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An ANN Controlled Three-Phase Auto-Tuned Passive Filter for Harmonic and Reactive Power Compensation

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ABSTRACT

Automatically tuned passive filters can improve power quality to a great extent in power systems. A novel three-phase shunt auto-tuned filter is designed to effectively compensate source current harmonics and to provide reactive power required by the non-linear load, which draws a highly reactive, harmonic-rich current from the supply. An artificial neural network (ANN) based controller selects filter component values in accordance with reactive power requirement and harmonic compensation. Traditional passive filters are permanently connected to the system and draw large amounts of source current even under light load conditions. By using auto-tuned filters, the passive filter components can be controlled according to load variations and, hence, draw only required source currents. The selection is done by the ANN with the help of a properly tuned knowledge base to provide instantaneous compensation using a digital controller.

Keywords: Auto-tuned passive filter, ANN controller, Harmonics compensation, Reactive power compensation

1. Introduction

Primarily due to their low cost and high efficiency, tuned filters have traditionally been used to absorb harmonics generated by large industrial loads [1-6], but this may cause parallel or series resonance with ac line impedance and tends to be susceptible to load and line switching transients. If an arrangement can be made to remove or vary the component values of tuned filters according to load variations, it will improve the performance of passive power filters (PPF) especially in retrofit/existing systems.

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2. A Novel Auto-tuned Filter

In this paper, a novel automatically tuned filter, which is made tunable by automatically switching the capacitance or by varying the inductance, is proposed. An ANN based controller[7] senses the fundamental frequency reactive power demand of the load and accordingly selects suitable capacitors (TSC) and tap positions of inductors (TSR) for the passive filters .

3. Proposed ANN Network

The exact relation between the reactive power demand of the load and the harmonics is complex and one cannot find a uniform rule suited for all different load characteristics under generalized operating conditions, so an ANN controller is proposed to determine the size of the passive filter that should be switched on to lower the utility THD. In the proposed ANN network, the reactive power required by the load is selected as an input variable. Output variables can be taken as the ON/OFF status of TSCs for the 5th and 7th order harmonic filters and tap settings of TSRs for the 5th and 7th order filters. The ANN is comprised of five layers: an input layer (6 neurons), an output layer (6 neurons) and hidden layers (4, 10, 4 neurons). For training of the network, the ANN uses the ICOSφ control algorithm [8]. The ICOSφ controller takes source voltages and load currents in the three phases (representing the input layer of 6 neurons) and the outputs of the ICOSφ controller are the PWM pulses to the six IGBTs of the inverter (representing the output layer of the 6 neurons). The direct relation between the input and output variables is unknown. The basic steps involved in ICOSφ control are filtering of the fundamental component of the load current (first hidden layer), determining the real part of the load current (ICOSφ)(second hidden layer), calculating the compensation current to be injected by the active filter(third hidden layer), and producing the PWM pulses according to the difference between the compensating current and the load current (output layer - 6 neurons).The number of neurons in each hidden layer is selected to check the accuracy of instantaneous output signals.

4. Training and Testing of ANN

As a case study, a three-phase system with a 400 V, 50 Hz balanced supply given to a 15kW AC-DC thyristor converter connected to an R-L load of 20 ohms, 80mH is considered. A stiff source is considered with 0.08p.u impedance. The firing angle of the ac-dc converter feeding R-L load is varied from light load to full load conditions and corresponding values of the reactive power demand Q of the load are noted. The capacitors in the TSC units are designed such that they provide the reactive power requirement of the load at fundamental frequency. The corresponding inductive reactance of the TSR unit in the $5^{th}/7^{th}$ harmonic filter is calculated based on the concept that the TSC-TSR filter provides the minimum impedance path at the $5^{th}/7^{th}$ harmonic frequency (i.e., $X_L=X_C$). The passive filter component values are noted in Table 1. Based on the data in Table 1, the network is trained using 50 training patterns with a performance goal of 0.001 and 1500 epochs. The back propagation learning rule is used to train the nonlinear multilayer network.

