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Modeling and Control of Three-Phase Shunt Active Power Filter

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Abstract: In this research the performance of a three-phase shunt active power filter (APF) using Model Reference Controller (MRC) has been compared with that using instantaneous active and reactive (p-q) theory. The novelty of this research lies in the application of MRC to generate the amplitude of the reference supply current required by the APF circuit and the successful implementation of the APF system for harmonic elimination. The entire system has been modeled using MATLAB 6.1 toolbox. Simulation results demonstrate the applicability of MRC for the control of APF.

Key words: APF, MRC, VSI, harmonics, THD, p-q theory, power quality

INTRODUCTION

The major causes of power quality problems are due to the wide spread application of static power electronic converters, saturable devices, fluorescent lamps and arch furnaces. Some of the adverse effects of poor power quality are reduced motor life, increased losses, mal-operation, electromagnetic interference, increased heating, and faulty timing signals. Even though there are no standard waveforms for the purpose of specifying power quality problems, IEEE standard, American national standard guides (ANSI), British standards (BS), European norms (EN), etc. are widely followed to maintain electrical power quality. The IEEE standard 519 is a recommended practice for power factor correction and harmonic impact limitation at static power converters. IEEE-519 standard limits the total harmonic distortion (THD) of voltage and current below 5 %.

Active power line conditioners have been proposed for harmonic elimination and power factor improvement[1-11], cancellation of negative and zero sequence components[12-15], voltage sag and swell[16]. Many conventional control strategies have been proposed and implemented for the successful control of APF system. Recent research shows the effectiveness of artificial intelligent (AI) based controllers such as fuzzy logic controller and neural network controllers for the control of APF system[17-25].

This research proposes MRC for the control of APF system. The novelty of this research lies in the application of MRC for the determination of amplitude of reference supply current required in an APF system. This research also discusses the control of APF system using p-q theory. The control strategies of APF system are detailed in the second part of this research. Simulation results in the third part demonstrate the effectiveness of MRC for the control of APF system.

CONTROL TECHNIQUES OF APF SYSTEM

In this part of study control scheme of APF system using p-q theory is discussed and compared with that using MRC.

Principle of operation: A three-phase system feeding an inverter load has been selected to study the performance of the APF system. It has been observed that due to the non-linear characteristics of power electronics loads the THD's of source current and terminal voltage fall well below the IEEE-519 standard and in principle APF system is used to inject a current equal in magnitude but in phase opposition to harmonic current to achieve a purely sinusoidal current wave in-phase with the supply voltage. Figure 1[26] shows the single-line diagram of a simple power system with APF system ON. The heart of the APF system is the IGBT based voltage source inverter (VSI). A dc capacitor is used to deliver power for the VSI. For the successful operation of APF, capacitor voltage should be at least 150 % of maximum line-line supply voltage. Since the PWM VSI is assumed to be instantaneous and infinitely fast to track the compensation currents, it is modeled as a current amplifier with unity gain and the

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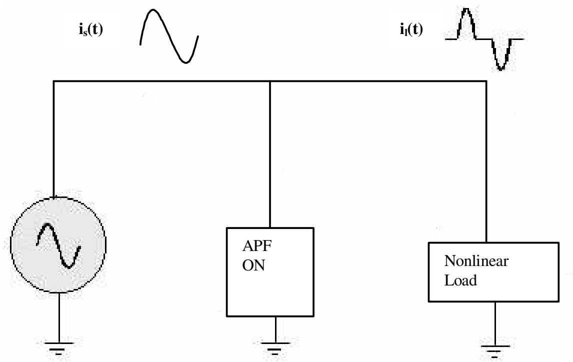

Fig. 1: Single-line diagram of a simple power system with APF ON

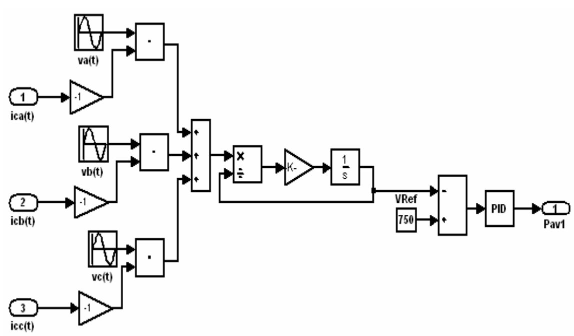

Fig. 2: Inverter sub-system

Simulink model of the inverter sub system used is shown in Fig. 2[27].

