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Grid Power Quality Enhancement Using Fuzzy Control-Based Shunt Active Filtering

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Abstract—Active filtering has proved efficient for the mitigation of harmonics in distribution grids. This paper deals with the design of fuzzy control strategies for a three-phase shunt active filter to enhance the power quality via the regulation of the DC bus voltage of the distribution network. The proposed control scheme is based on Interval Type 2 Fuzzy Logic controller. A simulation study is performed under Simulink/Matlab to evaluate the performance and robustness of the proposed control scheme.

Keywords—shunt active power filter, power quality, harmonic distortions, type 2 fuzzy logic..

I. INTRODUCTION

Power quality issues have become a major concern in recent years due to the widespread use of nonlinear loads such power electronic converters, variable speed motor drives and consumer electronics. Nonlinear loads introduce harmonics into the power network which cause a number of disturbances such as distortion of the current and voltage waveforms, electromagnetic interference, overheating of power distribution components inducing losses and reducing their lifetime [1], [2]. Active Power Filters (APFs) also called Active Power Line Conditioners (APLCs) are a relatively new technology which offers a more flexible alternative and provides superior filtering performance characteristics and faster transient response as compared to conventional passive filters consisting of custom-designed LC filters which are tuned to provide fixed frequency compensation [3].

APFs basically consist of a power electronic inverter and a control circuit. The performance of these filters systems depends mainly on the converter topology employed, the adopted reference current generation strategy for harmonic compensation as well as the controller for the regulation of the DC bus voltage. The regulation of the DC bus voltage consists of maintaining the voltage across the capacitor connected to the

inverter at the desired level. The role of the capacitor voltage is to compensate for inverter losses and any transient fluctuations in real power between the AC and DC sides following load changes. Various DC bus voltage control strategies have been proposed in the literature [4, 5].

Fuzzy systems have evolved for more than four decades and have proved to be a powerful technique in dealing with uncertainties, parameter variation and especially where the system model is complex or not accurately defined for the designed control action. They have been successfully implemented in many real world applications mainly focusing on quantitative modeling and control [6]. This paper presents a simplified design approach of an Interval Type-2 fuzzy logic controller (IT2FLC) [7,8] for DC bus voltage regulation. The proposed control strategies are evaluated through extensive simulation under various operating conditions of the SAPF such as system's parameters and nonlinear load variations.

The rest of the paper is organized as follows: Section 2 overviews the basic structure and control scheme of the shunt active power filter. Section 3 presents the proposed control strategy for the DC voltage. In Section 4, the overall system performance is evaluated and the simulations results are presented and discussed. Finally, Section 5 presents the conclusions of this work.

II. SHUNT AFP CONFIGURATION AND CONTROL SCHEME

A. Shunt AFP Configuration

The APF concept is to use an inverter to produce specific currents or voltages harmonic components to cancel the harmonic components generated by the load. The most commonly used APF configuration is the Shunt APF (SAPF)

which injects current harmonics into the point of common coupling (PCC). Fig. 1 shows basic principle of SAPF.

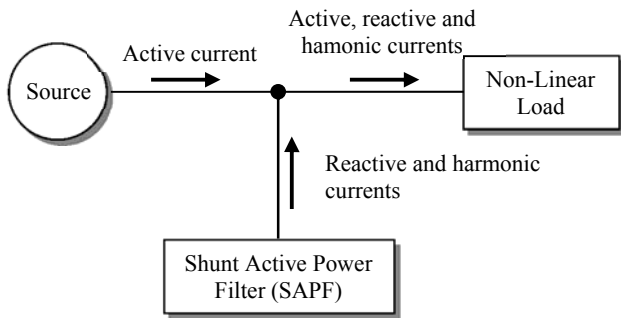


Fig. 1 Basic principle of a SAPF.

B. Control Scheme of the SAPF

The SAPF control strategy is implemented in three basic stages: The first is the harmonic detection method to identify harmonic level in the system. The second part is to derive the compensating currents and the third one is the control technique of the inverter for injecting these currents into the power system. The overall control system of the SAPF is depicted in Fig. 2.

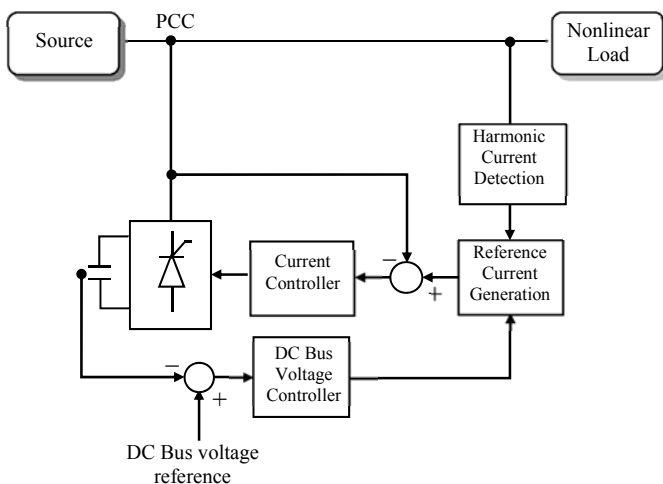


Fig. 2 SAPF control system implementation.

