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Dynamic Power Quality Compensator with an Adaptive Shunt Hybrid Filter

Sindhu M R, Manjula G Nair, T N P Nambiar
Department of Electrical and Electronics Engineering, AMRITA VISHWA VIDYAPEETHAM

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ABSTRACT

Major portion of nonlinear loads in industries are contributed by variable speed drives because of their desirable features such as energy saving, smooth control, flexible operation and fast response. These electric drives introduce large amount of current and voltage harmonic distortions at the point of common coupling. These distortions are propagated throughout the system and affect all other loads connected in the system. Hence these distortions are to be mitigated with suitable harmonic filters installed near to the respective load terminals. This paper presents an effective ANN based digital controller for shunt hybrid harmonic filter to provide instantaneous harmonic and reactive compensation. The performance of the adaptive shunt hybrid filter is verified by simulation and experimental studies under steady state and dynamic conditions. The results show that it is an effective, flexible and low rated hybrid filter configuration.

Corresponding Author:

Sindhu M R,
Department of Electrical and Electronics Engineering,
Amrita Vishwa Vidya Peetham,
Amrita nagar, Coimbatore – 641112.
Email:

1. INTRODUCTION

Utilities take efforts to maintain good power quality at the point of common coupling (PCC). Majority of industrial loads are induction motor drives [1, 2]. They are preferred because of saving in energy, rugged nature, easiness in control and cheapness [1, 2]. Various PWM techniques such as Space Vector pulse width modulation, sinusoidal PWM etc. are implemented [3]-[5]. These are implemented with digital controllers and it improved performance of induction motor drives. These equipment resulted in generation of large amounts of current and voltage harmonics, reduction in source power factor, voltage sag, voltage swell etc. [6]. The propagation of these power quality issues are prevented by installing harmonic filter of suitable configuration at point of common coupling. Different power quality improvement schemes such as passive filters [6] and active filters [7] are developed by various researchers. Passive filters have drawbacks such as bulky in size, high no load losses, resonance, fixed compensation etc [6]. Active filters provide effective and dynamic compensation with the help of efficient controllers [7]. But this scheme is expensive. Hence as an economical solution, hybrid filters were developed. Here, shunt passive filter contributes major part of reactive power compensation and remaining harmonics are compensated by shunt active filter. Various research papers on intelligent digital controller based harmonic filters are published [8-12]. This paper describes an ANN based adaptive shunt hybrid filter for harmonic mitigation and reactive power compensation of adjustable speed drives.ANN controller helps to provide instantaneous harmonic and reactive power compensation under steady state and dynamic conditions.

2. TEST SYSTEM

An industrial system is selected for performance study of the adaptive shunt hybrid filter. A scaled down laboratory model of industrial drive, three phase 3 HP, 4 pole, induction motor drive is used in this work. It is operated as an adjustable speed drive using three phase voltage source inverter. The specifications of the induction motor drive are shown in Table 1.

Table 1. Induction Motor Drive Specifications

Power rating	3 HP
Switching frequency	10kHz
Rotor resistance	1.24Ω
Stator resistance	1.517Ω
Vdc	300V
Base frequency	100Hz
Stator Leakage Reactance	5.12Ω
Rotor Leakage Reactance	120Ω
No. of poles	4
Moment of Inertia	0.2 kgm^2

The experimental set up is made as shown in the block diagram in Figure 1.

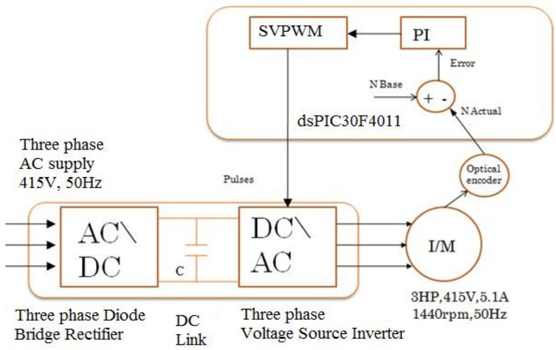

Figure 1. Schematic Diagram of Three Phase Test System

The VSI is controlled using space vector PWM. The space vector PWM based speed control is implemented through the following steps:

