harmonic currents eliminating the unbalance condition. SAF controlled by linear Quadratic Regulator[7]-based switching controller was developed for harmonic mitigation also provides solution for parallel resonance problem. Multilevel SAF was described in Reference 6 was used for mitigating the current harmonics along with reduction of switching losses. This multilevel SAF is controlled by fuzzy to improve the voltage behaviors of the floating capacitors at dynamic and steady state. Reduced Order Generalized Integrator (ROGI),[10] FLC,[11] and PR—Proportional Resonant Controller[9] are the proposed control techniques used in Space vector modulation (SVM) technique. ROGI controller[10] computations are less by 50% than the second order generalized integrator[12] and can be applied under stationary reference frame without transformation to rotational coordinate system. These techniques have better harmonic reduction capacity. In this article a controller is interfaced with SAF to enhance reactive power compensation. The performance analysis of the nonlinear load system and source current harmonic compensation process and proposed control techniques are analyzed in MATLAB/SIMULINK environment.

The major contribution of the article is given as follows. Section 2 focused on the SAPF. Section 3 describes the proposed system, Section 4 gives the simulation results of the proposed system, and Section 5 gives the conclusion part of the article that describes the concluding point considering the obtained results.

2 | SHUNT ACTIVE POWER FILTER (SAPF)

Nonlinear masses like variable speed drives, uninterrupted power provides harmonics and each one reasonably rectifies and results in nonsinusoidal source of current.[3] SAPF shown in Figure 1

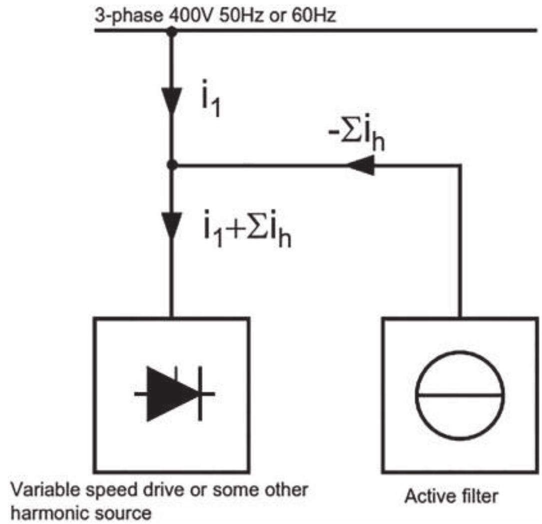

FIGURE 1 Nonlinear load with SAF

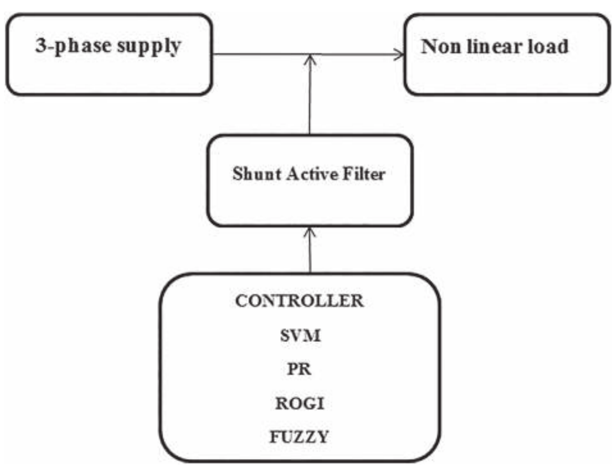

FIGURE 2 Block diagram of proposed method

works as a current supply such that the currents are same as harmonics and are in antiphase to the harmonics present in the system. When these currents are injected into system, they will suppress the harmonics which results in the improvement of power quality of system.[4] There are two active power filters, series and shunt. The series active power filter suppresses the voltage harmonics of the system and the SAPF reduces the current harmonics of system. As nonlinear loads add harmonics in current, the SAPF is considered for the proposed work.

