ANALYSIS OF SHUNT HYBRID ACTIVE POWER FILTER FOR MITIGATING CURRENT HARMONICS WITH NOVEL APPROACHES

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Abstract— Improving the power quality by mitigating the current harmonics in distribution system is essential for the safe operation of the power system. Shunt hybrid active power filter (SHAF) gives the optimum performance in mitigating the current harmonics as compared with other harmonic filters. In this research paper, two control techniques namely instantaneous reactive power theory (p-q) and synchronous reference frame theory (id- iq) are implemented to estimate the performance of SHAF under various balanced, unbalanced and distorted supply voltage conditions. The proposed SHAF was also tested under transient conditions. The effectiveness of fuzzy logic (Type-1&2) controller over PI controller in maintaining constant DC link capacitor voltage and mitigating current harmonics was also analyzed. Extensive MATLAB simulations have been carried out to compare the performance of the proposed SHAF under various supply and load conditions, control techniques and DC link voltage controllers.

Keywords— Harmonics, Shunt hybrid active filter, Instantaneous reactive power theory (p-q), Synchronous reference frame theory (id-iq) and DC link voltage controller

1. INTRODUCTION

Power quality is defined as maintaining the pure voltage and current waveforms at the load bus of point of common coupling (PCC) [1]. It is one of the down beat issues for the power semiconductor industries, tire making industries and food processing industries [2]. Power quality is one of the most important studies in electrical engineering. It has created a great challenge to both the electric utilities and the manufacturers. Many power quality issues like voltage sags, swells, interruptions, notches, flickers, transients and harmonics will affect the performance of the power system [3]. Most of the power quality issues are due to the bridge rectifiers, adjustable speed drives, lift elevators, fluorescent lamps, arc furnaces, induction motor. All these loads are non linear in nature [4]. The most frequent power quality issue in power system is the generation of harmonics. Harmonic generation leads to the malfunctioning of circuit breaker, damaging sensitive equipment, overheating of neutral conductor, copper and iron loss, thermal stresses in cables, transformers and rotating machines [5].

Power quality can be improved either by active filtering or passive filtering. Passive filtering offers cost effective solution, however few shortcomings are reported in terms of

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dependence on source impedance, losses, size, and flexibility in compensation [6]. Active filtering can eliminate all these drawbacks with relatively small increment in the cost and size whereas combination of active and passive filter called as hybrid filter topology gives the low cost and optimal solution as compared with the active filters alone [6]-[7]. Many hybrid filter topologies have been already implemented and realized in the literature.

SHAF is a combination of shunt active filter (SAF) and tuned passive filter (TPF). The performance of SAF depends on three controls namely reference current extraction, DC link capacitor controller and Pulse generator. The TPF can be either single tuned or double tuned. The double TPF gives superior performance, reduced size, low cost as compared with single TPF. TPFs are efficient in eliminating lower order current harmonics whereas SAF in eliminating higher order current harmonics hence the KVA burden on SAF is greatly reduced. Thus the combination of SAF and double TPF gives the most economical configuration called as SHAF in improving power quality in distribution systems under non linear loading conditions.

In this paper, SAF with two control techniques are analyzed. They are p-q and id-iq. The performances of double TPF over two single TPFs are analyzed. The effect of fuzzy logic controller (type-1 and type-2) over PI controller in regulating DC link capacitor voltage under various supply and load conditions was also analyzed.

In this research paper section 1 details about the introduction, Section 2 elaborates about p-q and id-iq theory, The design of TPFs are explained in section 3, DC link capacitor voltage controllers design was explained in section 4, The results and discussions are explained in section 5, Section 6 deals with the conclusions and future scope.

2. INSTANTANEOUS REACTIVE POWER THEORY (p-q) AND SYNCHRONOUS REFERENCE FRAME THEORY (id- iq)

Fig. 1 Block diagram of the proposed SHAF

Fig. 1 gives the topology of SHAF in which active filter and passive filter connected in shunt with the system to mitigate the current harmonics due to the bridge rectifier which acts as a nonlinear load. Two control techniques adopted in this work as a reference current extraction. They are instantaneous reactive power (p-q) theory and Synchronous reference power (id-iq) theory. PI, fuzzy-1 and fuzzy-2 DC link capacitor voltage controllers are implemented for both the p-q and id-iq control techniques. The performances of these DC link capacitor voltage controllers with p-q and id-iq control techniques for SAF is evaluated first then double TPF connected to the SAF. The performance of the SHAF is evaluated under various source and load conditions.