(a) Measure the motor quantities (speed and phase currents)
(b) Transform them to two phase system (α,β) using Clarke transformation
(c) Calculate rotor flux space vector magnitude and angle
(d) The stator current torque and flux components are separately controlled (i_{sd}, i_{sq})
(e) The output stator voltage space vector is calculated using decoupling block (v_{sd}, v_{sq})
(f) The stator voltage space vector is transformed by an inverse park transformation back from d –q reference frame into two phase system fixed with the stator ($v_{s\alpha}$, $v_{s\beta}$)
(g) Using space vector modulation, output three phase voltages is generated.

The whole process of the speed controller, implemented in the dsPIC30F4011, is explained using flow chart in Figure 2. Three phase source currents, and source voltages at the point of common coupling are sensed and harmonic analysis is performed with the help of power quality analyser. The power system quantities –magnitudes and waveforms of source currents and source voltages for different speed settings are shown in Figure 3.

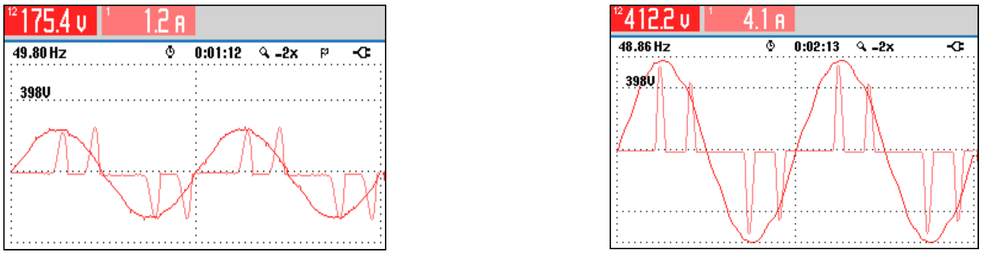

Figure 3. Source voltage and source current at the point of common coupling for variable speed induction motor drive with speed of (a)135 rad/sec (Case I) (b)320 rad/sec – (Case II)

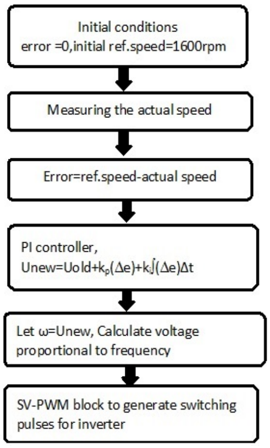

Figure 2. Flow chart of the speed controller

Table 2 shows large amount of harmonics in currents at the point of common coupling under steady state conditions. When the load is changed suddenly from 75% rated load to 25% rated load, the source current, reactive power demand and harmonic components are also changed correspondingly. The fundamental component of source current, THD in source current, % of current harmonic components, displacement power factor, distortion power factor, source power factor, real power, reactive power, apparent power and distortion power in each cycle is shown in Table 3.

Table 2(a). Fundamental component of source current and THD in source current at the point of common coupling with variable speed induction motor drive – under steady state conditions

Case	Fundamental component of source current (p.u.)			THD in Source Current (%)	% of 5^{th} harmonic	% of 7^{th} harmonic	% of 11^{th} harmonic	% of 13^{th} harmonic
	Phase a	Phase b	Phase c	Phase a	Phase A	Phase A	Phase a	Phase a
I	0.92	0.92	0.92	34.5	28.2	12.6	4.1	2.1
II	0.51	0.51	0.51	57.13	53.5	19.4	5.2	2.9

Table 2(b). Estimation of Power system parameters for the specified load conditions under steady state

Case	Displacement power factor	Distortion power factor	Source power factor	Real Power (pu)	Reactive Power (pu)	Apparent Power (pu)	Distortion Power (pu)
I	0.98	0.9453	0.9293	0.91	0.16	0.92	0.08
II	0.53	0.87	0.4342	0.46	0.7967	0.92	0.085

