Interval Type-2 Fuzzy Control of Shunt Active Power Filter

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ABSTRACT

This paper proposes a new adaptive control technique for shunt active power filter (SAPF) by applying the interval type-2 fuzzy controller (IT2FC) in the DC voltage outer loop. This adaptive method achieved the main control objectives and compensated the active filter parameters uncertainties besides the unbalanced loads compensation without neutral wire. The interval type-2 fuzzy controller (IT2FC) offers flexibility and compensates the uncertainties within large ranges due to its footprint of uncertainty. The IT2 fuzzy controller proved flexibility and faster DC voltage transient response than the PI and type-1 fuzzy controllers due to its type-2 membership functions which describe uncertainties in contrast to the type-1 membership functions which describe vagueness. Simulation results proved that the IT2 fuzzy controller has faster response and robust performance against parameters variations and unbalanced loads compared to PI and type-1 fuzzy controllers

***Key words:** Adaptive control / Shunt active power filter / Interval type-2 fuzzy controller / DC voltage control*

INTRODUCTION

In the last couple of decades, widespread application of power electronics equipment in the power system had given rise to current and voltage distortion in the local network. In addition, the local network has single phase electronic equipment such as power supplies, TVs, computers, communications equipments and commercial lighting systems. These devices increase the neutral current in the power system, damage sensitive loads and interact with the communication devices. These problems decrease the efficiency of the power system and affects the high frequency systems in the local network. In order to eliminate harmonic contamination due to nonlinear loads and improve power factor, an active power filter (APF) is commonly used as a substitute for traditional passive L-C filter in industry [(1-4)].

PI controller is a conventional solution because it achieves the main control objectives and it has common disadvantages namely, a slow response and inherent overshoot. In most cases, their parameters need to be optimized. In industry there is a need for a faster solution due to fast developments of devices and networks full of drives and single phase loads [(5-10)]. PI can't find solution for many problems resulting from these devices. This encourages the use of artificial control techniques to overcome these disadvantages of conventional controllers like fuzzy and neural network (NN) controllers.

Type-1 fuzzy controller has gained an interest as an alternative to PI controller because it doesn't need an accurate model, can handle imprecise inputs due to the nature of its type-1 membership functions. These functions describe vagueness which gives artificial intelligence advantage to the fuzzy controller, consequently, it can handle nonlinearity. This led to increasing its use as a controller in many systems [(11-23)].

A FLS, described completely in terms of type-1 fuzzy sets is called a type-1 fuzzy logic system (type-1 FLS). It is composed by a knowledge base that comprises the information given by the process operator in the form of linguistic control rules; a fuzzification interface, which has the effect of transforming crisp data into fuzzy sets; an inference system, that uses them in conjunction with the knowledge base to make inference by means of a reasoning method; and a defuzzification interface, which translates the fuzzy control action obtained into a real control action using a defuzzification method.

Type-1 fuzzy sets are not able to directly model such uncertainties because their membership functions are totally crisp. On the other hand, type-2 fuzzy sets are able to model such uncertainties because their membership functions are themselves fuzzy. A type-1 fuzzy set is a special case of a type-2 fuzzy set; its secondary membership function is a subset with only one element, unity [24]. Similar to a type-1 FLS, a type-2 FLS includes fuzzifier, rule base, fuzzy inference engine, and output processor. The output processor includes type-reducer and defuzzifier; it generates a type-1 fuzzy set output (from the type-reducer) or a crisp number (from the defuzzifier).

The membership functions of type-2 fuzzy systems are three dimensional and include a footprint of uncertainty which is the new third dimension and provide an additional degree of freedom to make it possible to directly model and handle uncertainties. To simplify the computation of type-2 fuzzy set (T2 FS), the secondary membership grades are set to either one or zero and are called interval type-2 fuzzy systems. Interval type-2 fuzzy logic systems which employ only interval type-2 fuzzy sets (IT2 FS) are widely used due to their lower computational requirement and ability to handle uncertainties [25-27].

The applications of IT2FLSs have been confined largely due to the computational bottleneck of the type reduction block. Although the iterative Karnik-Mendel (KM) procedure is an efficient method, it is still difficult to analyze and design IT2FLSs for real time applications because of the computational bottleneck of the centre of sets (COS) type reduction method which uses the KM algorithm [28-31]. Therefore in order to avoid the iterative procedure and reduce the computational complexity two methods were studied:

(1) Interval analysis based type reduction method;
(2) Nie-Tan method.

The two methods reduce the order of the type of IT2 fuzzy sets and give a closed form expression for the output of an IT2 FS [32-35]. In this work, IT2FC have employed Nie-Tan type reduction method as in [34]. The advantages of this method are:

1- It reduces the order of type-2 fuzzy sets by using the vertical slice instead of the wavy representation. Then, defuzzification is performed based on the general type-1 fuzzy sets to obtain a crisp output.
2- It makes easier to deal with the FOU as an important factor of IT2 fuzzy control.
3- It gives a closed form expression and avoids the iterative procedure and reduce the computational complexity.

In this paper, the proposed method achieves many control objectives and saves the fourth wire for unbalanced loads. It saves also the additional control strategy to balance the capacitor voltage in addition to the cost of the split capacitor. This paper is organized as follows: firstly the SAPF model in the d-q reference frame is presented in section 2. In section 3, Interval type-2 fuzzy controller design is developed. Section 4 presents the simulation results for PI, type-1 and type-2 fuzzy controllers. Finally the conclusions are drawn in section 5.