The Synchronous Detection Method (SDM) [9] is used here to calculate the reference current for SAPF due to its simplicity. It is based on the idea that the APF forces the source current to be sinusoidal and in phase with the source voltage despite the load variations.

In this algorithm, the peak values of source currents are assumed to be balanced after compensation.

$$I_{am} = I_{bm} = I_{cm} = I_m \quad (1)$$

Peak values of active current in each phase after compensation

$$I_{am} = \frac{2 \times p_a}{V_{am}} \quad I_{bm} = \frac{2 \times p_b}{V_{bm}} \quad I_{cm} = \frac{2 \times p_c}{V_{cm}} \quad (2)$$

Where p_a , p_b and p_c are real powers from each of the phases and V_{am} , V_{bm} and V_{cm} are peak values of phase voltages in the three phases. From equations (1) and (2):

$$\frac{2 \times p_a}{V_{am}} = \frac{2 \times p_b}{V_{bm}} = \frac{2 \times p_c}{V_{cm}} \quad (3)$$

The total average power is:

$$P_{av} = p_a + p_b + p_c \quad (4)$$

Rearranging gives:

$$p_a = \frac{V_{am}}{V_t} p_{av}; \quad p_b = \frac{V_{bm}}{V_t} p_{av}; \quad p_c = \frac{V_{cm}}{V_t} p_{av} \quad (5)$$

Where

$$V_t = V_{am} + V_{bm} + V_{cm} \quad (6)$$

The balanced current can be determined as:

$$i_{sa} = \frac{2 \times V_a \times p_a}{V_{am}^2} \quad (7)$$

$$i_{sb} = \frac{2 \times V_b \times p_b}{V_{am}^2} \quad (8)$$

$$i_{sc} = \frac{2 \times V_c \times p_c}{V_{cm}^2} \quad (9)$$

The compensation current references are thus,

$$i_{ca}^* = i_{sa} - i_a \quad (10)$$

$$i_{cb}^* = i_{sb} - i_b \quad (11)$$

$$i_{cc}^* = i_{sc} - i_c \quad (12)$$

The reference currents are then compared with the actual currents using hysteresis current comparator to generate the control signals for the inverter IGBT switches.

III. PROPOSED CONTROL STRATEGY FOR THE DC BUS VOLTAGE

The capacitor that powers the active filter acts as voltage source and its voltage must be kept constant to ensure that the performance of the filter is maintained and the voltage fluctuations of the semi-conductors do not exceed the limits prescribed [16]. The Interval Type 2 Fuzzy Logic Controller (IT2FLC) is implemented as shown in Fig. 3.

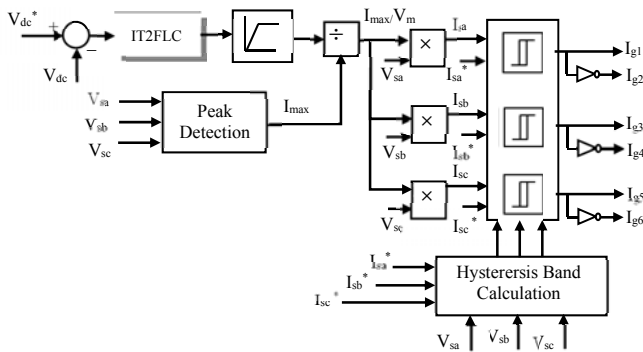


Fig. 3 Implementation of IT2FLC controller for the SAPF.

Type-2 fuzzy logic systems, introduced by Zadeh (1975) as an extension of ordinary Type-1 fuzzy logic systems, are characterized by fuzzy membership functions represented by fuzzy sets in $[0, 1]$ unlike a Type-1 fuzzy which have crisp membership functions. T2FLC consists of five components including fuzzifier, rule base, fuzzy inference mechanism, type-reducer and defuzzifier as depicted in Fig. 4.

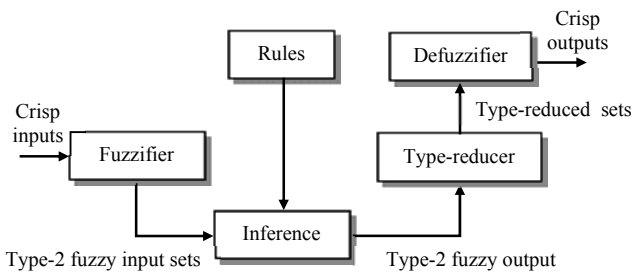


Fig. 4 Interval Type-2 fuzzy system (IT2FLS).