Table 3(a). Fundamental component of source current and THD in source current in each cycle at the point of common coupling with variable speed induction motor drive – under dynamic conditions

Cycle	Fundamental component of source current (p.u.)			THD in Source current (%)	% of 5^{th} harmonic	% of 7^{th} harmonic	% of 11^{th} harmonic	% of 13^{th} harmonic
	Phase a	Phase b	Phase c	Phase a	Phase A	Phase A	Phase A	Phase a
I	0.92	0.92	0.92	34.5	28.2	12.6	4.1	2.1
II	0.84	0.84	0.84	39.2	34.6	14.12	4.29	2.25
III	0.78	0.78	0.78	43.8	39.87	15.78	4.47	2.42
IV	0.70	0.70	0.70	47.96	44.3	17.24	4.7	2.63
V	0.62	0.62	0.62	53.2	49.7	18.3	4.95	2.81
VI	0.51	0.51	0.51	57.13	53.5	19.4	5.2	2.9

Table 3(b). Estimation of Power system parameters in each cycle with variable speed induction motor drive - under dynamic load conditions

Cycle	Displacement power factor	Distortion power factor	Source power factor	Real Power (pu)	Reactive Power (pu)	Apparent Power (pu)	Distortion Power (pu)
I	0.98	0.9453	0.9293	0.91	0.16	0.92	0.08
II	0.9397	0.945	0.888	0.7893	0.287	0.84	0.03
III	0.866	0.9289	0.8044	0.6755	0.39	0.78	0.026
IV	0.766	0.9143	0.7004	0.5362	0.45	0.7	0.0036
V	0.6428	0.8955	0.5756	0.3985	0.4749	0.62	0.0082
VI	0.53	0.87	0.4342	0.46	0.7967	0.92	0.085

Results show an effective harmonic filter is necessary to provide variable reactive power and harmonic compensation to meet IEEE standards of good power quality. Active filters are commonly used for dynamic power quality compensation. But these active filters are highly expensive. Hence as an economical solution, hybrid filters were introduced. Here, shunt passive filter contributes major part of reactive compensation and selected harmonic compensation. Only remaining harmonic compensation is to be met by the shunt active filter.

3. PROPOSED ADAPTIVE SHUNT HYBRID FILTER FOR POWER QUALITY COMPENSATION IN INDUCTION MOTOR DRIVES

The adaptive shunt hybrid filter consists of three phase adaptive shunt passive filters and adaptive shunt active filter. Adaptive shunt passive filters are developed by series combination of thyristor switched series combination of inductor and capacitor. Their values are designed such as to provide bypass path for fifth and seventh harmonics. It also provides fundamental frequency reactive power to the system. The capacitor values are selected as 210µF and inductor values are 15mH and 7mH respectively. Remaining amounts of harmonics and reactive compensation currents are provided by the adaptive shunt active filter. The shunt active filter is controlled to inject remaining amount of harmonics and reactive compensation currents such that source need to supply only real part of fundamental component of current. The schematic diagram of the filtering system is shown in Figure 4. The hybrid filter elements are controlled by ANN based intelligent digital controller. The responsiveness of filter is improved by hysteresis controller based closed loop control. PI controller is also used to compensate for inverter losses and regulation of dc link voltage.

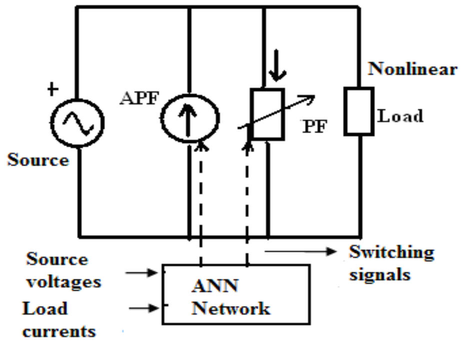

Figure 4. Three phase system feeding variable speed induction motor drive with Adaptive Shunt Hybrid Filter

3.1. Methodology

The load current in induction motor drive is represented by:

$$i_L(t) = i_{L1}\sin(\omega t - \phi_{L1}) + \sum_{h=3,5,}^{\infty} i_{Lh}\sin(h\omega t - \phi_{Lh}) \tag{1}$$

= Real part of fundamental component of load current +Reactive part of fundamental component of load current + Harmonic components of load current

Adaptive shunt passive filter compensates for major part of fundamental frequency reactive power and harmonics. Adaptive shunt active filter injects remaining small amount of harmonics and helps to obtain unity power factor sinusoidal current at the point of common coupling.