3 | PROPOSED METHODOLOGY

The block diagram of proposed model is shown in Figure 2. The voltage source is connected to nonlinear load by means of a transmission line system. Due to the nonlinear load connected to system, the source waveform gets distorted and interrupts the whole power system performance. The appropriate reactive power compensation is required to make the system to function continuously without affecting the source current. SAPF is deployed for reactive power compensation. The SVM is used to provide gating pulse to the Voltage Source Inverter (VSI). The DC-Link voltage provides input to the VSI. The filter is required to reduce the harmonic content in the VSI. This compensation system prevents the source current from the negative effects produced due to the nonlinear load thus reducing the harmonic distortion.

3.1 | Proposed controller

The literature has different control techniques for generating the trigger pulses to the converter switch used for active power filters for the topology shown in Figure 2. Finally, the three phase currents i_f (1, 2, 3) must follow the reference three phase currents i_{fr} (1, 2, 3) with the smallest possible error. The ripple in the current waveform from filters should be as small as possible and also the switching losses should be minimized to a low value. In existing works, the synchronized on-off current control methods are preferred for the active power filters for its easier implementation on slower microcontrollers compared to conventional PI used for SVM. Also, the commutation frequency of synchronized on-off current control methods is a bit lower than conventional PI. The proposed controllers are introduced to provide the solution for this problem. Combination of SVM, PR, and ROGI & FUZZY controllers are used to enhance the performance of the nonlinear load connected SAF.

3.2 | Proportional resonant (PR) controller

PR controller is same as PI Controller consisting of positive and negative sequence rotating frames. This controller uses these rotating frames and can track the sinusoidal reference wave of variable frequency at zero error during steady state to enhance the power quality. The transfer function of PI controller in stationary frame applied in a positive sequence SRF axes is obtained by shifting the frequency by $-h\omega1$ for all frequencies that is, by substituting s with $s-h\omega1$ as shown in Equation (2). Similarly, for negative sequence components, each frequency is shifted by $h\omega1$ substituting s with $s+h\omega1$ as shown in Equation (3) to get the transfer function of PI in stationary frame applied in a negative-sequence SRF axes. Addition of Equations (2) and (3) results in the following transfer function of the PR controller given in Equation (4).

$$G_{\mathrm{PI}}^{+} = K_P + \frac{K_I}{s} \tag{1}$$

$$G_{\mathrm{PI}_h}^{+} = G_{\mathrm{PI}_h}(s - jh\omega1) = K_{P_h} + \frac{K_{I_h}}{s - jh\omega1} \tag{2}$$

$$G_{\mathrm{PI}_h}^{-} = G_{\mathrm{PI}_h}(s + jh\omega1) = K_{P_h} + \frac{K_{I_h}}{s + jh\omega1} \tag{3}$$

$$G_{\mathrm{PR}_h} = G_{\mathrm{PI}_h}^{-} + G_{\mathrm{PI}_h}^{+} = K_{P_h} + \frac{K_{I_h}}{s^2 + h^2\omega1^2} \tag{4}$$

The gain of unity and zero phase shift is achieved in closed loop at the resonant frequency hω1 for which G_{PR_h}(s) gives an infinity gain. This adds an advantage of not requiring additional damping terms. The resonant component ω1(s) provides infinity gain for the G_{PR_h}(s) controller and is a Laplace transform of cosine function for better stability. Basically it can control the dynamics factors of the system in terms of bandwidth phase and gain margin. Harmonic compensation and harmonic regulation can be violated without any stability limits.[9]

3.3 | PIPR reduced order generalized integrator (PIPR ROGI)

ROGI is defined as a complex SVM system, complex co-efficient have coupled by imaging gain values among the $\alpha\beta$ axis and the integrator reference frames (dq) has been rotated with rotation angle also obtain the stationary reference frame.[10] The three phase signal is represented in stationary alpha-beta frame using Equation (5).

$$x_{\alpha\beta}(t) = x_{\alpha}(t) + jx_{\beta}(t) = \sum_{n=1}^{\alpha}(X_n^{+}e^{jn\omega_1 t} + X_n^{-}e^{jn\omega_1 t}) \tag{5}$$

$$x_{dq}(t) = x_{\alpha\beta}(t)e^{-jn\omega_1 t} = X_1^{+} + \sum_{n=k-1}^{\alpha}(X_n^{+}e^{jn\omega_1 t} + X_n^{-}e^{jn\omega_1 t}) \tag{6}$$