Hysteresis current controller (HCC) was served as a pulse generator for the entire analysis.

2.1. P-Q CONTROL THEORY

Fig. 2 Block diagram of the conventional p-q control theory

p-q control depends on instantaneous values in three phase systems with or without neutral wire. It is applicable to steady-state and transient conditions, as well as for ideal voltage and current waveforms [8]-[11]. It consists of Clarke transformation of the three-phase voltages and currents in the a-b-c coordinates to the α - β -0 coordinates, followed by the calculation of the p-q theory instantaneous power components [8]-[11].

The conventional p-q theory as shown in Fig. 2 can be used to control the active filters. Conventional p-q control does not hold well in case of distorted supply voltage conditions. Modified p-q control allows sinusoidal control strategy which holds well even under distorted supply voltage conditions. The interesting points from modified p-q are:

- It can be applied to any three phase system (balanced or unbalanced, with or without harmonics in both voltages and currents).
- It allows very good dynamic response.

Modified p-q control makes use of positive sequence voltage detector which extracts the positive sequence supply voltage from the distorted supply voltage as shown in Fig.3. The modified p-q control as shown in Fig.4 is same as conventional p-q control theory except positive sequence voltage detector.

Fig. 3 Positive sequence voltage detector

Fig. 4 Modified p-q control theory

2.2. id-iq CONTROL THEORY

Fig.5 id-iq control theory

The id-iq control theory as shown in Fig.5, in which current signals are converted to a park transformation. Fundamental signals become DC quantities, and then the harmonic signals are extracted [17]-[19]. The feedback in DC bus voltage is generally used to get self-supporting DC bus [20]-[25].

Park's transformation is a rotational transformation which always gives better dynamic performance than Clark's transformation since Clark's transformation is a stationary frame does not give better performance under dynamic loading conditions.

3. DESIGN OF TUNED PASSIVE FILTER (TPF)

TPFs are very effective in eliminating lower order current harmonics thus these filters will greatly reduce the KVA burden on SAF. Mainly TPFs are classified into single TPF and double TPF.

3.1. DESIGN OF SINGLE TPF

Fig. 6 Single TPF and its characteristics

The circuit diagram of single TPF and its characteristics is shown in Fig.6

The inductive reactance X_L is given by Eqn. (1)

$$X_L = 2\pi f_n L_n \quad (1)$$

Where f_n is the n^{th} harmonic frequency

The capacitive reactance X_C is given by Eqn. (2)

$$X_C = \frac{1}{2\pi f_n C_n} \quad (2)$$

At resonance

$$X_L = X_C \quad (3)$$

$$2\pi f_n L_n = \frac{1}{2\pi f_n C_n} \quad (4)$$

The resonant frequency f_n is given in Eqn. (5)

$$f_n = \frac{1}{2\pi \sqrt{L_n C_n}} \quad (5)$$

The desired value of capacitance for tuning is given in Eqn. (6)

$$C_n = \frac{1}{L_n (2\pi f_n)^2} \quad (6)$$

The desired value of inductance for tuning is given in Eqn. (7)

$$L_n = \frac{1}{C_n (2\pi f_n)^2} \quad (7)$$

The desired value of resistance for tuning is given in Eqn. (8)

$$R_n = \frac{L_n(2\pi f_n)}{Q} \quad (8)$$

The quality factor is given by Eqn. (9)

$$Q = R_n \sqrt{\frac{C_n}{L_n}} \quad (9)$$

The quality factor lies 15 to 100. It gives the sharpness of filtering.

The selection of C is based on the reactive power demand of the load. The formula to choose the value of C is given by Eqn. (10)

$$Q_C = \frac{V_{L-L}^2}{X_C} \quad (10)$$

Where Q_C is the reactive power generation by C

X_C is the capacitive reactance

V_{L-L}^2 is the line voltage

3.1. DESIGN OF DOUBLE TPF

Fig. 7 Double TPF and its characteristics

Double tuned passive filter as shown in Fig.7 offers lower impedance path for the two tuned frequencies at the resonance condition. Double tuned filter gives better performance in eliminating current harmonics as compared with two single tuned filters of the same tuned frequencies. The design of double tuned filters is done by two methods equivalent method and parametric method. In this research, parametric method was considered due to its superior performance than equivalent method. The equations to calculate the parameters of double TPF is given by Eqn. (11), (12), (13) & (14)

