INSTANTANEOUS POWER AND CURRENT STRATEGIES FOR CURRENT HARMONICS CANCELLATION USING SHUNT ACTIVE POWER FILTER WITH PI AND FUZZY CONTROLLERS

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ABSTRACT

In our day-to-day life, every load creates harmonics. The prevalent difficulties with harmonics are voltage and current waveform distortions. In addition, electronic equipment like computers, battery chargers, electronic ballasts, variable frequency drives and switched mode power supply generate large amount of harmonics. Issues related to harmonics are of a greater concern because they can overheat the building wiring, cause nuisance tripping, overheat transformer units, and cause random end-user equipment failures. Thus power quality is becoming more and more serious with each passing day. As a result, active power filters (APFs) have gained a lot of attention due to their excellent harmonic compensation.

The main objective of this paper is to analyse shunt active filters with fuzzy logic and PI controllers. To carry out this analysis active and reactive power(P-Q) and instantaneous active and reactive current (I_d-I_q)control strategies are considered. Extensive simulations will be carried out with PI and fuzzy controller for both active and reactive power (P-Q) and instantaneous active and reactive current(I_d-I_q)control strategies under different voltage conditions such as balanced, unbalanced and non-sinusoidal conditions. Using instantaneous active and reactive current (I_d-I_q) control method with fuzzy logic controllers gives an outstanding performance under any voltage conditions.

KEYWORDS— Harmonic Compensation, Shunt Active Filter (SHAF), and p-q Control Strategy, id-iq Control Strategy, PI Controller and Fuzzy Controller

INTRODUCTION

In recent years power quality has become an important and growing problem due to the proliferation of nonlinear loads such as power electronic converters in typical power distribution systems. Particularly, voltage harmonics and power distribution equipment problems are the result of current harmonics produced by nonlinear loads.
Eminent issues always arise in three-phase four-wire systems. It is well-known that zero line may be overheated or causes a fire as a result of excessive harmonic current going through the zero line three times or times that of three. Thus a perfect compensator is necessary to avoid the negative consequences of harmonics. Though several control techniques and strategies have been developed they still have contradictions with the performance of filters.

A shunt active power filter (SAPF) generates a harmonic current spectrum that is opposite in phase to the harmonic and/or reactive current it perceives at the load end. Harmonic and reactive currents are thus cancelled at the source end and the result is undistorted sinusoidal balanced currents. Fig.1 shows the general schematic of the voltage source active power filter. The Active filters overcome the problems occurring in the passive filter. Major Advantage of Active Filter over Passive Filter is that it can be controlled to compensate for harmonics in such a way that Total Harmonic Distortion(THD) lower than 5% at the Point of Common Coupling can effectively be achieved. The shunt Active Filter can also be made to act as a damping device in a parallel resonance circuit formed by the passive filter and the power supply system by adopting a lead function in its controller. Thus it can prevent harmonic propagation resulting from harmonic resonances

POWER QUALITY PROBLEMS & ISSUES

A recent survey of Power Quality experts indicates that 50% of all Power Quality problems are related to grounding, ground bonds, and neutral to ground voltages, ground loops, ground current or other ground associated issues. Electrically operated or connected equipment is affected by Power Quality [1, 2, 3, 4, 5, and 6]. Determining the exact problems requires sophisticated electronic test equipment. The following symptoms are indicators of Power Quality problems:
• Piece of equipment misoperates at the same time of day.
• Circuit breakers trip without being overloaded.
• Equipment fails during a thunderstorm.
• Automated systems stop for no apparent reason.
• Electronic systems fail or fail to operate on a frequent basis.
• Electronic systems work in one location but not in another location.

The commonly used terms those describe the parameters of electrical power that describe or measure power quality are Voltage sags, Voltage variations, Interruptions Swells, Brownouts, Blackouts, Voltage imbalance, Distortion, Harmonics, Harmonic resonance, Interharmonics, Notching, Noise,Impulse, Spikes (Voltage), Ground noise, Common mode noise, Critical load, Crest factor, Electromagnetic compatibility, Dropout, Fault, Flicker, Ground, Raw power, Clean ground, Ground loops, Voltage fluctuations, Transient, Dirty power, Momentary interruption, Over voltage, Under voltage, Nonlinear load, THD, Triplens, Voltage dip, Voltage regulation, Blink, Oscillatory transient etc [7,8,9,10,11].
The issue of electric power quality is gaining importance because of several reasons:
• The society is becoming increasingly dependent on the electrical supply. A small power outage has a great economical impact on the industrial consumers. A longer interruption harms practically all operations of a modern society.
• New equipments are more sensitive to power quality variations.

