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ARTIFICIAL NEURAL NETWORK BASED SYNCHRONOUS REFERENCE FRAME THEORY IN THE dq0 AXES FOR REFERENCE HARMONIC CURRENTS GENERATION OF A FOUR LEG SHUNT ACTIVE POWER FILTER

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Key words: Four-leg shunt active power filter, Synchronous reference frame (SRF) theory, Artificial neural network (ANN), Backstepping, 3D space vector modulation (SVM), Harmonics, Zero sequence current.

This paper presents the modelling and simulation of a three-phase four leg shunt active power filter (SAPF) using artificial neural network (ANN) based synchronous reference frame theory (SRF) in the dq0-axes for power quality improvement. It is used for harmonics and zero-sequence current elimination, and reactive power compensation under unbalanced nonlinear loads. Backstepping regulators are used to control the reference currents and the dc bus voltage of four leg inverter based SAPF to robustness, stabilizing the system and to improve the response and to reduce the overshoot and undershoot of traditional proportional-integral (PI). The success of the proposed control is demonstrated through simulation using MATLAB SIMULINK.

1. INTRODUCTION

The degradation of power quality distribution system is the major problem in present day [1, 2]. Single phase non-linear loads such as single phase rectifiers, large number of low-power electronic-based appliances, speed drives, electric traction, are the major sources of harmonics and zero-sequence current, these generate significant distortions in the three-phase four-wire electrical networks and causing power quality problems such as production loss, equipment damage or even be destructive to human health [2, 3]. Various solution power devices and filters are used to eliminate these power quality problems for power factor correction, harmonics and zero-sequence current elimination, and reactive power compensation to the level of international standards [4, 5]. One of the solution celebrated as four leg shunt active power filter (SAPF) is widely used for harmonics and zero-sequence current elimination correlated power quality problems in the four-wire electrical networks [2, 3, 6]. The performance of SAPF depends on the strategies selected for reference currents generation, reference currents and dc bus voltage regulation and gate switching pulses generation. Patel *et al.* [7] have explicated the instantaneous active and reactive current components (id–iq) called synchronous reference fame theory (SRF) for reference currents generation with fuzzy logic (FLC) for dc bus voltage control and hysteresis PWM for switching signals generation based SAPF for decrease of power quality problems. For improvement the SAPF performances, authors [6, 8] have described the pq theory on the performance of SAPF to reduce these problems. In all of them publications, have confirmed that these methods are valid only if the source and line voltages are non-distorted and them publications has been shown that the SAPF with SRF theory has simple structure, easy to realized and good harmonics extracting than pq. Some other works have described the performance of several control algorithms based SAPF under unbalanced conditions [9–13]. In these efforts, authors [10, 11] have used the direct power control of SAPF using high selectivity filter (HSF) [10] and FLC [11].

In others various publications many modifications on SRF theory based SAPF are suggested for improvement the performances. Benchouia *et al.* [14] have enhanced the SRF theory by a sSelf-tuning filter (STF) called multi variable filter (MVF) and [15] have described the phase locked loop (PLL) based SRF theory for extracted the fundamental current components of an SAPF for improved performance. These modifications are also not fully effective in the application of SAPF due to the limitation of PLL [15]. In [16] we are improved the PLL based pq0 theory by an MVF for extracted the fundamental components of the source voltages, directly in the αβ0-*axes* of a four leg SAPF for improved performances. This PLL with MVF or $\mathrm{PLL}_{\mathrm{MVF}}$ gives very good performances.