$$C_1 = C_a + C_b \quad (11)$$

$$C_2 = \frac{C_a C_b (C_a + C_b) (L_a + L_b)^2}{(L_a C_a - L_b C_b)^2} \quad (12)$$

$$L_1 = \frac{L_a L_b}{L_a + L_b} \quad (13)$$

$$L_2 = \frac{(L_a C_a - L_b C_b)^2}{(C_a + C_b)^2 (L_a + L_b)} \quad (14)$$

4. Design of DC Link Capacitor Voltage Controller

4.1. DESIGN OF PI CONTROLLER

Ziegler–Nichols method Heuristic tuning method is very popular in calculating Kp and Ki values. First Ki and Kd gains are first set to zero. The Kp is increased until it reaches the gain Ku, where the output of the loop starts to oscillate [26]. Ku and the oscillation period Pu are used to set the gains as shown in Table I.

Table I. Ziegler–Nichols method of tuning PI controller

Control Type	Kp	Ki	Kd
P	0.50Ku	-	-
PI	0.45Ku	1.2Kp/Pu	-
PID	0.60Ku	2Kp/Pu	KpPu/8

These gains are applicable to the ideal, parallel form of the PID controller. For the standard PID controllers, the time constants for integral and derivative Ti and Td are purely dependent on the oscillation period Pu [26].

4.2. DESIGN OF FUZZY LOGIC CONTROLLER

Fig. 8 Block diagram of type-1 fuzzy logic controller

The block diagram of Type-1 fuzzy logic controller is shown in Fig.8 [27]-[33]. In this proposed paper both Type-1 and Type-2 fuzzy logic controllers are implemented. The advantage of Type-2 fuzzy logic controller is that it handles uncertainties effectively as compared with Type-1 fuzzy logic controller [34]-[39]. The rules for implementing both Type-1 and Type-2 are shown in Table 2.

Fig.9 shows the membership functions used for Type-1 and Type-2 fuzzy logic controllers. In this project triangular membership functions are being used. Fig.10 shows the block diagram of Type-2 fuzzy logic controller. An open source tool box was used for implementing the Type-2 fuzzy logic controller as shown in Fig.11 [40].

Fig. 9 Type-1 and Type-2 fuzzy logic membership functions

Fig. 10 Type-2 Fuzzy logic controller

Fig. 11 Type-2 Fuzzy logic tool boxes in MATLAB

Table II. Fuzzy Rules

ΔE \ E	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

6. RESULTS AND DISCUSSIONS

The following results are obtained by considering all the aforementioned practical conditions. The proposed shunt hybrid active filter worked well for the entire practical system conditions and met the IEEE 519-2014 standards on harmonics.

6.1. P-Q BASED SHUNT HYBRID ACTIVE FILTER WITH PI CONTROLLER AS A VOLTAGE REGULATOR

Fig.12, 13, 14 & 15 shows the performance of hybrid shunt active filter under balanced & unbalanced supply conditions and dynamic conditions with PI controller as a voltage regulator. The proposed hybrid shunt active filter works well for all the practical system conditions. The THD levels are well below the IEEE-519-2014 standards on harmonics. The DC link voltage was maintained constant under all practical conditions.

Active filter is switched on at 0.1 sec whereas passive filter is switched on at 0.2 sec and second load (Bridge Rectifier) is switched on at 0.4 sec. As an evident that system under balanced supply conditions, THD of shunt hybrid active filter was found 1.91 whereas THD of only active filter is 2.26 similarly proposed hybrid shunt active filter working well for all the practical conditions.

Fig.12 (a) Balanced Supply voltages with fixed load (b) FFT window (c) DC Link voltage

Fig.13 (a) Un-Balanced Supply voltages with fixed load (b) FFT window (c) DC Link voltage

Fig.14 (a) Balanced Supply voltages with dynamic load (b) FFT window (c) DC Link voltage

Fig.15 (a) Un-Balanced Supply voltages with dynamic load (b) FFT window (c) DC Link voltage

6.2. P-Q BASED SHUNT HYBRID ACTIVE FILTER WITH TYPE-1 FUZZY LOGIC CONTROLLER AS A VOLTAGE REGULATOR

Fig.16, 17, 18 & 19 shows the performance of hybrid shunt active filter under balanced and unbalanced supply conditions and dynamic conditions with Type-1 fuzzy logic controller as a voltage regulator. The proposed hybrid shunt active filter works well for all the practical system conditions. The THD levels are well below the IEEE-519-2014 standards on harmonics. The DC link voltage was maintained constant under all practical conditions.