In a IT2FLC at least some of the fuzzy sets used in the antecedent and/or consequent parts and each rule inference output are type-2 fuzzy sets. Generally speaking, in a T2FLC, the crisp inputs are first fuzzified, usually into Type-2 fuzzy sets. The fuzzified Type-2 fuzzy sets then activate the inference engine and rule base to yield output Type-2 fuzzy sets by performing the union and intersection operations of Type-2 fuzzy set and compositions of Type-2 relations. Then a type-reduction process is applied to these output sets in order to generate Type-1 fuzzy sets (called type-reduced sets) by combining these output sets and performing a centroid calculation. Finally, the type-reduced Type-1 set is defuzzified to produce crisp output [7, 10].

A generalized rule for Type-2 fuzzy system is:

$$\text{IF } x_1 \text{ is } \bar{A}_{k1} \text{ and } x_2 \text{ is } \bar{A}_{k2} \text{ and } \dots \text{ and } x_n \text{ is } \bar{A}_{kn} \\ \text{THEN } u_k = \sum_{i=1}^n p_{ik} x_i + b_k \quad (13)$$

Where x_k 's and u_k 's are the input and output linguistic variables respectively; \bar{A}_{ki} 's are Type-2 fuzzy sets for the k^{th} rule and i^{th} input; p_{ki} and b_k are consequent parameters of the rules which are Type-1 fuzzy sets.

The fuzzy controller inputs (DC bus voltage error (e) and change of error (de)) are implemented using Gaussian membership functions as shown in Fig. 5. The fuzzy labels are negative (N), environ zero (EZ), positive (P).

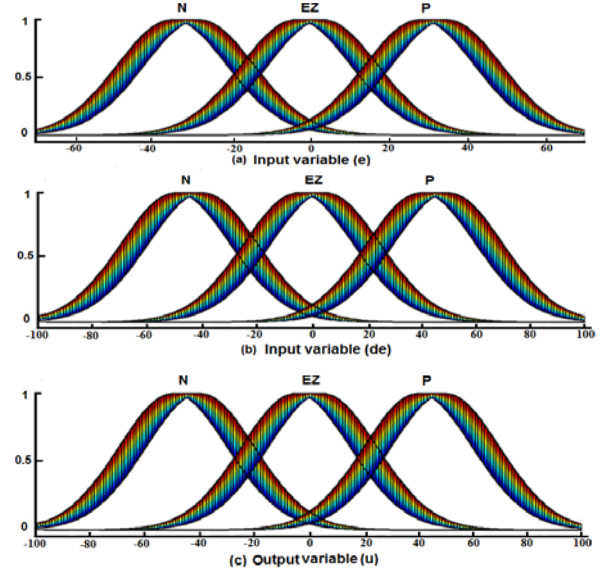


Fig.5 Membership functions for (a) error and (b) change of error and (c) control (u).

The control rules are given in Table 1.

TABLE I. IT2FLC FUZZY CONTROL RULES

e Δe	N	EZ	P
N	N	N	EZ
EZ	N	EZ	P
P	EZ	P	P

IV. SIMULATION RESULTS

The SAPF model and controller have been implemented using Simulink and SimPowerSystems toolboxes. The model parameters used for these simulations are listed in Table 2.

In this simulation study, the performance of IT2FLC designed for the DC bus voltage are first analysed in terms of current waveforms and related Total Harmonic Distortion (THD). The robustness of these controllers is then compared with respect to changes in the filter inductance L_f .

TABLE II. SYSTEM PARAMETERS

System Parameter		Value
Three Phase Source Voltage	V_s	220 V
Frequency	f	50 Hz
Nonlinear Load	R_s, L_s	3.12 Ω , 2500 μ H
Filter inductance	L_f	3 mH
DC Capacitance	C_{dc}	2200 μ F
DC Reference Voltage	V_{dc}	700 V

A. Simulation results using without filter

Initially, the system is simulated without the SAPF. Fig. 6(a) and Fig. 6(b) show the load voltage and current respectively which demonstrates a considerable distortion in the current waveform. The THD in Fig. 6(c) has been estimated to 23.74 %.