In Equation (6), the DC component X_1^{+} is the positive sequence signal of fundamental component and to have an infinite gain of it in AC fundamental, an integrator is added as in Equation (7).

$$y_{dq}^{+}(s) = x_{dq}^{+}(s).\frac{k_i}{s} \tag{7}$$

Adding Equations (6) and (7) results in Equation (9)

$$y_{\alpha\beta}^{+}(s + j\omega 1) = x_{\alpha\beta}^{+}(s + j\omega 1).\frac{k_i}{s} \tag{8}$$

Transforming the integrator back to stationary frame $\alpha\beta$ by replacing s in Equation (8) by $s - j\omega 1$

$$y_{\alpha\beta}^{+}(s) = x_{\alpha\beta}^{+}(s).\frac{k_i}{s + j\omega 1} \tag{9}$$

Expanding Equation (9) into α and β components results the ROGI controller (10). The block diagram of ROGI controller is shown in Figure 3.

$$\begin{aligned} y_{\alpha}^{+}(s) &= \frac{1}{s}[k_i x_{\alpha}(s) - \omega_1.y_{\beta}(s)] \\ y_{\beta}^{+}(s) &= \frac{1}{s}[k_i x_{\beta}(s) - \omega_1.y_{\alpha}(s)] \end{aligned} \tag{10}$$

ROGI controller is mathematically very strong and efficient; it is three phase arrangement and has less computational time and avoids the additionally required transformations.

The stationary frame can also be achieved using resonant controller with asymptotic AC reference tracking. The commonly used resonant controllers are: proportional resonant,[13]

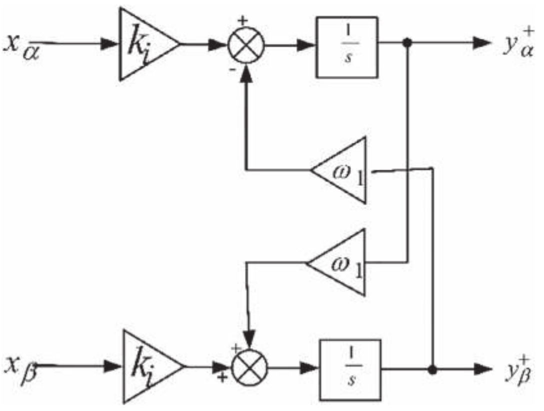

FIGURE 3 Block diagram of ROGI controller

proportional integral resonant PIR[14] and first order P-ROGI regulator.[15] The integral in PR that is, PIR tracks the DC component present in AC current, which is important for uninterruptible power supplies, AC motor drives, and so on. The P-ROGI is first order whereas PR is second order controller but the same performance of PR controller can be obtained using P-ROGI controller. The P-ROGI controller transfer function is shown in Equation (14).

$$G_{\text{P-ROGI}}(s) = \frac{y(s)}{e(s)} = k_p + \frac{k_R}{s - j\omega_n} \tag{11}$$

PR and P-ROGI controller from Equations (4) and (11) cannot control the DC current component of AC component which can effect with its presence in various applications. This DC component can be detected by applying integral control to P-ROGI controller, called as PI-ROGI controller and can have the same performance with increase in order. The transfer function of PI-ROGI controller is shown in Equation (12). The block diagram of P-ROGI and PI-ROGI controllers are shown in Figures 4 and 5.

$$G_{\text{PI-ROGI}}(s) = \frac{y(s)}{e(s)} = k_p + \frac{k_i}{s} + \frac{k_R}{s - j\omega_n} \tag{12}$$

3.4 | Fuzzy controller

In this proposed arrangement, the ROGI act as a current controller, also provide the satisfactory performance. It gives the signals to the fuzzy controller, while the fuzzy is an error value and it is generated by the current controller. Fuzzy logic offers the formal methodology of manipulating, for a human's heuristic knowledge; the logic constructed by nonlinear controllers via the user function of heuristic information.[11] This combination of ROGI controller with Fuzzy gives better performance than ROGI alone. The membership functions used in FLC are shown in Table 1.