Active filter is switched on at 0.1 sec whereas passive filter is switched on at 0.2 sec and second load (Bridge Rectifier) is switched on at 0.3 sec. As an evident that system under balanced supply conditions, THD of shunt hybrid active filter was found 0.84 whereas THD of only active filter is 1.3 similarly proposed hybrid shunt active filter working well for all the practical conditions.

Fig.16 (a) Balanced Supply voltages with fixed load (b) FFT window (c) DC Link voltage

Fig.17 (a) Un-Balanced Supply voltages with fixed load (b) FFT window (c) DC Link voltage

Fig.18 (a) Balanced Supply voltages with dynamic load (b) FFT window (c) DC Link voltage

Fig.19 (a) Un-Balanced Supply voltages with dynamic load (b) FFT window (c) DC Link voltage

6.3. P-Q BASED SHUNT HYBRID ACTIVE FILTER WITH TYPE-2 FUZZY LOGIC CONTROLLER AS A VOLTAGE REGULATOR

Fig. 20, 21, 22 & 23 shows the performance of hybrid shunt active filter under balanced & unbalanced supply conditions and dynamic conditions. The proposed hybrid shunt active filter works well for all the practical system conditions. The THD levels are well below the IEEE-519-2014 standards on harmonics. The DC link voltage was maintained constant under all practical conditions.

Active filter is switched on at 0.1 sec whereas passive filter is switched on at 0.3 sec and second load (Bridge Rectifier) is switched on at 0.6 sec. As an evident that system under balanced supply conditions, THD of shunt hybrid active filter was found 3.32 whereas THD of only active filter is 3.9 similarly proposed hybrid shunt active filter working well for all the practical conditions.

Fig. 20 (a) Balanced Supply voltages with fixed load (b) FFT window (c) DC Link voltage

Fig. 21 (a) Un-Balanced Supply voltages with fixed load (b) FFT window (c) DC Link voltage

Fig. 22 (a) Balanced Supply voltages with dynamic load (b) FFT window (c) DC Link voltage

Fig. 23 (a) Un-Balanced Supply voltages with dynamic load (b) FFT window (c) DC Link voltage

6.4. SRF BASED SHUNT HYBRID ACTIVE FILTER WITH PI AS A VOLTAGE REGULATOR

Fig.24, 25, 26 & 27 shows the performance of hybrid shunt active filter under balanced and unbalanced supply conditions and dynamic conditions. The proposed hybrid shunt active filter works well for all the practical system conditions. The THD levels are well below the IEEE-519-2014 standards on harmonics. The DC link voltage was maintained constant under all practical conditions.

Active filter is switched on at 0.2 sec, passive filter is switched on at 0.3 sec and second load (Bridge Rectifier) is switched on at 0.5 sec. As an evident that system under balanced supply conditions, THD of shunt hybrid active filter was found 1.70 whereas THD of only active filter is 1.98 similarly proposed hybrid shunt active filter working well for all the practical conditions.

Fig. 24 (a) Balanced Supply voltages with fixed load (b) FFT window (c) DC Link voltage

Fig. 25 (a) Un-Balanced Supply voltages with fixed load (b) FFT window (c) DC Link voltage

Fig. 26 (a) Balanced Supply voltages with dynamic load (b) FFT window (c) DC Link voltage

Fig. 27 (a) Un-Balanced Supply voltages with dynamic load (b) FFT window (c) DC Link voltage

6.5. SRF BASED SHUNT HYBRID ACTIVE FILTER WITH TYPE-1 FUZZY LOGIC CONTROLLER AS A VOLTAGE REGULATOR

Fig.28, 29, 30 & 31 shows the performance of hybrid shunt active filter under balanced & unbalanced supply conditions and dynamic conditions. The proposed hybrid shunt active filter works well for all the practical system conditions. The THD levels are well below the IEEE-519-2014 standards on harmonics. The DC link voltage was maintained constant under all practical conditions.