Several researchers described the effect of switching frequency and gate switching pulses on the performance of SAPF [3, 17]. Authors [17] have compared three techniques of gate switching pulses generation and it has been shown that the SAPF controlled by 3D-SVM has operating with fixed switching frequency, simple simulation in Matlab, lower commutation losses and gives good performances than the hysteresis and PWM. Also same others researchers have demonstrated the effect of DC bus voltage and reference currents regulation on the performance of SAPF. Yi *et al.* [13] demonstrated the good performances gives in the application of PI regulators. However, under loads unbalanced and parameter variations, the PI regulator presents in the DC capacitor voltage the overshoot which affect the SAPF performances [5]. Therefore, the dynamic performance of SAPF with PI is not robust, not suitable due to loads unbalanced and parameter variations [5, 9]. The backstepping regulators (BSRs) possibly will be used for improving the dynamics of PI to have increase the robustness, the stabilization, and gives the good regulation on the DC bus voltage to eliminating the overshoot [10, 18].

In this paper, an enhanced SRF theory by an artificial neural network (ANN) based of $\mathrm{PLL}_{\mathrm{MVF}}$ is proposed for on four leg SAPF under unbalanced loads with an backstepping regulators to dc bus voltage and reference currents regulation and 3D SVM for gate switching pulses generation.

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The ANN is used to replace the low pass filter (LPF) for extracting the fundamental active component of loads current in the *d-axe*, it has less switching ripple in SAPF and source currents, good performance under unbalanced loads, and a major advantage of the application of ANN, has improving the dynamic performances and conserve the good filtering quality due to the elimination of LPF. The BSRs and 3D SVM are described in our previous works [3, 9]. This paper is organized as follows: Section 2 gives the controller configuration and mathematical model of the four leg SAPF. In Section 3, the conventional SRF theory and the $\mathrm{PLL_{MVF}}$ are introduced, with their detail structures. The novel SRF theory with ANN with its basic structures in detail is proposed in Section 4. Section 5 gives feature comparisons between the proposed SRF theory with ANN and the conventional SRF theory. Finally, in Section 6, related the conclusions obtained in this paper.

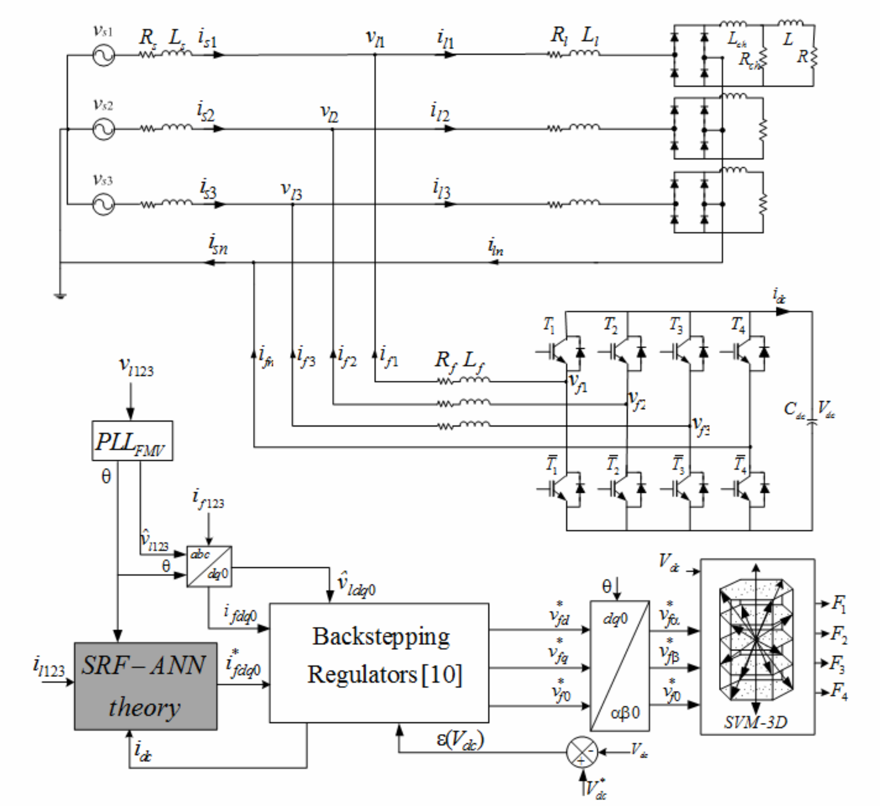


Fig. 1 – Schematic diagram of four leg SAPF and their control.