• The advent of new power electronic equipment, such as variable speed drives and switched mode power supplies, has brought new disturbances into the supply system.
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POWER QUALITY STANDARDS

Power quality is a worldwide issue, and keeping related standards current is a never-ending task. It typically takes years to push changes through the process. Most of the ongoing work by the IEEE in harmonic standards development has shifted to modifying Standard 519-1992.

IEEE 519

IEEE 519-1992, Recommended Practices and Requirements for Harmonic Control in Electric Power Systems, established limits on harmonic currents and voltages at the point of common coupling (PCC), or point of metering [12,13].
The limits of IEEE 519 are intended to:
1) Assure that the electric utility can deliver relatively clean power to all of its customers;
2) Assure that the electric utility can protect its electrical equipment from overheating, loss of life from excessive harmonic currents, and excessive voltage stress due to excessive harmonic voltage. Each point from IEEE 519 lists the limits for harmonic distortion at the point of common coupling (PCC) or metering point with the utility. The voltage distortion limits are 3% for individual harmonics and 5% THD. All of the harmonic limits in IEEE 519 are based on a customer load mix and location on the power system. The limits are not applied to particular equipment, although, with a high amount of nonlinear loads, it is likely that some harmonic suppression may be necessary.

IEEE 519 Standard for Current Harmonics

• *General Distribution Systems [120V- 69 kV]*
Below current distortion limits are for odd harmonics. Even harmonics are limited to 25% of the odd harmonic limits [12,14,15]. For all power generation equipment, distortion limits are those with $I_{SC}/I_L<20$. I_{SC} is the maximum short circuit current at the point of coupling “PCC”.I_L is the maximum fundamental frequency 15-or 30- minutes load current at PCC. TDD is the Total Demand Distortion (=THD normalized by IL) General Sub-transmission Systems [69 kV-161 kV] The current harmonic distortion limits apply to limits of harmonics that loads should draw from the utility at the PCC. Note that the harmonic limits differ based on the I_{sc}/I_L rating, where I_{SC} is the maximum short circuit current at the PCC, and I is the maximum demand load current at the PCC.

Voltage Source Active Power Filter, Based on Multi-Stage Converter and Ultracapacitor DC-Link

A multi-stage inverter using three-state converters is being analyzed for active filter and static var compensator applications. Each phase of the converter is composed of four three-state converters, all of them connected to the same DC link and its output connected thorough output transformers scaled in powers of three. The Filter can compensate load currents with high harmonic content and low power factor, obtaining sinusoidal currents from the source. A 1F Ultra capacitor is used in the DC link, making it possible to obtain a very stable voltage at the DC bus, even with highly contaminated currents. This high capacity also makes it possible to continue feeding the contaminating load during a Voltage Dip. The capacitor voltage is controlled simply by changing the phase angle of the converter, and thus changing the amount of active current flowing to and from the converter. The control is implemented with a non-linear PI gain and a modulation control to maintain a stable AC voltage during DC voltage drops. The great advantage of this kind of converter is the minimum harmonic distortion obtained. Simulation results for this application are shown and compared with similar results obtained with conventional PWM converters.

Harmonic Elimination, Power Factor Correction and Load Unbalancing Compensation

An active power filter is designed, simulated, implemented, and tested. It can work in different modes: active power filtering, power factor correction, and load unbalance compensation. It is based on a current controlled voltage-source inverter with fixed carrier PWM. The control algorithm generates the source reference currents based on the controlled DC link voltage. The dimensioning criteria of the inductive and capacitive power components is studied. The implementation is validated with simulated and experimental results obtained in a 5 kVA prototype.

Novel Three-Phase Active Power Filter

The performance and dynamic characteristics of a three-phase three-wired active power filter is proposed and analysed. In this paper both sliding mode (SLMC) and proportional-integral (PI) control algorithms are used. The SLMC controller regulates the external DC voltage control-loop that keeps the voltage across the DC capacitor constant, while the PI controller deals with the internal current control-loop for harmonic current suppression. The reactive power compensation is achieved without sensing or computing the reactive current of the load. Current harmonic compensation is implemented in the time domain allowing a fast time response. This proposed scheme employed the shunt APF topology together with the three-phase PWM voltage-source inverter. The principles of operation of the proposed three-phase active power filter along with the control circuit components are discussed in detail. The performance of this system has been assessed, using pspice simulator.