Control of APF system using p-q theory: The p-q theory proposed by Akagi[1] to determine the compensation current to be injected by the APF system for harmonic elimination and reactive power uses Park's transformation from three-phases (a,b,c) to two phases (α and β). Thus the three phase supply voltages and load currents could be transformed into the (α-β) orthogonal coordinates as follows:

$$\begin{bmatrix} v_{s\alpha}(t) \\ v_{s\beta}(t) \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_{sa}(t) \\ v_{sb}(t) \\ v_{sc}(t) \end{bmatrix}$$

$$\begin{bmatrix} i_{l\alpha}(t) \\ i_{l\beta}(t) \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{la}(t) \\ i_{lb}(t) \\ i_{lc}(t) \end{bmatrix}$$

According to p-q theory, determination of instantaneous real power p_l (t) and imaginary power q_l (t) is given by the expression

$$\begin{bmatrix} p_l(t) \\ q_l(t) \end{bmatrix} = \begin{bmatrix} v_{s\alpha}(t) & v_{s\beta}(t) \\ -v_{s\beta}(t) & v_{s\alpha}(t) \end{bmatrix} \begin{bmatrix} i_{l\alpha}(t) \\ i_{l\beta}(t) \end{bmatrix}$$

where p_l (t) and q_l (t) contain dc and ac terms and can be written as

$$p_l(t) = \bar{p} + \tilde{p}$$
$$q_l(t) = \bar{q} + \tilde{q}$$

To achieve unity power factor and harmonic elimination, the ac term $\tilde{p}$ and the imaginary power $q_l(t)$ have to be eliminated. The compensation power $\tilde{p}$ could be obtained by filtering out the ac components from $p_l(t)$. Thus

$$p^*_c(t) = \tilde{p} \quad \text{and}$$
$$q^*_c(t) = q_l(t)$$

The reference compensation current in the (α-β) plane is given by the expression

$$\begin{bmatrix} i^*_{c\alpha}(t) \\ i^*_{c\beta}(t) \end{bmatrix} = \begin{bmatrix} v_{s\alpha}(t) & v_{s\beta}(t) \\ -v_{s\beta}(t) & v_{s\alpha}(t) \end{bmatrix}^{-1} \begin{bmatrix} p^*_c(t) \\ q^*_c(t) \end{bmatrix}$$

and the reference compensation currents for phase a, phase b and phase c could be evaluated using Park's backward transformation and given in matrix form as follows:

$$\begin{bmatrix} i^*_{ca}(t) \\ i^*_{cb}(t) \\ i^*_{cc}(t) \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i^*_{c\alpha}(t) \\ i^*_{c\beta}(t) \end{bmatrix}$$

Figure 3 shows the simulink model of APF control system using p-q theory.

Control of APF system using MRC: MRC is successfully used for the control of UPQC[28]. Fig. 4 shows the simulink model of MRC controlled APF system, whereas in Fig. 5 the detailed control structure of APF system using MRC is illustrated. Model reference controller uses two neural networks: a plant model network and a controller network. To train the controller, first of all neural network plant model shown in Fig. 6 has been identified and trained. Following that