MODELING OF SHUNT ACTIVE POWER FILTER (SAPF)

Figure 1 shows a standard six-switch three-phase shunt active power filter in parallel with nonlinear load. Under a balanced three phase ac supply, neglecting the resistance of the power switches and performing the Park's transform on line voltages and currents, the dynamical model of the shunt APF under consideration in the rotating *d-q* frame may be expressed as [36-40]:

$$\frac{di_d}{dt} = -\frac{R_c}{L_c} i_d + w i_q - \frac{v_{dc}}{L_c} d_d + \frac{v_d}{L_c} \tag{1}$$

$$\frac{di_q}{dt} = -\frac{R_c}{L_c} i_q - w i_d - \frac{v_{dc}}{L_c} d_q + \frac{v_q}{L_c} \tag{2}$$

$$\frac{dv_{dc}}{dt} = d_d \frac{i_d}{C} + d_q \frac{i_q}{C} \tag{3}$$

where

: The 3-phase inverter currents in the *d-q* reference frame. i_d, i_q

: The three phase switching state functions in the *d-q* reference frame. d_d, d_q

: The supply frequency. w

: The supply voltages in the *d-q* reference frame. v_d, v_q

d_d, d_q: The DC capacitor voltage.

L_c, R_c: The filter resistance and inductance.

C: The DC link capacitance.

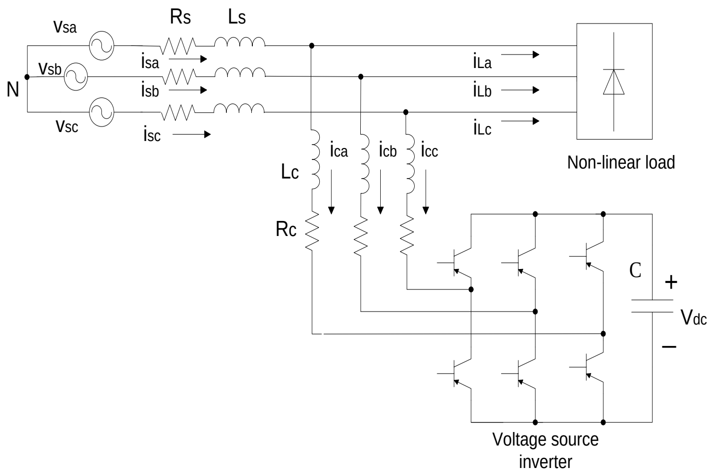


Fig. (1): SAPF with a voltage source inverter

Manipulation and substitutions of the SAPF model eqs. (1) - (3) results the switching state equations (d_d, d_q) as described in [35].

$$d_d = \frac{v_d + L_C w i_q - u_d}{v_{dc}} \tag{4}$$

$$d_q = \frac{v_q - L_C w i_d - u_q}{v_{dc}} \tag{5}$$

The active current component to maintain the DC link voltage can derived as

$$(6)\, i^*_{do} = \sqrt{\frac{2}{3}} \frac{v_{dc}}{\hat{V}} u_{dc}$$

The SAPF consists of two loops, the DC voltage outer loop and the current inner loop. The SAPF model can be represented by the eqs. (1)-(3). The voltage control loop and the current control loop take into account the SAPF model and ensure the correspondence of the injected current and its reference. The PI controllers are inserted in the current and DC voltage loops and the block diagram of SAPF can be represented as shown in Fig. 2.

To achieve the harmonics compensation and reactive power compensation, the current and DC voltage loops can be controlled by the PI controllers or the IT2 fuzzy controllers. The DC voltage outer loop must be added to the inner current control loop to achieve the balancing of dynamic compensation of active filter to supply losses of the active filter. Therefore the various objectives of this work were achieved through applying the controllers in this loop which is not mentioned in [34].