Active filter is switched on at 0.04 sec, passive filter is switched on at 0.3 sec and second load (Bridge Rectifier) is switched on at 0.5 sec. As an evident that system under balanced supply conditions, THD of shunt hybrid active filter was found 2.01 whereas THD of only active filter is 2.26 similarly proposed hybrid shunt active filter working well for all the practical conditions.

Fig. 28 (a) Balanced Supply voltages with fixed load (b) FFT window (c) DC Link voltage

Fig. 29 (a) Un-Balanced Supply voltages with fixed load (b) FFT window (c) DC Link voltage

Fig. 30 (a) Balanced Supply voltages with dynamic load (b) FFT window (c) DC Link voltage

Fig. 31 (a) Un-Balanced Supply voltages with dynamic load (b) FFT window (c) DC Link voltage

6.6. SRF BASED SHUNT HYBRID ACTIVE FILTER WITH TYPE-2 FUZZY LOGIC CONTROLLER AS A VOLTAGE REGULATOR

Fig.32, 33, 34 & 35 shows the performance of hybrid shunt active filter under balanced & unbalanced supply conditions and dynamic conditions. The proposed hybrid shunt active filter works well for all the practical system conditions. The THD levels are well

below the IEEE-519-2014 standards on harmonics. The DC link voltage was maintained constant under all practical conditions.

Active filter is switched on at 0.04 sec, passive filter is switched on at 0.2 sec and second load (Bridge Rectifier) is switched on at 0.5 sec. As an evident that system under balanced supply conditions, THD of shunt hybrid active filter was found 2.59 whereas THD of only active filter is 3.1 similarly proposed hybrid shunt active filter working well for all the practical conditions.

Fig. 32 (a) Balanced Supply voltages with fixed load (b) FFT window (c) DC Link voltage

Fig. 33 (a) Un-Balanced Supply voltages with fixed load (b) FFT window (c) DC Link voltage

Fig. 34 (a) Balanced Supply voltages with dynamic load (b) FFT window (c) DC Link voltage

Fig. 35 (a) Un-Balanced Supply voltages with dynamic load (b) FFT window (c) DC Link voltage

The comparison of p-q and SRF techniques with PI, fuzzy-1 and fuzzy-2 under mentioned practical conditions are shown in Fig. 36, 37 & 38

Fig. 36 p-q & SRF comparison with PI controller

Fig. 37 p-q & SRF comparison with fuzzy-1 controller

Fig. 38 p-q & SRF comparison with fuzzy-2 controller

The parameters for the proposed shunt hybrid active filter is shown in Table III.

Table III. Parameters for the proposed shunt hybrid active filter

Parameter	Value with units
Source Voltage ($V_{rms \text{ Ph-Ph}}$)	220 Volts
Source Resistance (R_s)	0.1Ω
Source Inductance (L_s)	$0.15e-3 \text{ H}$
Load Resistance(R_L)	60Ω
Load Inductance(L_L)	$20e-3 \text{ H}$
DC Link Capacitance(C_{dc})	$35e-6 \text{ F}$
Interfacing Inductance(L_f)	$15e-3 \text{ H}$
DC Link Voltage(V_{dc})	440 Volts
K_P, K_I Gain Parameters for PQ Control	0.2, 1.5
K_P, K_I Gain Parameters for SRF Control	0.001,0.005

7. CONCLUSIONS AND FUTURE SCOPE

From the above discussions it can be evident that the proposed shunt hybrid active filter is robust under all practical conditions like unbalancing, dynamic loading and distorted supply conditions. The Foot Point of Uncertainty (FoU) in Type-2 allows handling uncertainties in the system effectively as compared with Type-1 fuzzy logic. From the results it has been observed that Type-2 fuzzy logic controller is very effective with SRF control technique than PQ control technique.

Many new controllers like Proportional Resonant (PR) controller allow the harmonic mitigation without Phase Locked Loop (PLL) which in turn will reduce the overall cost of shunt hybrid active filter. PR controller enables the selective harmonic elimination of our choice whereas conventional control techniques don't have that feature.

Based on the simulation results, an experimental prototype can be developed using D-Space or RTDS which allows the validity of simulation results with real time environment. Due to the limited facilities in our research laboratory, the experimental prototype was not done for this proposed research.

Harmonic extraction methods such as Adaline, sliding mode controller will improve the robustness of shunt hybrid active filter than conventional extraction methods.

Smart impedance based shunt hybrid active filter eliminates the drawbacks associated with passive filters such as tuning procedure, detuning and resonance problems.

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