2. CONFIGURATION AND MATHEMATICAL MODEL OF THE FOUR LEG SAPF

The four leg SAPF, shown in Fig. 1, is a three-phase four leg inverter. It is connected in parallel with three inductors in the point of common coupling (PCC) to a three-phase four wire electrical network alimented three single phase non-linear loads, which injects current harmonics, compensate requires reactive power in the four wire electrical network and canceled the zero-sequence current of the fourth wire (neutral connected) [3, 6]. The mathematical model of this four leg SAPF in the dq0-axes is given by the Eqs. (1) [9].

$$\begin{cases} \dfrac{\mathrm{d}i_{fd}}{\mathrm{d}t} = -\dfrac{R_f}{L_f} i_{fd} + \omega i_{fq} + \dfrac{1}{L_f} v_{fd} - \dfrac{1}{L_f} v_{ld} \\ \dfrac{\mathrm{d}i_{fq}}{\mathrm{d}t} = -\dfrac{R_f}{L_f} i_{fq} - \omega i_{fd} + \dfrac{1}{L_f} v_{fq} - \dfrac{1}{L_f} v_{lq} \\ \dfrac{\mathrm{d}i_{f0}}{\mathrm{d}t} = -\dfrac{R_f}{L_f} i_{f0} + \dfrac{1}{L_f} v_{f0} - \dfrac{1}{L_f} v_{l0} \end{cases} . \quad (1)$$

3. CONVENTIONAL SRF THEORY WITH LOW PASS FILTER

The synchronous reference frame theory is appropriate for the control of SAPF [11]. The block diagram of this theory is shown in Fig. 2. This theory and all the steps are presented and described in detail in the previous work [9]. The three phase loads currents are converted in the dq0-axes by a rotational frame synchronous with the equation (2).

$$\begin{bmatrix} i_{ld} \\ i_{lq} \\ i_{l0} \end{bmatrix} = \begin{bmatrix} \sin(\hat{\theta}) & \sin(\hat{\theta} - \frac{2\pi}{3}) & \sin(\hat{\theta} + \frac{2\pi}{3}) \\ \cos(\hat{\theta}) & \cos(\hat{\theta} - \frac{2\pi}{3}) & \cos(\hat{\theta} - \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_{l1} \\ i_{l2} \\ i_{l3} \end{bmatrix} . (2)$$

$\hat{\theta}$ is the source voltages phase angle and it is determining and delivered by the PLL. In this study, the improved $\mathrm{PLL_{MVF}}$ developed in previous work [16] is shown in Fig. 3.

After the loads currents i_{ld} and i_{lq} in the dq0-axes (active component i_{ld} and oscillating component i_{lq}) are determined, it is necessary to pass the active component i_{ld} for a low pass filter to extract the ac or alternative current component ($\bar{i}_{ld}$)

and dc or direct current ($\bar{i}_{ld}$) component from equation (3).

$$i_{ld} = \bar{i}_{ld} + \tilde{i}_{ld} . \quad (3)$$

The dc current component ($\bar{i}_{ld}$) is associated with the responsibility for fundamental current and the ac current component ($\tilde{i}_{ld}$) is associated with the responsibility for harmonics and reactive power compensation. The filter used in the circuit of conventional SRF theory is the 2nd order low pass filter and their cut-off frequency is equal to one half of the fundamental frequency (25 Hz). For harmonic currents and reactive power compensated in the same time, the reference currents in the dq0-axes are given by:

$$i^*_{fd} = \tilde{i}_{ld} + i_{dc}, i^*_{fq} = i_{lq}, i^*_{fq\alpha} = i_{lq\alpha} \text{ and } i^*_{fq\beta} = i_{lq\beta} . \quad (4)$$