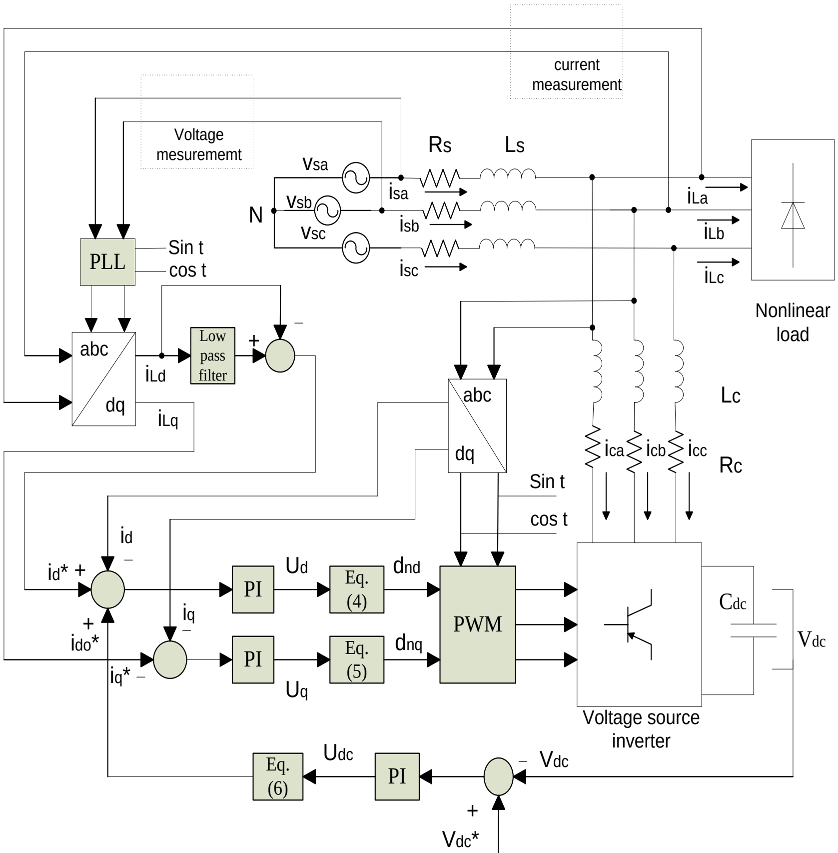


Fig. (2): The block diagram of PI based SAPF

DESIGN OF INTERVAL TYPE-2 FUZZY CONTROLLER (IT2FC)

The fuzzy logic control (FLC) system comprises mainly five components; the fuzzifier, the rule base, the inference engine, the type reduction and the defuzzifier as shown in Fig. 3. In this section we will design a simple and general method for IT2FC using Nie-Tan type reduction method not applied before in electrical systems.

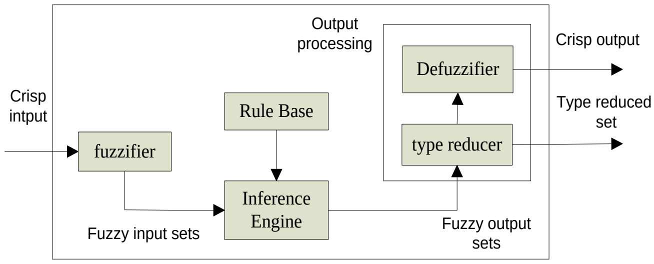


Fig. (3): The structure of the IT2 fuzzy controller (IT2FC).

A. Fuzzifier

Here the error (e) and change in error (Δe) are considered as inputs to IT2FLC and the output of FLC is the switching state function d_d or d_q. In this unit, the crisp value of the input is transformed into a fuzzy value (membership function with its grade). Singleton fuzzification is used in this stage. Seven triangular membership functions were used. The labels of these functions are negative big (NB), negative medium (NM), negative small (NS), zero (Z), positive small (PS), positive medium (PM) and positive big (PB).

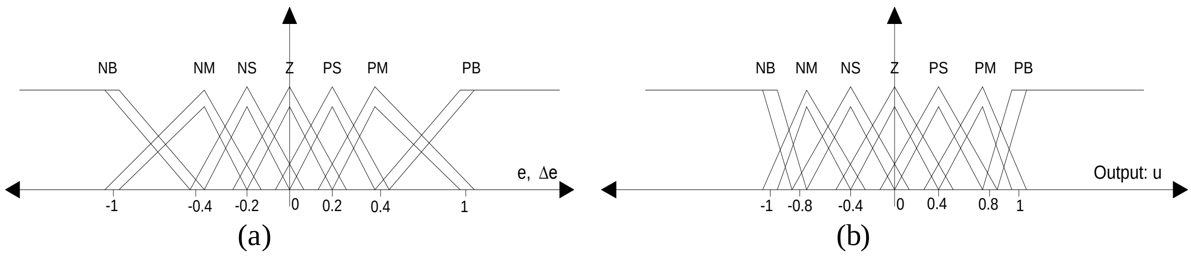


Fig. (4): The membership functions for
(a) Error and change of error. (b) Output (u).

B. Rule Base

The rule base store the linguistic control rule base need by rule evaluator. Large errors in transient state need coarse control and small errors need fine control in steady state. Based on these elements, 49 rules of the rule table are used based on IF-THEN rule in this paper as shown in Table I.

Table (I): Rule Table.

e \ ė	NB	NM	NS	Z	PS	PM	PB
NB	Z	NS	NM	NB	NB	NB	NB
NM	PS	Z	NS	NM	NM	NB	NB
NS	PM	PS	Z	NS	NS	NM	NB
Z	PM	PM	PS	Z	NS	NM	NM
PS	PB	PM	PS	PS	Z	NS	NM
PM	PB	PB	PM	PM	PS	Z	NS
PB	PB	PB	PB	PB	PM	PS	Z

C. Inference Engine

The inference engine use fuzzy logic principles to combine all fired rules (fuzzy IF-THEN rules) from the fuzzy rule base into mapping from fuzzy input sets to fuzzy output sets. In the inference engine, multiple antecedents are combined and evaluated using the max-min composition. The output membership functions are determined by this engine to be ready for output processing.

Assume that there are M rules in the rule base, each of which has the following form:

Rule k: IF x_1 is $\tilde{A}_1^k$ and x_2 is $\tilde{A}_2^k$ and ……and x_p is $\tilde{A}_p^k$ THEN y is $\left[\underline{\omega}^K, \overline{\omega}^K\right]$, Where k =1, 2,.., M ,p the number of input variables in the antecedent part, $\tilde{A}_i^k$ *(i=1,2,...,p, k=1, 2, ..., M)* are IT2FSs of the IF-part, and $\underline{\omega}^K, \overline{\omega}^K$ are the singleton lower and upper weighting factors of the THEN part.