The FLC receives two inputs, that is, “error” and “rate of error” and produces “output” according to the rule base. The rule base consists of 49 rules as mentioned in Table 1. The variables “error,” “rate of error,” and “output” take on the following values: positive large (PL), medium positive (MP), small positive (SP), zero (Z), large negative (LN), medium negative (MN), and small negative (SN). The triangular type member ship function is used for all variables. Mamdani type

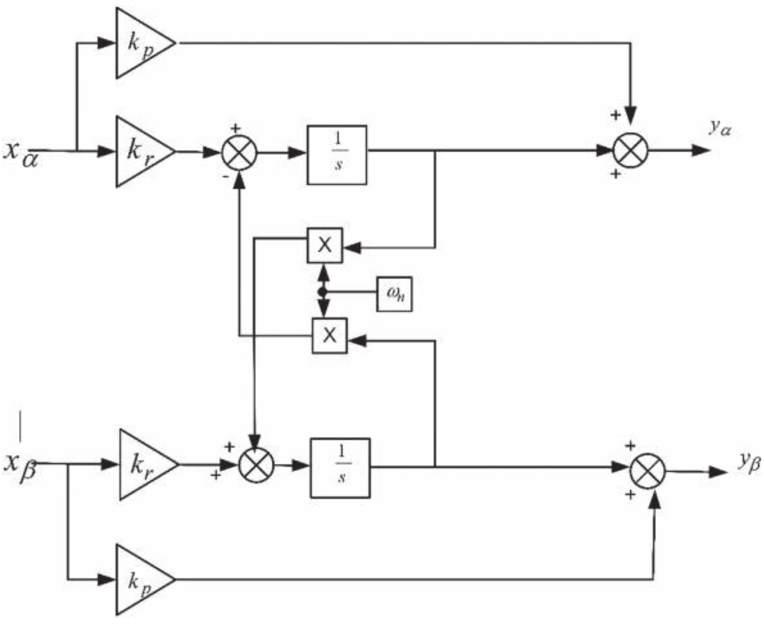

FIGURE 4 Block diagram of P-ROGI controller

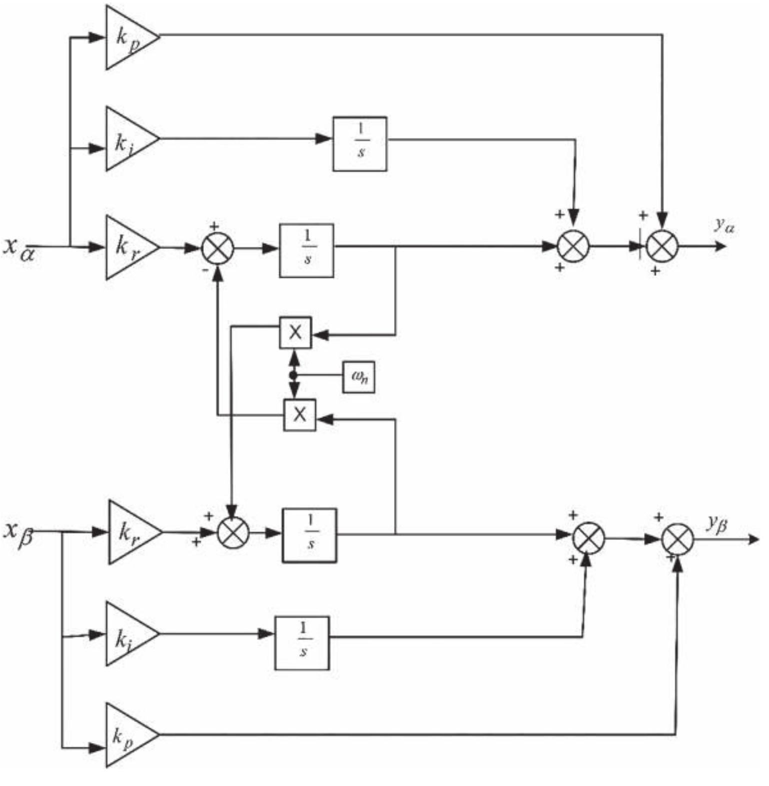

FIGURE 5 Block diagram of PI-ROGI controller

TABLE 1 FLC-membership function

Error								
		LN	MN	SN	Z	SP	MP	LP
Rate of change of error								
	LN	LN	LN	LN	LN	MN	SN	Z
	NM	LN	LN	LN	NM	SM	Z	SP
	SN	LN	MN	MN	SN	Z	SP	MP
	Z	LN	SN	SN	Z	SP	MP	LP
	SP	MN	Z	Z	PS	MP	LP	LP
	MP	SN	SP	SP	MP	LP	LP	LP
	LP	Z	MP	MP	LP	LP	LP	LP

TABLE 2 Circuit parameters

Voltage	400 V rms	Frequency	50 Hz
R_1	20 Ω	R_2	10 Ω
L_1	25 mH	L_2	9 mH
C_1	1000 μF	C_2	1000 μF
Cdc_1	80 μF	R_L	348 Ω
Cdc_2	80 μF	L_L	35 mH

fuzzy is employed along with "centroid" defuzzification. The range of variables is selected from experimental analysis.

4 | RESULTS