Three phase instantaneous source voltages, fundamental load currents and filter compensation currents are selected as input quantities for training adaptive ANN. The reference compensation currents are developed by analog controller circuit. The actual compensation currents are compared with reference compensation currents to generate switching pulses to IGBTs of three phase voltage source inverter. The current transducers and voltage transducers sample instantaneous load currents, compensation currents and source voltages. Sampled value of instantaneous load current is expressed as:

$$\text{i.e. } i_L[k] = \sum_{n=1,2,3,\ldots}^{N} [W_{1n}\sin(nk\omega\Delta t) + W_{2n}\cos(nk\omega\Delta t)]$$

$$= [W_{11}\cos(nk\omega\Delta t) + W_{21}\sin(nk\omega\Delta t)] + \sum_{n=2,3,\ldots}^{N}[W_{1n}\sin(nk\omega\Delta t) + W_{2n}\cos(nk\omega\Delta t)]$$

$$= i_{L1,re}[k] + i_{L1,im}[k] + \sum_h ih\,[k] \tag{2}$$

where W_{1n} and W_{2n} are amplitudes of sine and cosine components of the measured load current.

The equation is represented in vectorial form as:

$$i_L[k] = [W_{11}\ W_{21}\ \text{---------}W_{1N}\ \ W_{2N}]\begin{bmatrix}\sin(k\omega\Delta t)\\ \cos(k\omega\Delta t)\\ \sin(2k\omega\Delta t)\\ \cos(2k\omega\Delta t)\\ \\ \\ \sin(Nk\omega\Delta t)\\ \cos(Nk\omega\Delta t)\end{bmatrix}$$

The adaptive ANN network is implemented using Widrow-Hoff weights updating algorithm [6], [7]. The weights of the connection links are updated using error in the estimated fundamental component and actual real part of fundamental component of load current. The back propagation neural network was trained with MATLAB using 1500 training patterns for 2500 epochs with goal of 0.001.Training method used is Levenberg – Marquardt algorithm. Trained artificial neural network consists of two layers: input layer (6 neurons), output layer (7 neurons) and hidden layer (6 neurons). The ANN network is shown in Figure 5. The performance characteristics of neural network training is shown in Figure 6. The ANN is programmed and implemented using dsPIC30F4011 microcontroller. Two bipolar ADCs are used for conversion of analog quantities to digital quantities. Sampling frequency of 3kHz is selected considering time for sensing input samples, digital conversion, program execution and generation of switching signals. The switching pulses are amplified and given to IGBTs in shunt active filter. The isolation between power circuit and controller circuit is done using an optocoupler 6N136. The shunt active power filter circuit includes power inverter (SKM50GB12B) with three phase IGBT bridge and two capacitors of 2200μF. The compensating currents injected by three phase inverter through coupling inductors to the point of common coupling. For $\left(\frac{di_F}{dt}\right)_{\max} = 10A/\mu s$, 400V 5A 10mH coupling inductor is used. The experimental results with the insertion of ANN Controller based shunt hybrid filter are discussed in following section.