Once a crisp input X = $(x_1, x_2, ..., x_p)^T$ is applied to the IT2FLS, through the singleton fuzzifier and the inference process, the firing strength of the k[th] rule which is an interval type-1 set can be obtained as

$$F^k = [\underline{f}^k, \overline{f}^k], \text{ Where}$$

$$\underline{f}^k = \underline{\mu}_{\tilde{A}^k{}_1}(x_1) * \underline{\mu}_{\tilde{A}^k{}_2}(x_2) * ...... * \underline{\mu}_{\tilde{A}^k{}_p}(x_p), \overline{f}^k = \overline{\mu}_{\tilde{A}^k{}_1}(x_1) * \overline{\mu}_{\tilde{A}^k{}_2}(x_2) * ...... * \overline{\mu}_{\tilde{A}^k{}_p}(x_p)$$

In which $\underline{\mu}(), \overline{\mu}()$ denotes the grades of the lower and upper membership functions of IT2FSs and * denotes minimum or product t-norm. To generate a crisp output, the outputs of the inference engine should be type reduced and then defuzzified.

D. Type Reduction

The type reduction block maps a T2FS into a T1FS using Nie-Tan method after which it is a simple matter to defuzzify the T1FS to obtain a crisp number at the output of the IT2FS. This new method gives a simple method for dealing with the footprint of uncertainties (FOU). The Nie-Tan method supposed that the continuous vertical slice is descretized into n points, and then the centroid of each vertical slice can be computed as follows:

$$u_j = \sum_{i=1}^{n_j} u_j^i * 1 / \sum_{i=1}^{n_j} 1 = \frac{1}{n_j} \sum_{i=1}^{n_j} u_j^i \tag{7}$$

For an IT2 FSs, the average of a vertical slice that comprises n discrete points is the mean of the upper and lower MF, Hence,

$$u_j = \frac{1}{n_j} \sum_{i=1}^{n_j} u_j^i = \frac{1}{2}(\overline{u}_j + \underline{u}_j) \tag{8}$$

Where $\overline{u}$ and $\underline{u}$ are the upper and lower grades of the type reduced set. The centroid (or the defuzzified value) of the interval type-2 fuzzy set can be expressed as:

$$x_c = \sum_{j=1}^{N} x_j * u_j / \sum_{j=1}^{N} u_j = \sum_{j=1}^{N} x_j * [0.5 * (\overline{u}_j + \underline{u}_j) / \sum_{j=1}^{N} 0.5 * \left(\overline{u}_j + \underline{u}_j\right)$$
$$= \left(\sum_{j=1}^{N} x_j * \overline{u}_j + \sum_{j=1}^{N} x_j * \underline{u}_j \right) \Big/ \left(\sum_{j=1}^{N} \overline{u}_j + \sum_{j=1}^{N} \underline{u}_j \right) \tag{9}$$

e. Defuzzification

There are many methods for defuzzification such as centroid, centre of sums, mean of maxima and height method. Height defuzzification method is inexpensive and gives satisfactory results especially after type reduction from type-2 to type-1.

SIMULATION RESULTS

In order to verify the effectiveness and the accuracy of the proposed interval type-2 fuzzy controller, the model in Fig. 2 is simulated in Matlab/SimPower Systems using PI, type-1 fuzzy and IT2 fuzzy controllers. The controllers were inserted in the DC voltage loop. The aim of simulation is to examine three different aspects. The set up parameters of the system are shown in table II.

A. Step Change of Load

Fig. 5 shows the DC voltage transient response of PI based SAPF, the active filter current, the source current and the nonlinear load current when the load resistance is step decreased at t=0.1s.

Table (II) Set up parameters.

Model parameters	value
Supply voltage (rms)	120 V
Supply parameters R_s and L_s	1.5 Ω and 0.01mH
SAPF parameters R_c and L_c	0.2 Ω and 2 mH
DC link capacitance	0.1 mF
Nonlinear load parameters	R_L=10 Ω, L_L= 20 mH and 1.3kVA
Switching frequency	25000 Hz