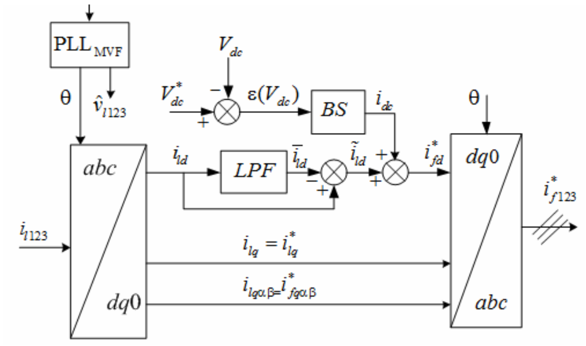


Fig. 2 –Blok diagram of the conventional SRF based on PLL$_{MVF}$.

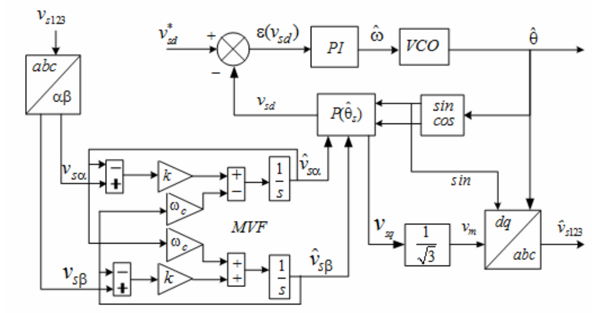


Fig. 3 – Blok diagram of the improved PLL with MVF or PLL$_{MVF}$ [18].

The reference currents in the dq0-axes are transforming to αβ0-axes (stationary reference frame) using:

$$\begin{bmatrix} i^*_{f\alpha} \\ i^*_{f\beta} \\ i^*_{f0} \end{bmatrix} = \begin{bmatrix} \sin(\hat{\theta}) & \cos(\hat{\theta}) & 0 & 0 \\ -\cos(\hat{\theta}) & \sin(\hat{\theta}) & 0 & 0 \\ 0 & 0 & -\cos(\hat{\theta}) & -\sin(\hat{\theta}) \end{bmatrix} \begin{bmatrix} i^*_{fd} \\ i^*_{fq} \\ i^*_{fq\alpha} \\ i^*_{fq\beta} \end{bmatrix} . (5)$$

The three phase reference currents in the abc-axes are obtained by the inverse Concordia transformed from αβ0-axes to the abc-axes as follows:

$$\begin{bmatrix} i^*_{f1} \\ i^*_{f2} \\ i^*_{f3} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i^*_{f\alpha} \\ i^*_{f\beta} \\ i^*_{f0} \end{bmatrix} . \quad (6)$$

To obtain a good compromise between the stability and the dynamic response, one chooses of the PLL$_{MVF}$, the cutoff frequency f_c = 1500 Hz and k = 210.

4. PROPOSED ENHANCED SRF THEORY WITH ANN

The ANN is becoming an attractive extraction and regression technique in several control applications due to its parallel calculating nature and high learning ability [19]. Many ANN structures have been proposed for extracted the harmonics and current controllers for SAPF, such as ANN adaptive linear neuron structure (ADALINE) and ANN multilayer perceptron neural network (MPNN) [19,20]. Among these structures, the most powerful ANN used in harmonics extraction for SAPF has been the MPNN structure. In this work we are replaced the low pass filter used in SRF theory by an ANN a MPNN structure. The block diagram of the proposed enhanced SRF theory with MPNN is shown in Fig. 4 and the MPNN basic structure used in this theory is shown in Fig. 5.

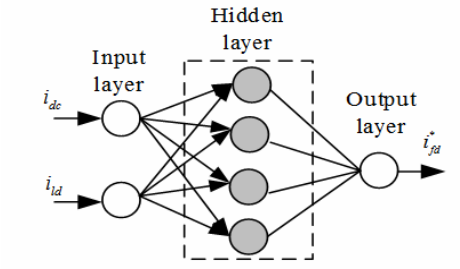


Fig. 4 – Multilayer perceptron neural network.