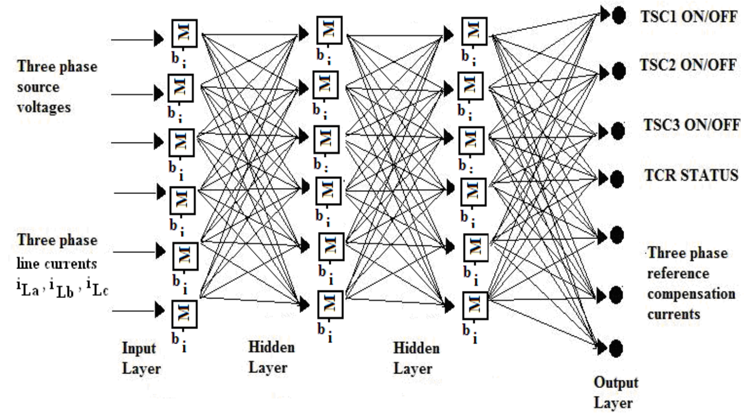

Figure 5. Artificial Neural Network for controlling adaptive shunt hybrid filter

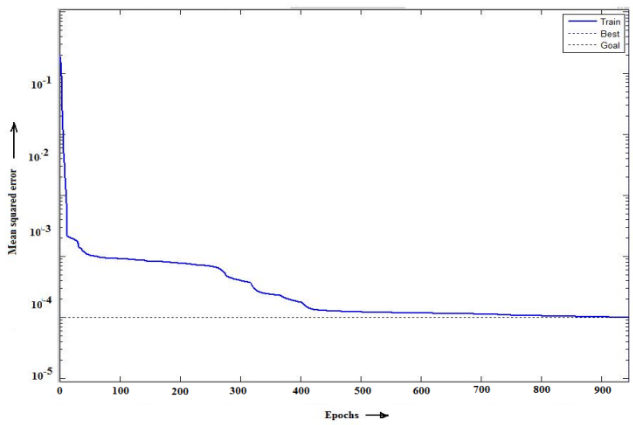

Figure 6. Performance plot of training neural network for controlling the adaptive shunt hybrid filter

4. PERFORMANCE OF ANN CONTROLLED SHUNT ACTIVE FILTER UNDER DYNAMIC CONDITIONS–RESULTS AND DISCUSSION

The operating performance of the adaptive shunt hybrid filter is studied under dynamic conditions – with the application of 25% load and 75% load at t = 0.5s. Fundamental component of source current, THD in source current and power system parameters at the point of common coupling with the installation of adaptive shunt hybrid filter is shown in Table 4 and 5. Figure 7, and 8 show waveforms of source voltage, load current, filter current and source current with the installation of adaptive shunt hybrid filter under dynamic conditions. The performance of adaptive shunt hybrid filter is verified with reduction in source current harmonics and sinusoidal source currents in phase with source voltages. Waveforms also confirm the performance of the filter under dynamic conditions.

Table 4(a). Fundamental component of source current and THD in source current at the point of common coupling with variable speed induction motor drive with Adaptive Shunt Hybrid Filter – Steady state conditions

Case	Fundamental component of source current (p.u.)			THD in Source Current (%)	% of 5th harmonic	% of 7th harmonic	% of 11th harmonic	% of 13th harmonic
	Phase a	Phase b	Phase c	Phase a	Phase A	Phase A	Phase a	Phase a
I	0.84	0.84	0.84	3.15	2.2	1.6	0.7	0.4
II	0.23	0.23	0.23	3.19	2.5	1.4	1.2	0.9

Table 4(b). Estimate of Power system parameters for the specified load conditions – with Adaptive Shunt Hybrid Filter – Steady state conditions

Case	Displacement power factor	Distortion power factor	Source power factor	Power Delivered by Source			
				Real Power (pu)	Reactive Power (pu)	Apparent Power (pu)	Distortion Power (pu)
I	1	0.9991	0.9991	0.84	0	0.84	0
II	1	0.9995	0.9995	0.23	0	0.23	0

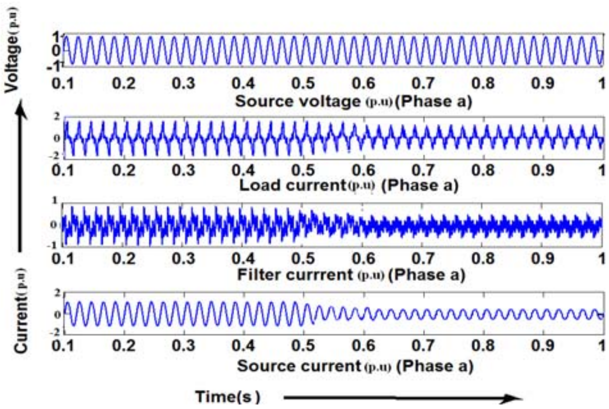

Figure 7. Source voltage, Load current, Filter current, Source current waveforms for induction motor drive load at 25% rated load under balanced system with adaptive shunt hybrid filter –dynamic conditions