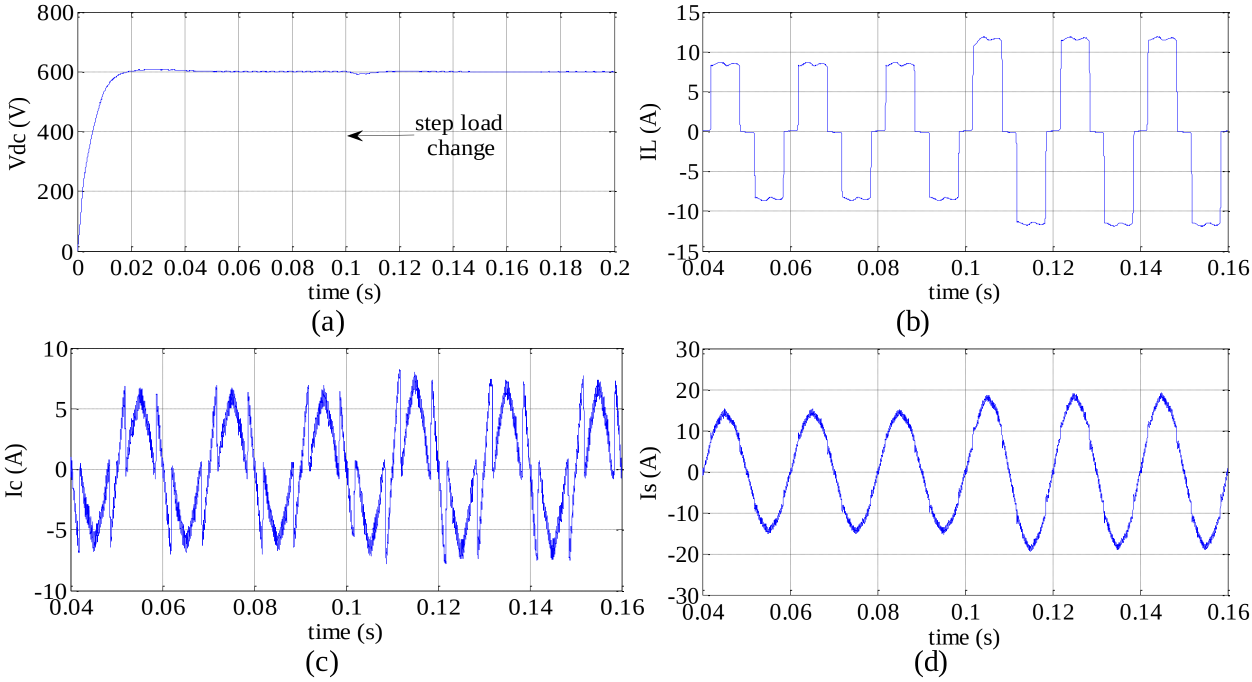


Fig. (5): The simulation results of PI based SAPF due to step change of load
(a) The DC voltage; (b) The source current; (c) The filter current; (d) The nonlinear load current.

Fig. 6 shows the simulation results of IT2FC based SAPF due to step change of load at t=0.2s. The type-2 fuzzy controller was inserted in the DC voltage loop (outer loop) in the simulation model as shown in Fig. 7.

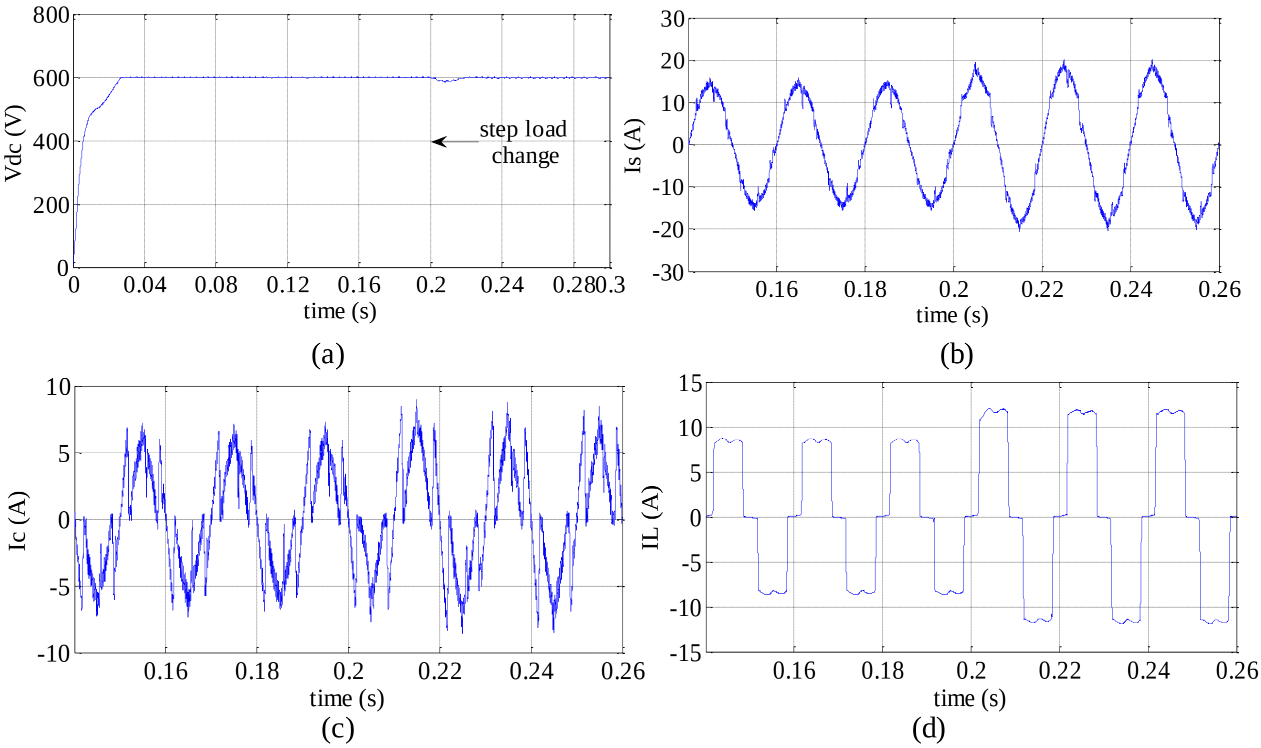


Fig. (6): The simulation results of IT2FC based SAPF due to step change of load
(a) The DC voltage; (b) The source current; (c) The filter current; (d) The load current.