5. Simulation Results

The simulation is done on a three-phase system with a balanced ac supply applied to a nonlinear load such as a thyristor converter feeding an RL load which may be varied to introduce load transients. The simulations are initially done on the three phase system with no filters, then with 5th and 7th passive filters and finally with TSC –TSR filter banks. A comparative study of the three conditions gives a clear idea of the effective harmonic elimination and reactive power compensation. These novel

Table 1 5th & 7th order harmonic filter settings & reactive power demand

C_1 30μF	C_2 60μF	C_3 120μF	5^{th} harmonic TSC-TSR Filter		7^{th} harmonic TSC-TSR Filter		Reactive power supplied
			Inductor TCR(mH)	Tap Setting	Inductor TCR (mH)	Tap setting	
ON	OFF	OFF	13.48	1	6.87	1	500VAR
OFF	ON	OFF	6.73	2	3.44	2	1000 VAR
ON	ON	OFF	4.49	3	2.29	3	1500 VAR
OFF	OFF	ON	3.37	4	1.72	4	2000 VAR
ON	OFF	ON	2.70	5	1.38	5	2500 VAR
OFF	ON	ON	2.25	6	1.15	6	3000 VAR
ON	ON	ON	1.92	7	0.981	7	3500 VAR

TSC-TSR filters have added advantages such as reduced loading on the three-phase supply.

Case A: Three-phase system without filters:

A three-phase 400 V, 50 Hz balanced supply is given to a nonlinear-reactive load of a 15kW AC-DC thyristor converter connected to an R-L load of 10 ohms and 200mH (load A). The source voltage and source current waveforms and the harmonic spectrum of the current drawn from the source under this load condition are shown in Fig. 1. The study is repeated for a different load condition of 100 ohms and 500mH (load B). The waveforms and harmonic spectrum are given in Fig. 2.

```
Sampling time      = 5e-006 s
Samples per cycle = 4000
Fundamental        = 38.24 peak (27.04 rms)
Total Harmonic Distortion (THD) = 18.04%

    0 Hz (DC)       0.11 %
   50 Hz Fund       100.00 %
  100 Hz (h2)       0.18 %
  150 Hz (h3)       0.10 %
  200 Hz (h4)       0.04 %
  250 Hz (h5)       15.82 %
  300 Hz (h6)       0.08 %
  350 Hz (h7)       8.34 %
  400 Hz (h8)       0.06 %
  450 Hz (h9)       0.05 %
  500 Hz (h10)       0.04 %
  550 Hz (h11)       1.54 %
  600 Hz (h12)       0.06 %
  650 Hz (h13)       0.57 %
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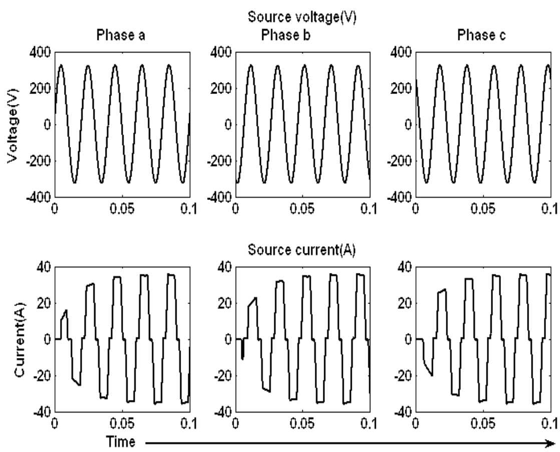
(a) Simulation with Load A: Harmonic spectrum of source current



(b) Simulation with load A: Source voltage and source current

Fig. 1. Harmonic spectrum, source voltage and source current without filter compensation.

Case B: With conventional passive filter:

Based on the reactive power requirement of the system under the present / rated load condition, passive LC filters for the 5th harmonic frequency and the 7th harmonic frequency are designed and inserted. However, as the passive filters tend to load the system under the fundamental frequency, the current drawn from the mains is increased to 39 A compared to 27 A in the system without filters. The simulation is then repeated for load B with the same 5th and 7th order filters as designed for load A to show the limitation of fixed compensation in conventional passive filters. The waveforms and the harmonic spectrum of the source current after compensation for load A and load B are shown in Fig. 3 and Fig. 4, respectively.