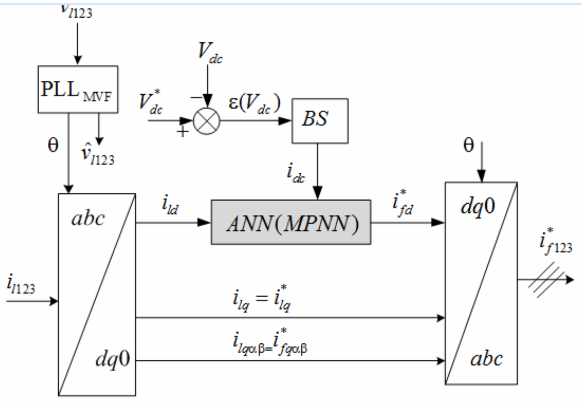


Fig. 5 – Block diagram of proposed enhanced SRF by an MPNN based of PLL$_{MVF}$.

The MPNN consists of three layers: 1) the input layer, 2) the hidden layer, and 3) the output layer Fig. 4. The input layer of MPNN are the loads current i_{ld} and the output of the dc bus voltage regulator i_{dc}, and the output layer is the alternative current component ($\tilde{i}_{ld}$). The hidden layer of MPNN is comprehends 4 neurons with a sigmoid activation function and the output layer comprehends 2 neurons with a linear activation function. The necessary steps for adjusting the hidden neurons can be found in Qasim [19] and the MPNN is expert with 2 000 training examples using Levenberg-Marquardt back propagation algorithm.

Figure 6 shows the dynamic performance of the alternative current component ($\tilde{i}_{ld}$) extracted by the two techniques of extraction. By examining the extracted component, it is clear that there is a divergence between the component ($\tilde{i}_{ld}$) extracted by the LPF and the MPNN. The difference between $\tilde{i}_{ld-LPF}$ and $\tilde{i}_{ld-MPNN}$ magnitudes in the transitory regime is around 24 A and the response time in the MPNN is lower and better then the LPF application.