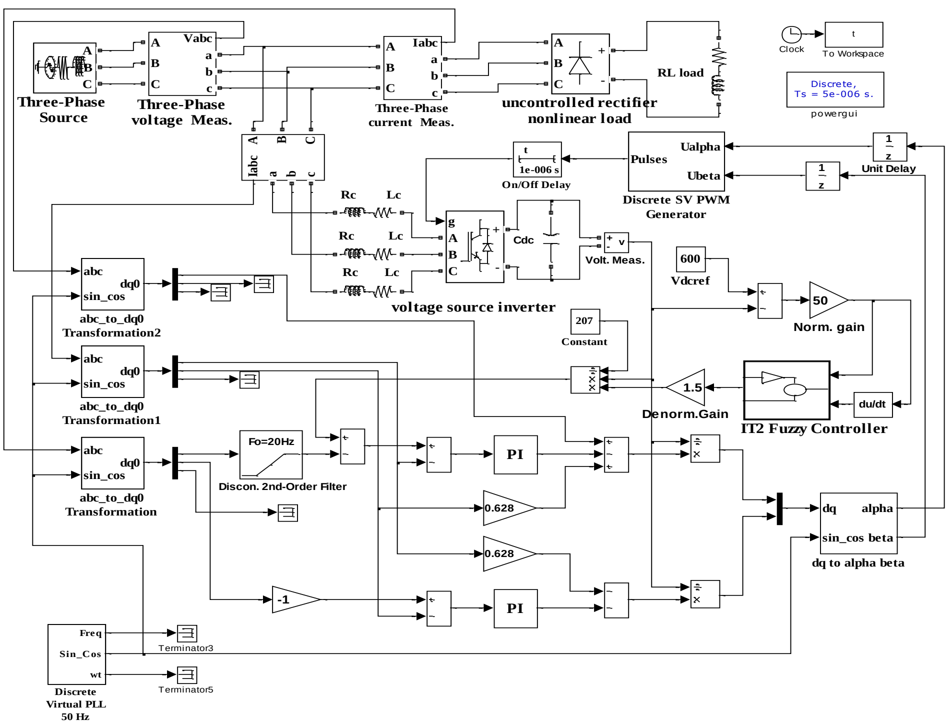


Fig. (7): The simulation model of IT2FC based SAPF

From the simulation results, it is clear that the PI controllers achieved the conventional control objectives such as fast current tracking and good DC voltage regulation with low overshoot. Also the two controllers improve the THD of the line voltage. However, the type-2 fuzzy controller exhibits faster transient response (20 ms) for the DC voltage response without any overshoot or under shoot compared to 40 ms for PI controller. Table III shows the values for THD of the line currents and voltages before and after the compensation. The two controllers exhibit the permissible limits for the THD of line currents and voltages.

Table (III): THD of source current and voltage.

THD % / compensation	I_s	V_s
Without compensation	24.66%	6.6%
compensation using PI controller	4.5%	2.1%
compensation using IT2FC	5.5%	2.75%

B. **Compensation of R_c and L_c Uncertainties**

Figs. 8, 9 and 10 show the transient response when the uncertainties were introduced by 100% and -75% for the values of R_c and L_c. This aspect tests the adaptive control capability of the active filter using the PI, type-1 and type-2 fuzzy controllers. The figures show the effects of variable values of uncertainties and the effect of interval type-2 fuzzy controller compared to the type-1 fuzzy and the PI controllers as the uncertainties increases.

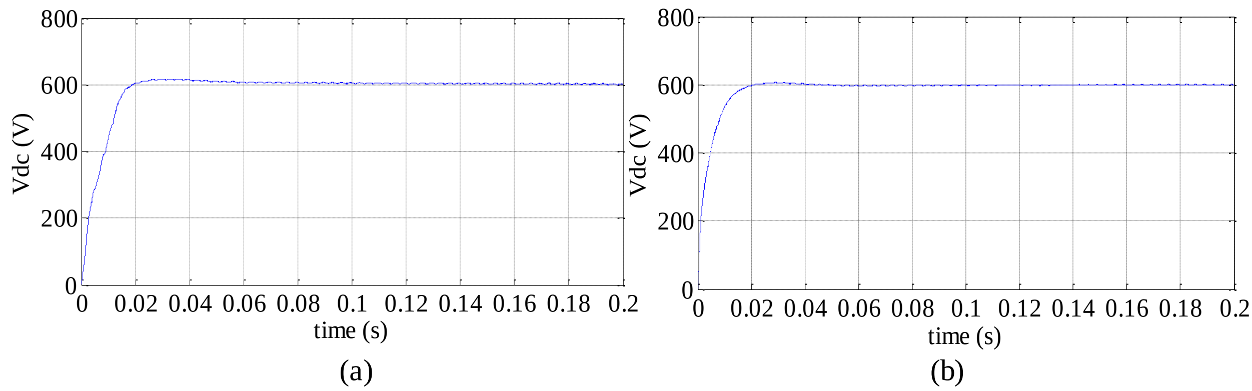


Fig. (8): The effect of PI controller for 100% and -75% uncertainties of R_c and L_c
(a) The effect of 100% uncertainties; (b) The effect of -75% uncertainties.