```
Sampling time      = 5e-006 s
Samples per cycle = 4000
Fundamental        = 5.433 peak (3.842 rms)
Total Harmonic Distortion (THD) = 28.71%

    0 Hz (DC)       0.00 %
   50 Hz Fund       100.00 %
  100 Hz (h2)       0.00 %
  150 Hz (h3)       0.03 %
  200 Hz (h4)       0.00 %
  250 Hz (h5)       20.90 %
  300 Hz (h6)       0.00 %
  350 Hz (h7)       14.23 %
  400 Hz (h8)       0.00 %
  450 Hz (h9)       0.03 %
  500 Hz (h10)       0.00 %
  550 Hz (h11)       9.14 %
  600 Hz (h12)       0.00 %
  650 Hz (h13)       7.29 %
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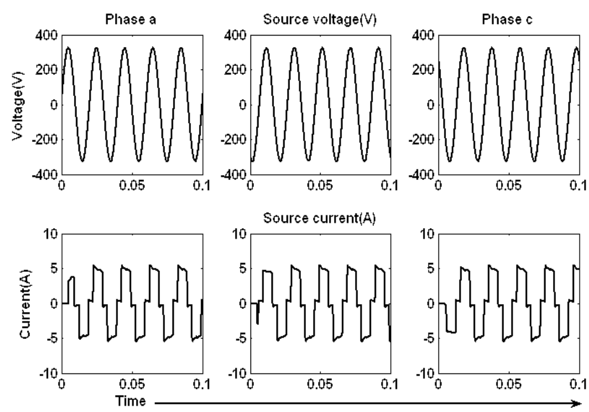
(a) Simulation with load B: Harmonic spectrum of source current

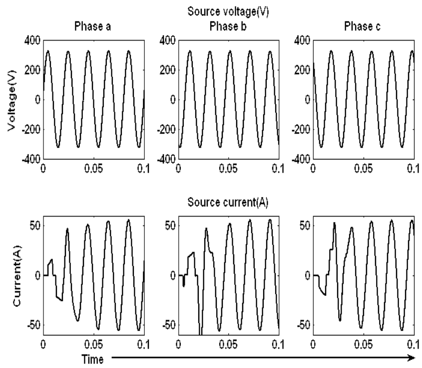


(b) Simulation with load B: Source voltage and source current

Fig. 2. Harmonic spectrum, source voltage and source current without filter compensation.

Sampling time	= 5e-006 s
Samples per cycle	= 4000
Fundamental	= 55.77 peak (39.43 rms)
Total Harmonic Distortion (THD)	= 1.15%
0 Hz (DC)	0.27 %
50 Hz Fund	100.00 %
100 Hz (h2)	0.36 %
150 Hz (h3)	0.29 %
200 Hz (h4)	0.17 %
250 Hz (h5)	0.33 %
300 Hz (h6)	0.49 %
350 Hz (h7)	0.13 %
400 Hz (h8)	0.12 %
450 Hz (h9)	0.10 %
500 Hz (h10)	0.08 %
550 Hz (h11)	0.54 %
600 Hz (h12)	0.08 %
650 Hz (h13)	0.45 %

(a) Simulation with load A: Harmonic spectrum of source current

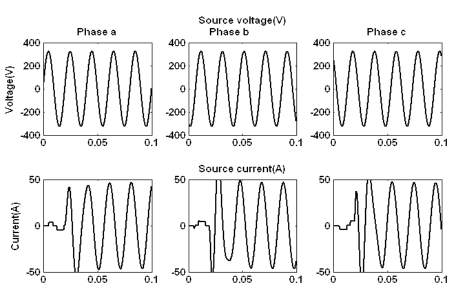


(b) Simulation with load A: Source voltage and source current

Fig. 3. Harmonic spectrum, source voltage and source current with passive filter compensation at 0.02sec.

Sampling time	= 5e-006 s
Samples per cycle	= 4000
Fundamental	= 46.57 peak (32.93 rms)
Total Harmonic Distortion (THD)	= 0.39%
0 Hz (DC)	0.05 %
50 Hz Fund	100.00 %
100 Hz (h2)	0.31 %
150 Hz (h3)	0.11 %
200 Hz (h4)	0.06 %
250 Hz (h5)	0.01 %
300 Hz (h6)	0.05 %
350 Hz (h7)	0.02 %
400 Hz (h8)	0.02 %
450 Hz (h9)	0.02 %
500 Hz (h10)	0.02 %
550 Hz (h11)	0.11 %
600 Hz (h12)	0.01 %
650 Hz (h13)	0.10 %

(a) Simulation with load B: Harmonic spectrum of source current



(b) Simulation with load B: Source voltage and source current

Fig. 4. Harmonic spectrum, source voltage and source current with passive filter compensation at 0.02sec.

Here again, the source current is increased to 32 A as compared to 3.8 A for load B for the system without filters. It is noted from Fig. 4 that though the elimination of the 5th and 7th order harmonics is as effective as for load A, the filters, which were designed for load compensation, cannot provide effective power factor correction as the reactive power compensation is not suitable for load B.