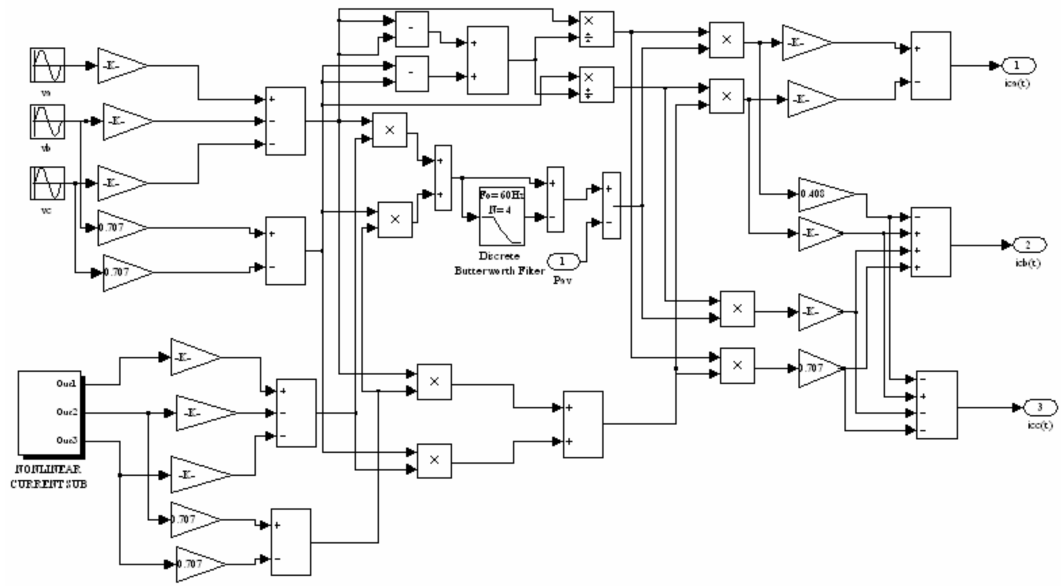

Fig. 3: Simulink model of APF system using p-q theory

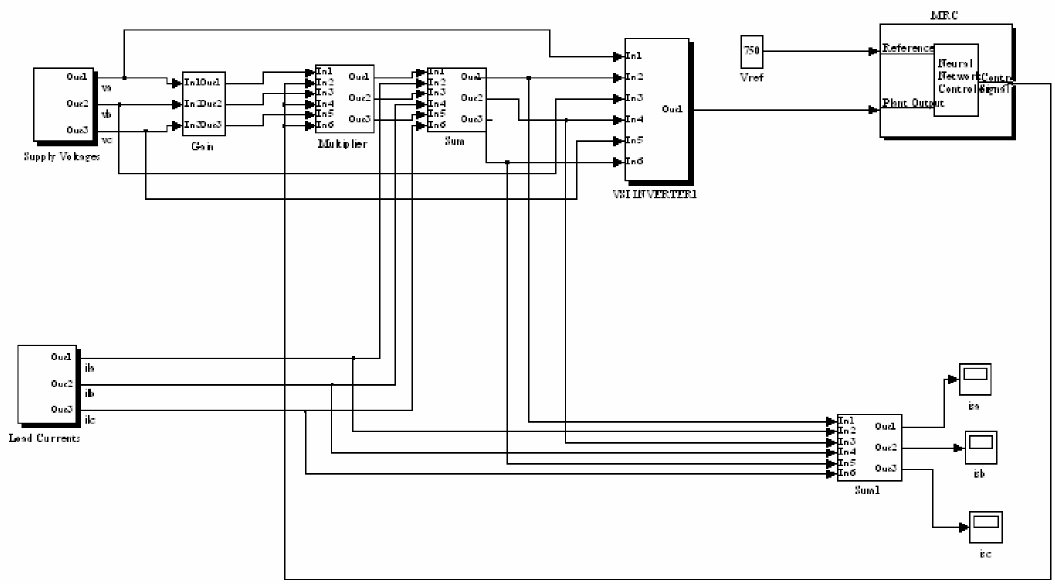

Fig. 4: APF system using MRC

training data has been generated using a simulink reference model. The Levenberg-Marquadrat algorithm is used for training the neural network plant model. The controller training is computationally expensive and time consuming as it requires dynamic back propagation. The BFGS (Broyden, Fletcher, Goldfarb, and Shanno) training algorithm was used to train the controller.

As shown in Fig. 4, the control input of the plant is the amplitude of the desired mains current and the capacitor voltage is the plant output. MRC checks the desired capacitor voltage and the actual capacitor voltage and the control input is adjusted to achieve the reference value. Table 1 and 2 show the specifications of the plant model network and controller network. It has been observed that the complicated equations in p-q