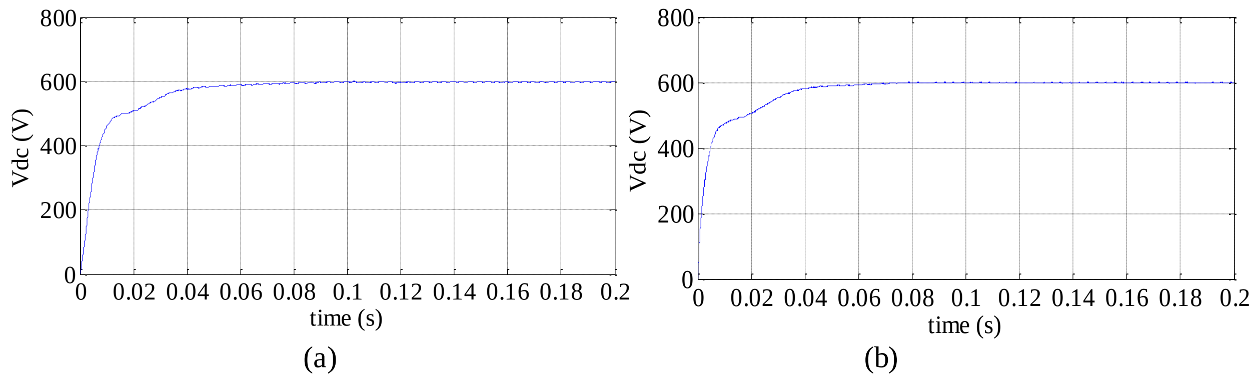
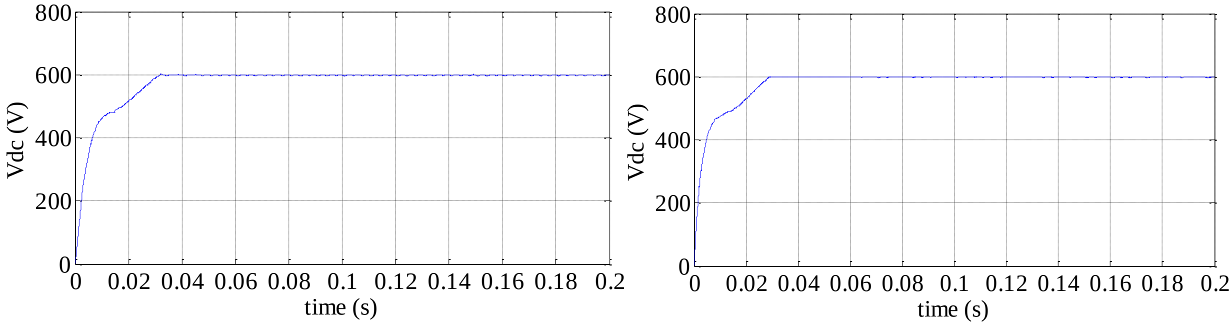


Fig. (9): The effect of type-1fuzzy controller for 100% and -75% uncertainties of R_c and L_c
(a) The effect of 100% uncertainties; a) The effect of -75% uncertainties.



(a) (b)

Fig. (10): The effect of IT2 fuzzy controller for 100% and -75% uncertainties of R_c and L_c
(a) The effect of 100% uncertainties; (b) The effect of -75% uncertainties

Comparison of Figures 8, 9 and 10 reveals that the response of IT2 fuzzy controller is better and faster than type-1 fuzzy and PI controllers for compensating the uncertainties of the active filter parameters R_c and L_c within large ranges of uncertainties.

C. Unbalanced Loads Compensation

In this section, the effect of unbalanced load compensation was studied by inserting a single phase resistance load (20 Ω) between two phases of the three phases and measuring the rms values of supply currents before and after compensation. This test aims to evaluate the active filter capability to compensate non characteristic current harmonics. Table IV shows the values of THD of the line currents and the phase voltages before and after compensation. The two controllers improve the THD of line currents and voltages under this condition to about 8% and 4% respectively. Table V shows the r.m.s. values of supply currents before and after the connection of the shunt active power filter for the PI and IT2 fuzzy controllers.

Table (IV): THD of source currents and voltages for unbalanced load comp.

THD% / compensation	phase voltages			line currents		
	V_a	V_b	V_c	I_a	I_b	I_c
Without compensation	6.04	6.3	6.26	22.94	16.7	16.2
compensation using IT2FC	3.85	3.2	3.8	8.6	6.24	8
compensation using PI	3.3	3.56	3.59	7.3	6.82	7.88

From table V, it is clear that the IT2 fuzzy controller compensates the unbalanced loads from 26.8% to 6.24% compared to the PI controller which improves the compensation of the unbalanced loads from 26.8% to 10.62%. Consequently, the IT2 fuzzy controller has better capability than PI controller for unbalanced loads compensation without neutral wire.

Table (V): RMS values of source currents without and with compensation.

rms current (A) / compensation	I_a	I_b	I_c
Without compensation	9.87	12.89	13.07
compensation using IT2FC	14.09	15	14.66
compensation using PI	14.19	15.76	14.4

$$Unbalance = \frac{\max\{|I_a - I_b|, |I_b - I_c|, |I_a - I_c|\}}{(I_a + I_b + I_c)/3}$$

Another test by changing the value of the inserted resistance to (30Ω) was carried out to show the effect of unbalanced load compensation and measuring the values of the load and source currents. Table VI shows the values of THD of the line currents and the phase voltages without and with compensation. The two controllers improve the THD of line currents and voltages under this condition to less than 8% and 4% respectively. Table VII shows the r.m.s. values of supply currents without and with the connection of the shunt active power filter for the PI and IT2 fuzzy controllers.