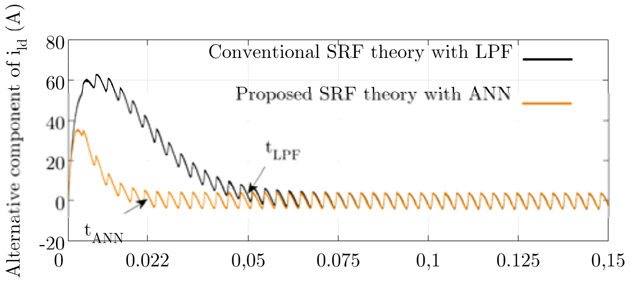


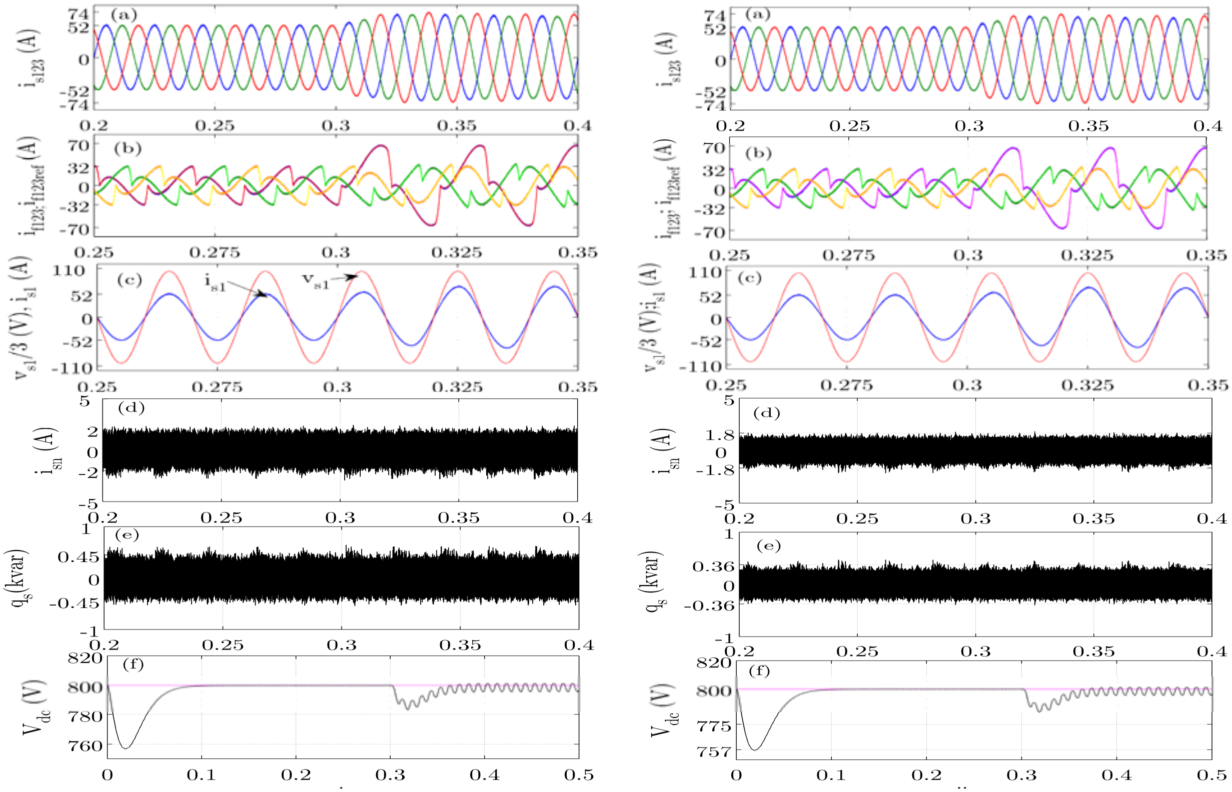
Fig. 6 – The alternative current component
extracted by the two extraction techniques LPF and ANN .

5. SIMULATION RESULTS AND DISCUSSION

A simulation of four leg SAPF control algorithms, shown in Fig. 1, is implemented using the Sim Power Systems and S-Function of Matlab/simulink. The system specifications are described previously in [3].

The dc bus voltage and reference currents are regulated by backstepping regulators and the gate switching pulses are generated by a 3D SVM control circuit. The unbalanced in the loads is performed by the insertion at t = 0.3 s of a new single-phase load (R = 5 Ω, L = 10 mH) in parallel with the single-phase non-linear load connected to the first rectifier bridge.