Fuzzy based evolutionary algorithm for reactive power optimization with FACTS devices

The optimization techniques such as Genetic Algorithm (GA) and Differential Evolution (DE) along with Fuzzy Logic (FL) is used for the optimal setting of power system variables, including Flexible AC Transmission Systems (FACTS) devices. Here, two types of FACTS devices, Thyristor Controlled Series Compensator (TCSC) and Static Var Compensator (SVC) are used for the optimal operation of the power system as well as in reducing congestion in transmission lines. Optimal placement of FACTS devices in the heavily loaded power system reduces transmission loss, controls reactive power flow, improves voltage profile of all nodes and also reduces operating cost. In this proposed approach fuzzy membership function is used for the selection of weak nodes in the power system for the placement of SVC’s as one of the FACTS devices while the location of TCSC’s are determined by the reactive power flow in lines. The proposed technique is compared with other optimization methods using different globally accepted evolutionary algorithms where the nodes are detected by eigen value analysis and the amount of FACTS devices are determined by evolutionary techniques like, Genetic Algorithm (GA), Differential Evolution (DE) and Particle Swarm Optimization (PSO). The superiority of the proposed fuzzy based optimization approach is established by the results and the comparative analysis with other methods.

PI and fuzzy logic controllers for shunt active power filter

It presents a shunt Active Power Filter (APF) for power quality improvements in terms of harmonics and reactive power compensation in the distribution network. The compensation process is based only on source current extraction that reduces the number of sensors as well as its complexity. A Proportional Integral (PI) or Fuzzy Logic Controller (FLC) is used to extract the required reference current from the distorted line-current, and this controls the DC-side capacitor voltage of the inverter. The shunt APF is implemented with

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PWM-current controlled Voltage Source Inverter (VSI) and the switching patterns are generated through a novel Adaptive-Fuzzy Hysteresis Current Controller (A-F-HCC). The proposed adaptive-fuzzy-HCC is compared with fixed-HCC and adaptive-HCC techniques and the superior features of this novel approach are established.

The controller is the most significant part of the active power filter and currently various control strategies are proposed by many researchers [16–18]. There are two major parts of the controller, one is reference current extraction from the distorted line current and another is the PWM-current controller to generate switching patterns for inverter [19, 20]. Many control strategies are proposed in the literature to extract the harmonic components. However, the conventional PI controller requires precise linear mathematical model of the system, which is difficult to obtain under parameter variations and non-linear load disturbances. Another drawback of the system is that the proportional and integral gains are chosen heuristically [21, 22]. Recently, Fuzzy Logic Controllers (FLCs) have been used in various power electronic applications and also in active power filters [23,24]. The advantage of FLCs over the conventional controllers is that it does not need an accurate mathematical model. It can handle nonlinearity and is more robust than conventional PI or PID controllers [25, 26].

Instantaneous active and reactive power (p–q) theory

Instantaneous reactive power theory (or pq theory) was first proposed by Akagi and co-authors in 1984 [27], and has since been the subject of various interpretations and improvements. In this method [28], a set of voltages (v_a, v_b, v_c) and currents (i_{la}; i_{lb}; i_{lc}) from phase coordinates are first transferred to the 0αβ coordinates using Clarke transformation:

$$\begin{bmatrix} V_0 \\ V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \tag{2}$$

The p–q formulation defines the generalized instantaneous
power, p(t), and instantaneous reactive power vector, q(t) [29] in terms of the a–b–0 components as

$$\begin{bmatrix} p_0 \\ p \\ q \end{bmatrix} = \begin{bmatrix} v_0 & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \tag{3}$$

The objective of the p–q strategy [29] is to get the source to
give only the constant active power demanded by the load $Ps(t) = P_{L0}(t) + P_{Lab}(t)$ In addition, the source must deliver no zero sequence active power $is_{0ref} = 0$ (so that the zero-sequence component of the voltage at the PCC does not contribute to the source power). The reference source current in the a–b–0 frame is therefore

$$\begin{bmatrix} i_{c\alpha ref} \\ i_{c\beta ref} \\ i_{c0ref} \end{bmatrix} = \frac{\overline{P_{L\alpha\beta}} + \overline{P_{L0}}}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha \\ v_\beta \\ 0 \end{bmatrix} \tag{4}$$

Instantaneous active and reactive current (Id–Iq) theory

In this method [30, 31], only the currents magnitudes are transformed and the p–q formulation is only performed on the instantaneous active i_d and instantaneous reactive i_q components. If the d axis has the same direction as the voltage space vector $\bar{v}$, then the zero-sequence component of the current remains invariant. Therefore, the I_d–I_q method can be expressed as follows:

$$\begin{bmatrix} i_0 \\ i_{ld} \\ i_{lq} \end{bmatrix} = \frac{1}{v_{\alpha\beta}} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_0 \\ i_{l\alpha} \\ i_{l\beta} \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{1}{\sqrt{v_\alpha^2 + v_\beta^2}} \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (6)$$

Each current component (I_d–I_q) has an average value or dc component and an oscillating value or ac component

$$\begin{aligned} i_{ld} &= \overline{i_{ld}} + \tilde{i}_{ld} \\ i_{lq} &= \overline{i_{lq}} + \tilde{i}_{lq} \end{aligned} \quad (7)$$