Table (VI): THD of source currents and voltages for unbalanced load comp.

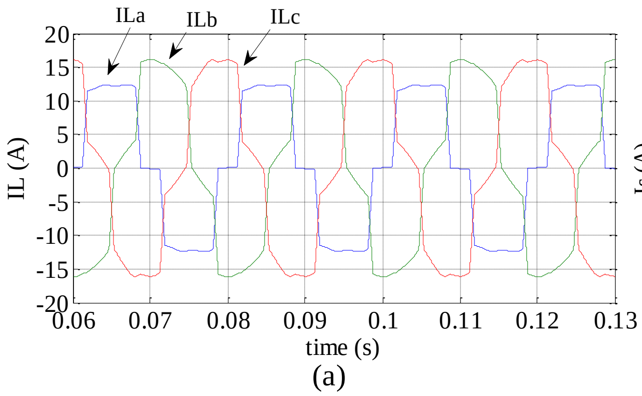
THD% / compensation	phase voltages			line currents		
	V_a	V_b	V_c	I_a	I_b	I_c
Without compensation	6.19	6.38	6.35	23. 4	18.7	18.7
compensation using IT2FC	3.29	2.8	3.2	7.5	6	7.5
compensation using PI	2.66	2.88	2.88	6.16	6.1	6.6

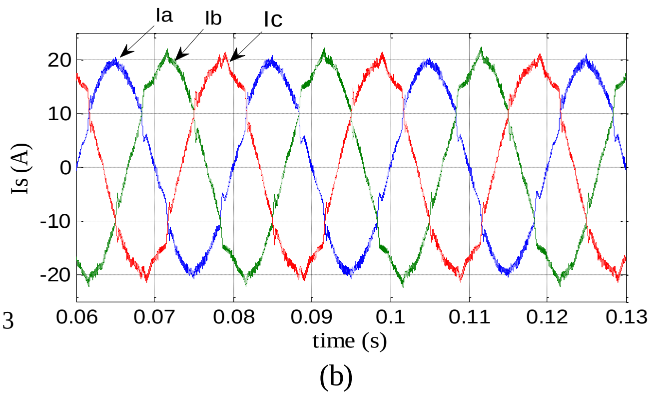
Table (VII): RMS values of source currents without and with compensation.

rms current (A) / compensation	I_a	I_b	I_c
Before compensation	9.92	12.02	12.2
compensation using IT2FC	13.68	14.3	14
compensation using PI	13.7	14.85	13.9

From table VII, it is clear that the IT2 fuzzy controller compensates the unbalanced loads from 20% to 4.4% compared to the PI controller which improves the compensation of the unbalanced loads from 20% to 8.13%. Therefore, the IT2 fuzzy controller has better capability than PI controller for unbalanced loads compensation. It was obvious that as the inserted resistance decreases from 30 Ω to 20 Ω and consequently the unbalance increases from 20% to 26.8%, the IT2 fuzzy controller improves the compensation of unbalanced loads to 4.4% and 6.24% respectively. This assures the robustness of its compensation.

Fig. 11 shows the nonlinear load currents, the source currents with unbalanced loads compensation using IT2 fuzzy controller and the PI controller.





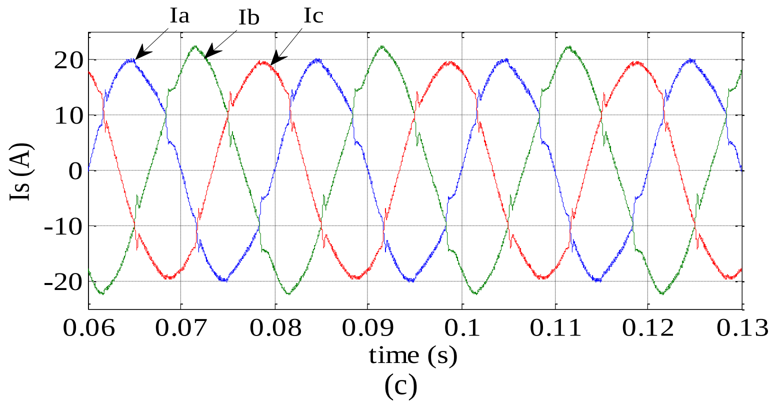


Fig. (11): The load and source currents for unbalanced loads compensation.
(a)The nonlinear load currents; (b) The source currents using the IT2 fuzzy controller; (c) The source currents using the PI controller.

CONCLUSIONS

In this paper, the SAPF was modeled in synchronous reference frame (SRF) and the controllers were designed in this reference frame and a comparison between the PI and IT2 fuzzy controllers was made. The IT2 fuzzy controller was designed with Nie-Tan type reduction method to reduce the complexity in the design stage. The IT2 fuzzy controller had superior performance over the type-1 fuzzy and PI controllers in achieving the conventional control objectives. The IT2 fuzzy controller has fast transient response for the DC voltage than the PI and fuzzy controllers without overshoot or undershoots. The IT2 fuzzy controller had better capability than the PI and type-1fuzzy controllers in compensating the uncertainties and also the unbalanced loads without fourth wire (neutral wire). This confirms that the footprint of uncertainty (FOU) has an important role in adaptively controlling the SAPF.

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