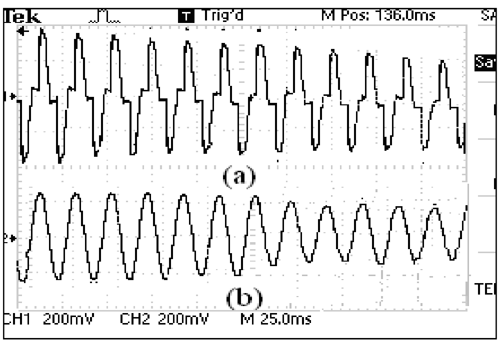

Figure 8 Experimental results - Source current waveforms for the induction motor drive load under balanced system with adaptive shunt hybrid filter – dynamic conditions; (a) Without filter, (b) With adaptive shunt hybrid filter

Table 5(a). Fundamental component of source current and THD in source current at the point of common coupling with variable speed induction motor drive after the installation of Adaptive Shunt Hybrid Filter – Dynamic conditions

Cycle	Fundamental component of source current (p.u.)			THD in Source Current (%)	% of 5^{th} harmonic	% of 7^{th} harmonic	% of 11^{th} harmonic	% of 13^{th} harmonic
	Phase a	Phase b	Phase c	Phase a	Phase A	Phase A	Phase a	Phase A
I	0.84	0.84	0.84	3.15	2.2	1.6	0.7	0.4
II	0.72	0.72	0.72	3.24	2.31	1.59	0.6	0.31
III	0.60	0.60	0.60	3.56	2.43	1.87	0.78	0.35
IV	0.48	0.48	0.48	3.32	2.36	1.63	0.63	0.32
V	0.36	0.36	0.36	3.26	2.34	1.60	0.58	0.29
VI	0.23	0.23	0.23	3.19	2.5	1.4	1.2	0.9

Table 5(b). Estimate of Power system parameters in each cycle under dynamic load conditions with the installation of Adaptive Shunt Hybrid Filter

Cycle	Displacement power factor	Distortion power factor	Source power factor	Power Delivered by Source			
				Real Power (pu)	Reactive Power (pu)	Apparent Power (pu)	Distortion Power (pu)
I	1	0.9991	0.9991	0.84	0	0.84	0
II	1	0.998	0.998	0.72	0	0.72	0
III	1	0.997	0.997	0.60	0	0.60	0
IV	1	0.997	0.997	0.48	0	0.48	0
V	1	0.998	0.998	0.36	0	0.36	0
VI	1	0.999	0.999	0.23	0	0.23	0

The simulation and experimental results related to the adaptive shunt hybrid filter illustrated:

a) A single controller is used for controlling both adaptive shunt passive filter and adaptive shunt active filter
b) The digital ANN based controller is flexible and easy to implement in large quantities.
c) In the case of adaptive shunt hybrid filter, the kVA delivered by source for the load is much less compared with shunt adaptive passive filter or ANN controller based shunt active filter.
d) The fundamental reactive power drawn from source is much reduced and hence source power factor is improved.
e) The performance of the ANN controller is satisfactory with balanced/ unbalanced source and balanced/unbalanced nonlinear load under steady state and dynamic conditions.

5. CONCLUSION

Adjustable speed induction motor drives cause large amounts of current and voltage harmonic distortions and reactive power absorption at the point of common coupling. The propagation of distortions throughout the power system affects lifetime of all other power system equipment. Various power quality improvement schemes were suggested by different authors. This paper shows an ANN based adaptive shunt hybrid filter for power quality enhancement in a variable speed drive system. The simulation and experimental results show effective performance of adaptive shunt hybrid filter under steady state and transient conditions.

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