The shunt active filter is designed with the help of ROGI by integrating PI controller for fuzzy-based SVM to reduce the current harmonics on the load side. The parameters used for the simulation of SAF are shown in Table 2. The implementation of SAF for nonlinear load with ROGI-PI-fuzzy controller is shown in the figure of Appendix 1. The dc link capacitor voltage is kept higher compared to the maximum value of the source voltage to make the inverter as an active power filter. The single phase voltage and current waveform measured on the nonlinear load side are shown in Figure 6, in which the voltage and current has in phase with each other thus indicating that the power factor is maintained at good value with the proposed system.

The source current waveform and FFT of the same obtained with ROGI, P-ROGI, PI-ROGI, PI-ROGI with fuzzy controllers are shown in Figures 7-11, and the THD values for the respective controllers are shown in Table 3. It is observed that the thermal harmonic distortion (THD) with only ROGI controller is 2.76% and with the introduction of proportional and proportional integral into ROGI controller, the THD of source current is 2.42% and 2.70%, respectively. Thus, the PI-ROGI controller shows the same approximately the same performance in the quality of source current compared to P-ROGI controller even though PI-ROGI is higher in order than P-ROGI. But, once the PI-ROGI controller output is given to fuzzy system to reduce the errors for pulse

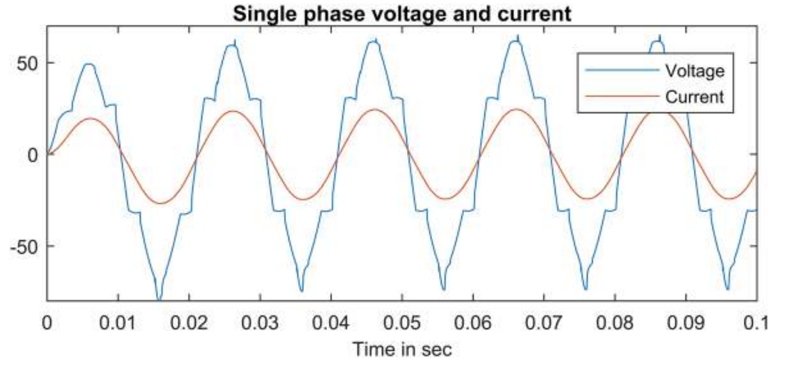

FIGURE 6 Load side single phase voltage and current [Color figure can be viewed at wileyonlinelibrary.com]