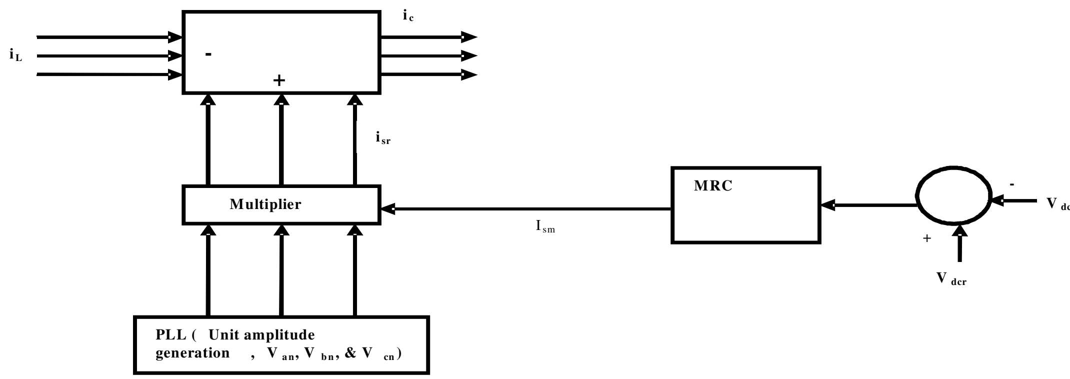

Fig. 5: Control circuit using MRC

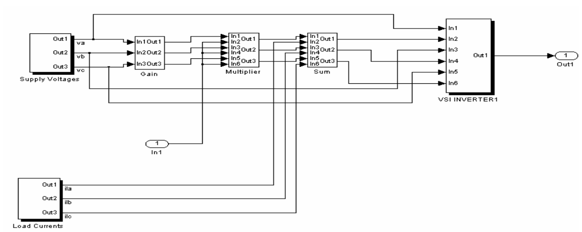

Fig. 6: Plant model

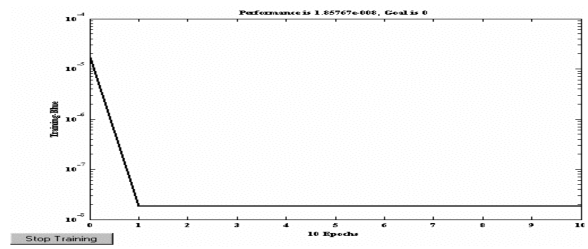

Fig. 7: Performance graph

Table 1: Plant model specifications

Size of hidden layer	1
Sampling interval (s)	$6.254e^{-5}$
No. of delayed plant inputs	2
No. of delayed plant outputs	1
Training samples	50000
Maximum plant input	1.8
Minimum plant input	1.5
Maximum interval value (s)	0.05
Minimum interval value (s)	0.01
Maximum plant output	800
Minimum plant output	700
Training Epochs	100
Training Function	trainlm
Use current weights	selected
Use validation data	selected
Use testing data	selected

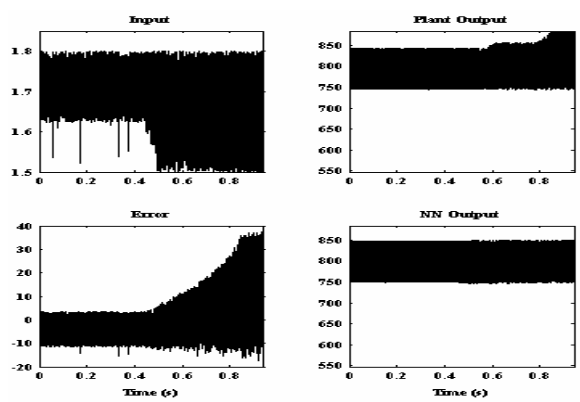

Fig. 8: Training data

Table 2: Specifications of Model reference control

Size of hidden layer	1
Sampling interval (s)	$6.254e^{-5}$
No. delayed reference inputs	1
No. delayed controller outputs	1
No. delayed plant outputs	1
Training samples	50000
Maximum plant input	1.8
Minimum plant input	1.5
Maximum interval value (s)	0.05
Minimum interval value (s)	0.01
Training Epochs	10
Controller training segments	2
Use current weights	selected
Use cumulative training	unselected

theory could be eliminated by the use of MRC. Sample performance graph, training data, reference model and neural network outputs obtained are illustrated in Fig. 7 and Fig. 8 and 9 respectively.

RESULTS AND DISCUSSION

An APF system based on MRC has been successfully modeled and tested using MATLAB 6.1 toolbox. The effectiveness of the system has been tested for various firing angles (α) in the range of 0° and 180°.