Case C: With proposed ANN controlled Auto-tuned filter:

The simulation model of the three-phase system with the proposed auto-tuned passive power filter based on the ANN controller is shown in Fig. 5. TSC-TSR based passive filters tuned to the 5^{th} and 7^{th} harmonic frequencies are connected in parallel as harmonic sinks. The ANN based digital controller receives the load currents and the phase voltages at the point of common coupling (PCC) as inputs. Based on the appropriately tuned knowledge base, the ANN selects the proper percentage combination of the passive filter elements. The capacitor sizes are selected on the basis of the reactive power requirement of the load. Let Q be the maximum reactive power requirement of the load, ω the fundamental supply frequency and V the supply voltage. The Inductor value is selected depending on the tuning frequency of the filter. $C_1 = \dfrac{Q}{V^2\omega}$;

$$L = \frac{1}{4\pi^2 f_r^{\,2} C}.$$

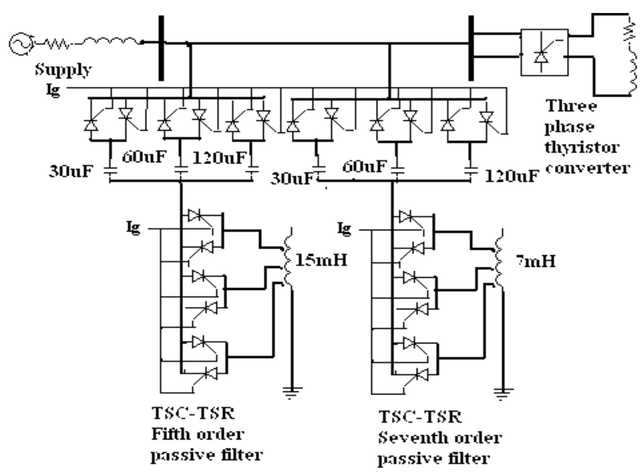


Fig. 5. Model of 3 phase system with ANN controlled TSC-TSR filter.

The waveforms and the harmonic spectrum of the source current after compensation for Load A and for Load B are shown in Fig. 6 and Fig. 7, respectively. With the flexible compensation made available using the TSC-TSR filters, the power factor correction is also found to be very effective for the present load (load B).

Table-2 shows that both the conventional passive filters and the newly proposed auto-tuned filters are capable of reducing the %THD of the source current in the system to meet the IEEE standards, whereas the conventional passive filters draw heavy currents under the fundamental frequency thereby unnecessarily loading the source, which is avoided in TSC-TSR filters. The TSC-TSR filters are also seen to maintain the power factor fairly well with the change in load. The newly proposed TSC-TSR auto-tuned filters can, hence, be thought of as a better alternative to the conventional passive filters.

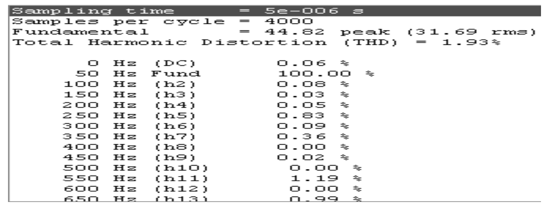
Table 2 Harmonic spectrum of source current

SYSTEM	LOAD A		LOAD B	
	%THD	Source current	%THD	Source current
Without Filter	18.04%	27A	28.71%	3.8A
With Passive Filter	1.15%	39A	0.4%	32.93A
With TSC-TSR Filter	1.93%	32A	1.9%	10A

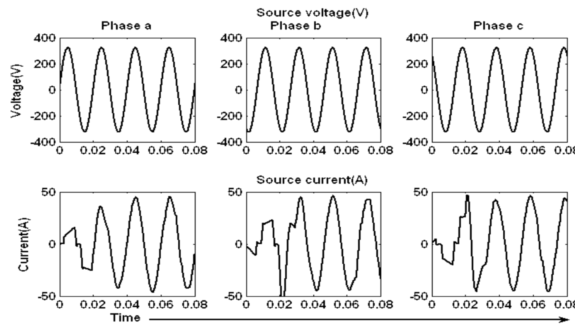
6. Experimental study

A three phase induction motor 415V, 4.8A, 1430 RPM is connected to a three phase balanced supply of 415 V, 50 Hz and run under no load conditions.