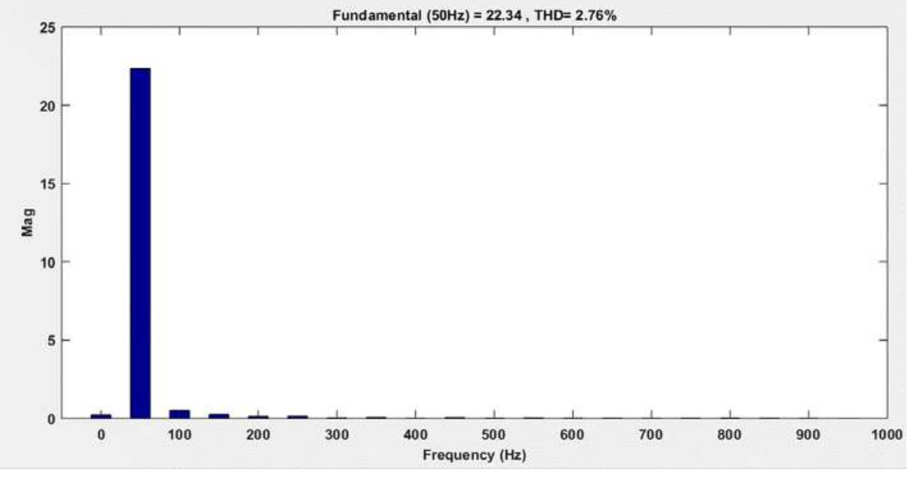

FIGURE 7 THD of load current using ROGI controller [Color figure can be viewed at wileyonlinelibrary.com]

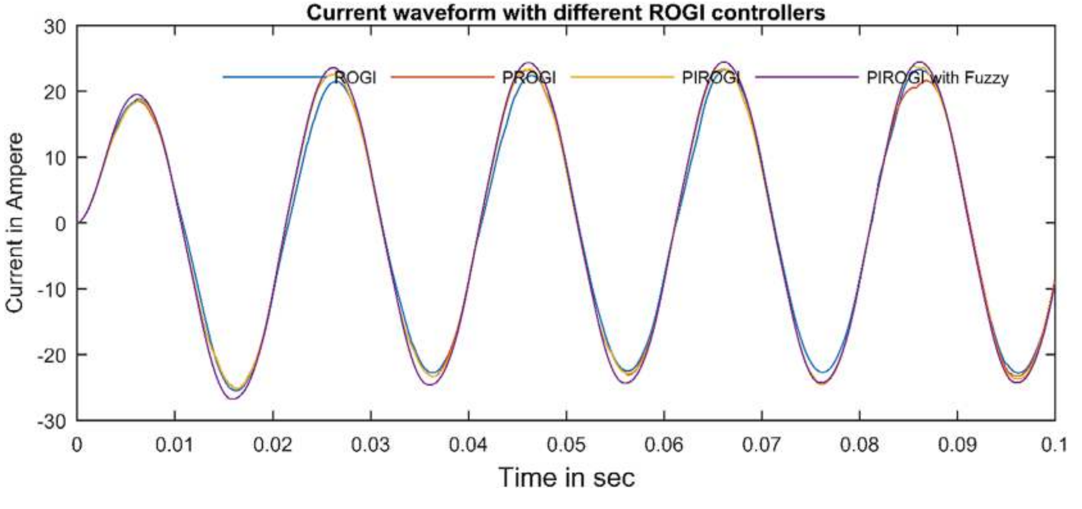

FIGURE 8 FFT analysis of load current using PR-ROGI [Color figure can be viewed at wileyonlinelibrary.com]

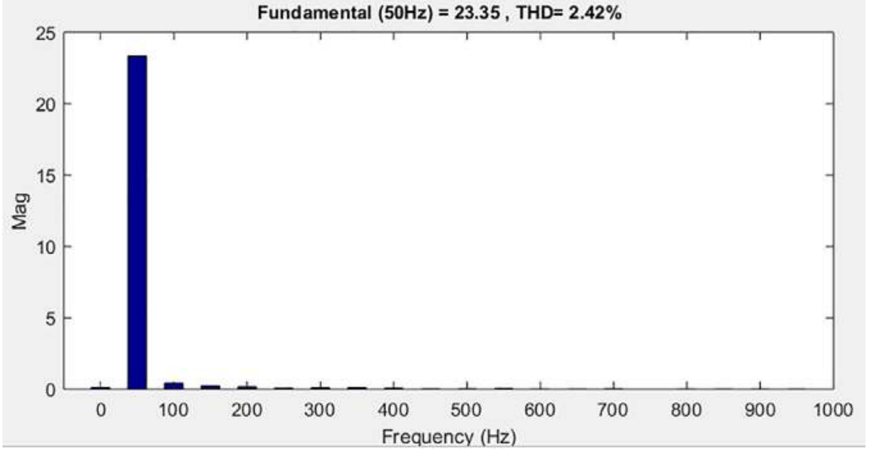

FIGURE 9 THD of load current using PR-ROGI [Color figure can be viewed at wileyonlinelibrary.com]