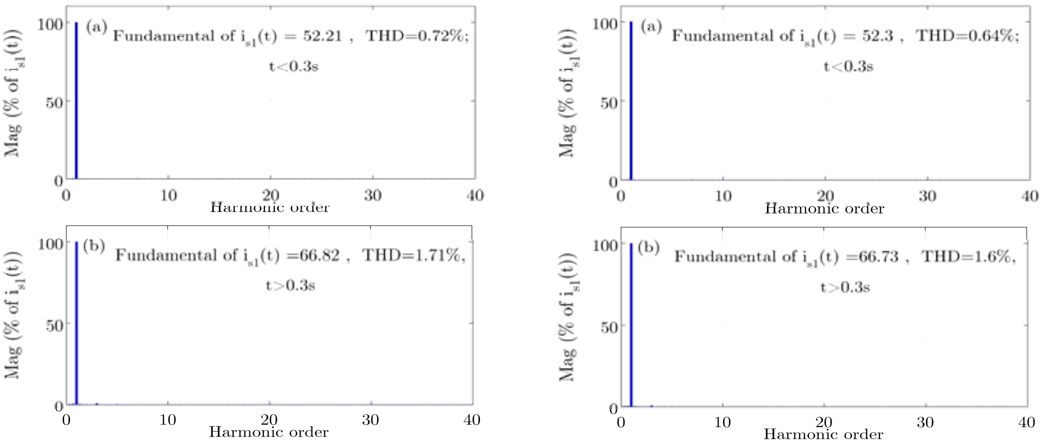
The simulation results for the MPNN and LPF of alternative current component extraction techniques for four leg SAPF controlled under unbalanced loads are given in Figs. 7, i and ii. Each figure is divided into six groups: a) source currents (i_{s123}); b) SAPF or compensating currents (i_{f123}) and their harmonic references ($i_{f123ref}$); c) first phase source current and corresponding voltage; d) source neutral wire current (i_{sn}); e) reactive power in the source (q_s); and f) dc bus voltage (V_{dc}). In both extraction techniques (SRF-LPF and SRF-MPNN), the source currents perfectly sinusoidal and with a unity power factor operation for the two reference currents generation strategies before and after unbalanced loads Figs. 7, i and ii (a and c). The SAPF or compensating currents (i_{f123}) and the harmonic reference currents ($i_{f123ref}$) are constructed with zero errors using the two reference currents generation strategies Figs. 7, i and ii (b). The source neutral wire current is successfully reduced with the two extraction techniques based four leg SAPF before and after unbalanced loads, as well as lower magnitude in the SRF-MPNN extraction technique then the SRF-LPF application (1.8 A) Figs. 7, ii (d). For both extraction techniques based four-leg SAPF, the reactive power in the source is oscillated around the zero before and after unbalanced loads, as well as smaller oscillations in the SRF-MPNN based four-leg SAPF (0.36 kvar) Figs. 7, ii (e). One can observe from Figs. 7, i and ii (d) that in both extraction techniques, the dc bus voltage has a 0 % overshoot which verifies the effectiveness of backstepping regulator in case of unbalanced loads Figs. 7, i and ii (f).



-i- -ii-

Fig. 7 – Performance of four leg SAPF based on PLLMVF under unbalanced non-linear loads using:
(i) conventional SRF theory with LPF, (ii) proposed SRF theory with MPNN.

Spectral analysis of source currents using the two reference currents generation strategies before and after unbalanced loads at $t = 0.3$ s are demonstrated in Figs. 8, i and ii (a and b). It is observed from these figs that the source harmonic currents values are accordance in the IEEE 519 standard (THD < 5 %) using the two reference currents generation strategies before and after unbalanced loads, with lower values in the application of proposed SRF theory with MPNN, the total harmonic distortion THD before unbalanced loads at $t < 0.3$ s is 0.64 % Fig. 8, ii (a) when after at $t > 0.3$s it's 1.6 % Fig. 8, ii (b) which verifies the effectiveness of MPNN for extracting the alternative current component of loads current and the good quality for the compensation of harmonic currents.



-i- -ii-

Fig. 8 – Magnitude spectrum of source currents before and after unbalanced loads:
(i) conventional SRF theory with LPF, (ii) proposed SRF theory with MPNN.

Table 1

Comparison of the two techniques

	SRF theory with LPF		SRF theory with MPNN	
	Balanced lLoads	Unbalanced loads	Balanced loads	Unbalanced loads
Source current THD (i_{s1})	0.72%	1.71 %	0.64%	1. 6%
Source neutral current (i_{sn})	2A		1.8 A	
Source reactive power (q_s)	±0.45 kvar		±0.36 kvar	

6. CONCLUSIONS

In this paper, two widely used alternative current component extraction techniques based SRF theory for SAPF controlled are studied and examined for power quality improvement in a four wire distribution system: 1) the LPF based SRF theory; and 2) the MPNN based SRF theory. A simulation of these two extraction techniques based SRF theory for four leg SAPF before and after unbalanced loads are implemented using the Sim Power Systems and S-Function of Matlab/simulink. The performance of these two extraction techniques based SRF theory for four leg SAPF is evaluated through detailed simulation studies. Based on the study conducted in this paper, it is observed that the MPNN based SRF theory performs better under unbalanced loads than the LPF based SRF theory and improving the dynamic performances and conserve the good filtering quality.

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