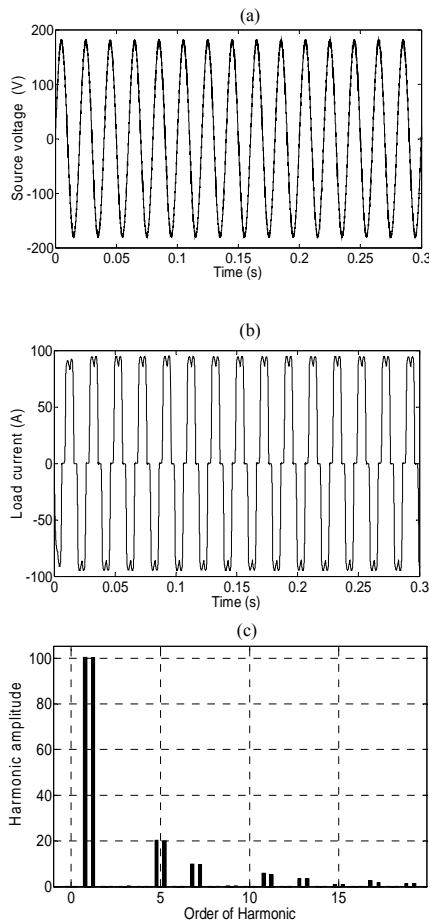


Fig. 6 Source voltage and current without SAPF.

B. Simulation results using with SAPF

The source current waveform and its harmonic spectrum (THD) after introducing the SAPF application using IT2FLC are respectively shown in Fig. 10 (a) and (b). The output DC capacitor voltage (V_{dc}) is given in Fig. 7 (c).

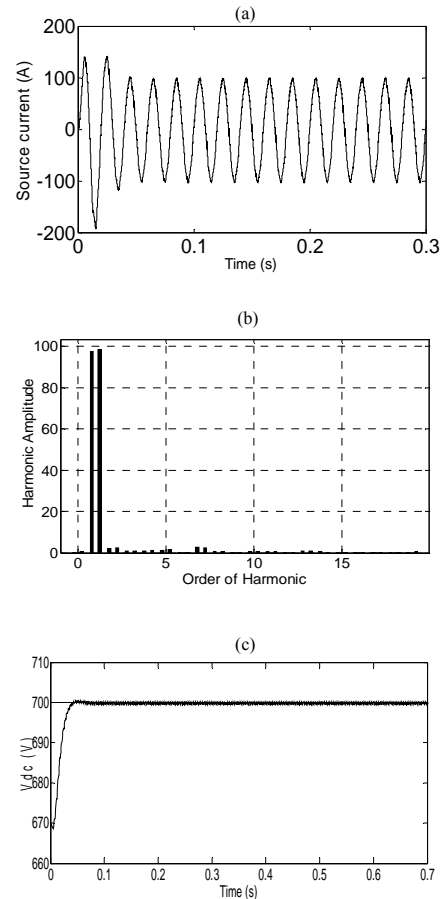


Fig. 7 SAPF control using T2FLC (a) source current (b) THD (c) V_{dc} .

The ability of the SAPF to compensate for the harmonic current of the load is demonstrated in Fig. 7 (a) and (b). The THD dropped from 23.74 % to 3 % when using the SAPF.

C. IT2FLC performance under changing system's parameters

In order to assess the robustness of these controllers, the filter inductance L_f has been increased by 50%. Fig. 13 shows the DC bus voltage response under PI controller and IT2FLC was performed.

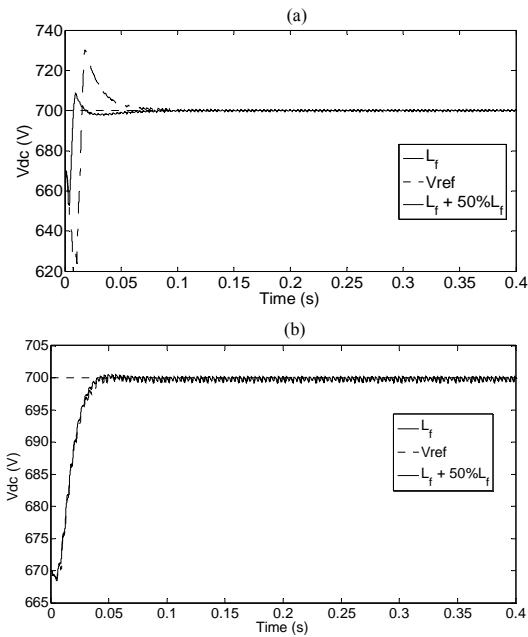


Fig. 8 Comparison of (a) PI (b) T2FLC under parameter variations.

V. CONCLUSIONS

The paper the control of a shunt active power filter based on type-2 fuzzy systems to mitigate harmonics and enhance the power quality under non-load conditions. The performance and robustness of the proposed controller has been evaluated in terms the harmonic distorsion of the source current waveforms and variations in the filter inductance respectively. The simulation study was performed under Matlab/Simulink and SimPowerSystems toolbox. The results show that with the proposed control scheme, the supply current waveforms were

almost perfectly sinusoidal and in-phase with the supply voltage and the harmonic distortion achieved with the proposed controller (3 %) was well below the limit imposed by the IEEE-519 standards.

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