The THD spectrum of the currents drawn by the motor (Fig. 8) shows that the 5th and 7th harmonics are predominant. A shunt passive filter, tuned between the 5th and 7th harmonic frequencies is designed and implemented for compensation. The steps of inductor-capacitor combinations for auto-tuned filter are selected as 10mH-40μF, 5mH-80μF, 20mH-20μF, respectively. For the given loading condition in Fig. 9, the combination of 10mH-40μF is selected as the most optimized filter combination and it improves input power factor to unity and THD is reduced to 5%.

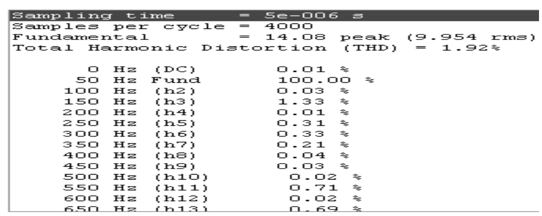


(a) Simulation with load A: Harmonic spectrum of source Current

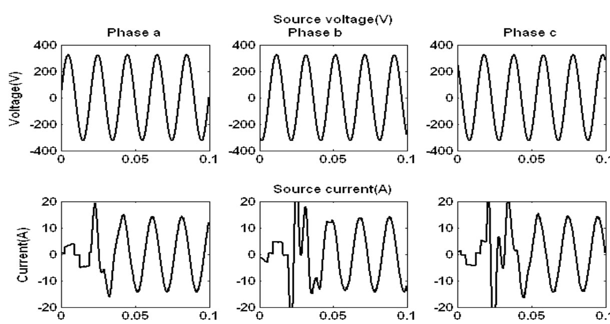


(b) Simulation with load A: Source voltage and source current

Fig. 6. Harmonic spectrum, source voltage and source current with auto -tuned passive filter compensation at 0.02sec.



(a) Simulation with load B - Harmonic spectrum of source current



(b) Simulation with load B: Source voltage and source current

Fig. 7. Harmonic spectrum, source voltage and source current with auto-tuned passive filter compensation at 0.02sec.

7. Conclusions

A three-phase system with a highly non-linear, reactive load is tested for compensation of the current harmonics and reactive power demand using a three-phase ANN based auto-tuned power filter. Both the simulation and hardware test results show that the ANN based auto-tuned power filter is able to achieve effective compensation and also avoids excessive reactive power compensation while maintaining good power factor at the source.

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Power & Energy — FULL — 0:00:05

	L1	L2	L3
kW	0.12	0.15	- 0.01
kVA	0.55	0.74	0.63
kVAR	0.53	0.73	0.63
PF	0.23	0.21	-0.02
CosΦ	0.23	0.21	-0.02
A rms	2.4	3.1	2.7
	L1	L2	L3
V rms	231.0	238.8	234.1

(a) Power and Energy spectrum

HARMONICS TABLE — 0:00:04

Amp	L1	L2	L3
THD%f	7.5	5.3	6.3
H3%f	1.6	1.5	0.6
H5%f	6.3	4.4	5.6
H7%f	3.6	2.5	2.8
H9%f	0.5	0.5	0.8
H11%f	0.6	0.4	0.4
H13%f	0.1	0.1	0.1
H15%f	0.1	0.0	0.1

(b) Harmonic spectrum

Fig. 8. Power and Energy spectrum, Harmonic spectrum of three phase induction motor at no load.

Power & Energy — FULL — 0:00:02

	L1	L2	L3
kW	0.77	0.89	0.66
kVA	0.77	0.91	0.67
kVAR	0.08	0.16	0.13
PF	1.00	0.98	0.98
CosΦ	1.00	0.99	0.98
A rms	3.4	3.9	3.0
	L1	L2	L3
V rms	225.8	233.2	228.4

(a) Ower and Energy spectrum

HARMONICS TABLE — 0:00:06

Amp	L1	L2	L3
THD%f	5.6	5.2	5.8
H3%f	2.5	1.2	1.9
H5%f	4.2	4.0	4.8
H7%f	2.4	2.8	2.2
H9%f	0.7	0.7	0.8
H11%f	0.9	1.0	1.2
H13%f	0.4	0.4	0.1
H15%f	0.2	0.3	0.1

(b) Harmonic spectrum

Fig. 9. Power and Energy spectrum, Harmonic spectrum of three phase induction motor with auto-tuned filter (combination of 10mH-40μF).

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