The compensating strategy [30–32] (for harmonic reduction and reactive power compensation) assumes that the source must only deliver the mean value of the direct-axis component of the Load Current. The reference source current will therefore be

$$i_{cdref} = \overline{i_{ld}}; \quad i_{cqref} = i_{c0ref} = 0 \quad (8)$$

$$i_{ld} = \frac{v_\alpha i_{l\alpha} + v_\beta i_{l\beta}}{v_{\alpha\beta}} = \frac{P_{l\alpha\beta}}{\sqrt{v_\alpha^2 + v_\beta^2}} \quad (9)$$

Since the reference source current must to be in phase with the
voltage at the PCC [31, 32] (and have no zero-sequence component), it is calculated (in the a–b–0 coordinates) by multiplying the above equation by a unit vector in the direction of the PCC voltage space vector (excluding the zero-sequence component):

$$\begin{bmatrix} i_{c\alpha ref} \\ i_{c\beta ref} \\ i_{c0ref} \end{bmatrix} = \left(\frac{P_{l\alpha\beta}}{\sqrt{v_\alpha^2 + v_\beta^2}} \right)_{dc} \frac{1}{\sqrt{v_\alpha^2 + v_\beta^2}} \begin{bmatrix} v_\alpha \\ v_\beta \\ 0 \end{bmatrix} \quad (10)$$

Fuzzy Logic Controller

The concept of Fuzzy Logic Controller (FLC) was proposed by Professor Lotfi Zadeh in 1965, at first as a way of processing data by allowing partial set membership rather than crisp membership. Soon after, it was proven to be an excellent choice for many control system applications. Fuzzy control is based on a logical system called fuzzy logic. It is much closer in spirit to human thinking and natural language than classical logical systems [16]. Nowadays, fuzzy logic controller is used in almost all sectors of industry, power systems and science. One of them is the harmonic current and reactive power compensation control [17].

Fuzzification

The fuzzification module converts the crisp values of the control inputs error signal E and its variation E into fuzzy values. A fuzzy variable has values which are defined by linguistic variables (fuzzy sets or subsets) such as low, Medium, high, big, slow . . . where each is defined by a gradually varying membership function.

Rule Elevator

The basic fuzzy set operations needed for evaluation of fuzzy rules are AND, OR and NOT

AND -Intersection: $\mu_{A \cap B} = \min[\ \mu_A(X), \mu_B(X)]$

OR-Union: $\mu_{A \cup B} = \max[\ \mu_A(X), \mu_B(X)]$

NOT -Complement: $\mu_A = 1 - \mu_A(X)$

Defuzzification

The rules of fuzzy logic controller generate required output in a linguistic variable (Fuzzy Number), according to real world requirements; linguistic variables have to be transformed to crisp output (Real number). This selection of strategy is a compromise between accuracy and computational intensity.

Database

The Database stores the definition of the triangular membership function required by fuzzifier and defuzzifier. The determination of the membership functions depends on the designer experiences and expert knowledge.

Rule Base

The Rule base stores the linguistic control rules required by rule evaluator (decision making logic The formulation of its rule set plays a key role in improving the system performance [18-19-20].

DC Capacitor Voltage Control

Among the various available powers filter controllers PI, PID, RST hysteresis and fuzzy logic controller. In this application, the fuzzy control algorithm is implemented to optimize the energy storage of the DC capacitor voltage based on DC voltage error E(t) processing and its variation E(t) in order to
improve the dynamic performance of APF and reduce the total harmonic source current distortion [4]. Fuzzy logic uses linguistic variables instead of numerical variables. In a control system, error signal E, its variation E and output signal D E can be assigned as negative Large: (NL); negative medium :(NM); negative small :(NS); zero: (ZE); positive small: (PS); positive medium: (PM) and positive Large: (PL) The triangular membership function is used for fuzzifications. The process of fuzzification convert numerical variable (real number) to a linguistic variable (fuzzy number).

Table 1 .fuzzy control rule

E / ΔE	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	ZE
NM	NL	NL	NL	NM	NS	ZE	PS
NS	NL	NL	NM	NS	ZE	PS	PM
ZE	NL	NM	NS	ZE	PS	PM	PL
PS	NM	NS	ZE	PS	PM	PL	PL
PM	NS	ZE	PS	PM	PL	PL	PL
PL	NL	NM	NS	ZE	PS	PM	PL

CONCLUSION

A simple fuzzy logic based three-phase shunt active power filter for current harmonic elimination and reactive power compensation is presented in this paper. The performance of fuzzy logic controlled shunt APF has been studied and compared with the conventional PI controller. The steady state performance is comparable to the PI controller whereas transient response is found better than the PI controller. The system has fast dynamic response for varying load condition and harmonic spectrum is found well below 5%, harmonic limit imposed by the IEEE-519 standard.

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