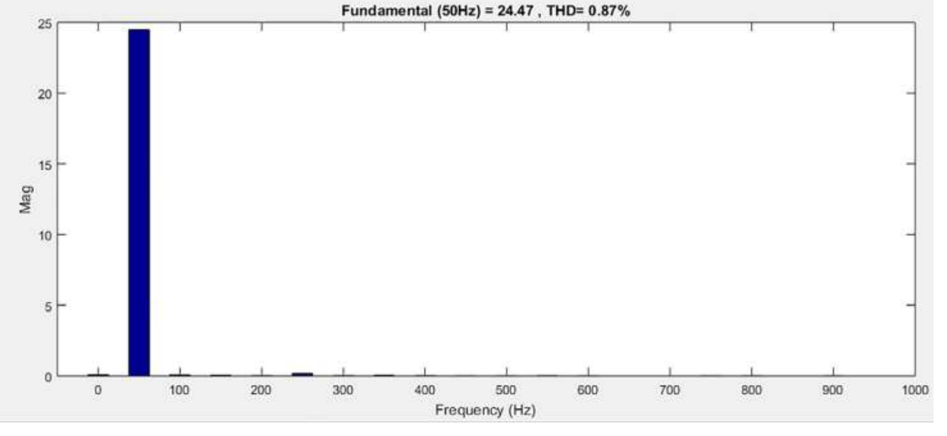

FIGURE 10 THD of load current using PI-ROGI [Color figure can be viewed at wileyonlinelibrary.com]

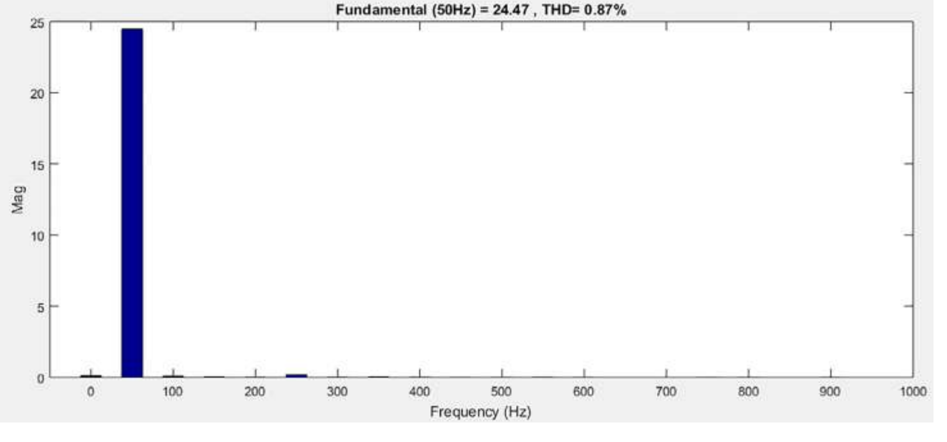

FIGURE 11 THD of load current using PI-ROGI Fuzzy Controller [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Source current THD comparison

Method	Source current THD in %
ROGI	2.78%
PI-ROGI	2.70%
PR-ROGI	2.42%
PI-ROGI with fuzzy	0.80%

width modulation, the source current THD has come down from 2.70% to 0.87%. This clearly says that the quality of source current with PI-ROGI fuzzy controller is better that PI-ROGI controller.

5 | CONCLUSION

In this article the ROGI and FLC are deployed to obtain better compensated output voltage with reduced current harmonics. FLC SVM proposed to operate the SAF with fixed switching frequency while the harmonics are reduced and better power quality is achieved on nonlinear load side. The results are achieved by MATLAB environment. The performances are analyzed under nonlinear load condition and with and without control technique is performed. Thus the proposed control technique achieved better THD −0.82% and better power factor Correction.

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