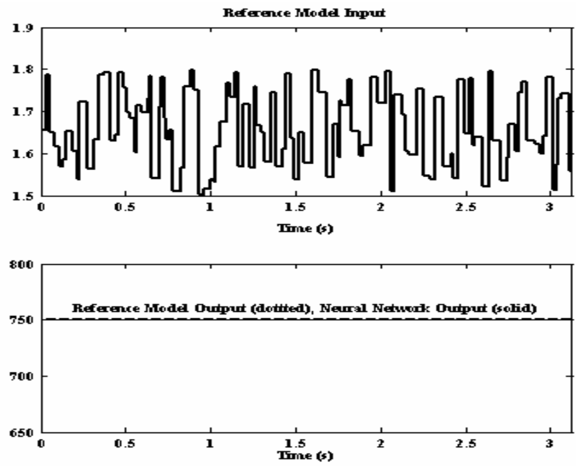

Fig. 9: Reference model and neural network outputs

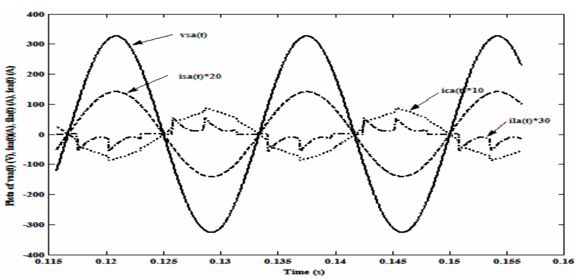

Fig. 10: Plots of vsa(t), isa(t), ila(t), ica(t) using MRC

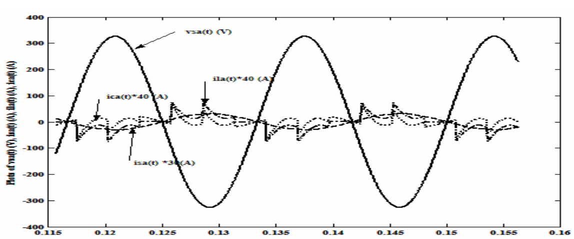

Fig. 11: Plots of vsa(t), isa(t), ila(t), ica(t) using p-q theory

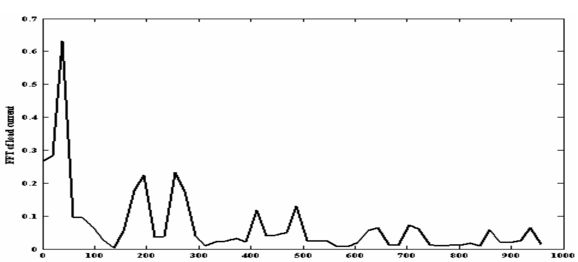

Fig. 12: Frequency spectrum of load current

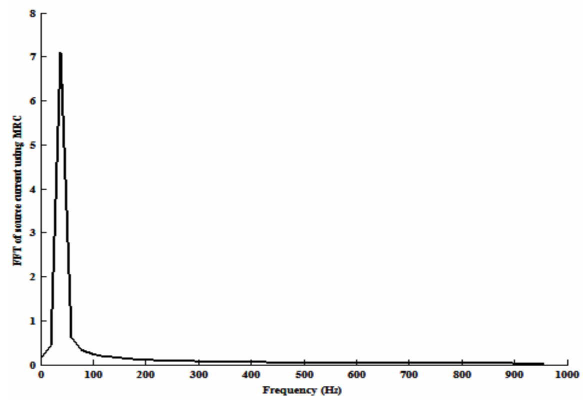

Fig. 13: Frequency spectrum of source current after compensation using MRC based APF system

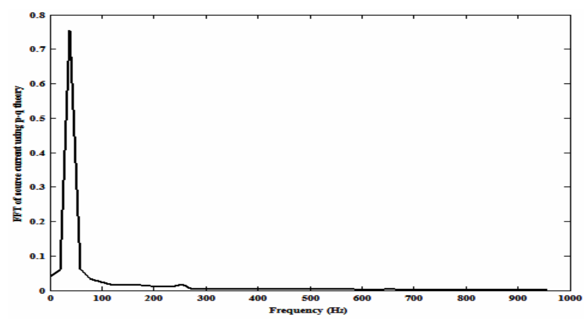

Fig. 14: Frequency spectrum of source current after compensation using p-q theory based APF system

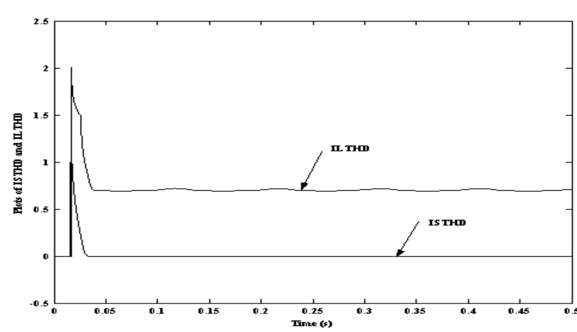

Fig. 15: THD of source and load currents after compensation using MRC

The performance of the developed system is illustrated with the one using p-q theory for $\alpha = 165°$ as shown in Fig.10-15. It has been observed that using p-q theory, for $\alpha = 165°$, as the load is in the inverter mode, the source currents are 180° out of phase with the respective supply voltages. However using MRC source currents are in-phase with the supply voltages. One may observe that in MRC based APF system, reference source currents are obtained by multiplying the required amplitude of the source currents with the unit amplitude waveform in-phase with the supply voltages.

CONCLUSION

An MRC based APF system has been modeled and successfully tested for the control of APF. The novelty of this research lies in the application of MRC to determine the amplitude of the reference source current required in an APF system. This research also discusses modeling and control of APF system using p-q theory. The performance of the different system has been compared. It has been observed that the complicated calculations used in p-q theory could be eliminated by the use of MRC.

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