

# Adaptive Control of Shunt Active Power Filter Using Interval Type-2 Fuzzy Logic Controller

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**Abstract** – This paper proposes new adaptive control technique for three phase shunt active power filter (SAPF) using interval type-2 fuzzy logic controller. The synchronous reference frame (SRF) is chosen to compare the performance of the active filter using PI controller, type-1 fuzzy and Interval type-2 fuzzy controllers (IT2FC). Design procedure of the IT2FC is explored in detail. An efficient type reduction method called as Nie-Tan method is used instead of the most commonly used methods which gives closed form expression and reduces the computing power needed to implement time reduction. We apply the interval type-2 fuzzy controller to control the line currents, output DC voltage and also to reduce the influence of parameter uncertainty. Simulation results clearly show that the proposed controller has a good performance and robust to the parameter uncertainties compared with other nonlinear strategies.

**Index Terms** – Shunt active power filter, Adaptive control, Interval type -2 fuzzy control.

## I. INTRODUCTION

The increased use of nonlinear loads such as rectifier devices in TV, ovens and telecommunications power systems and commercial lighting systems cause excessive neutral currents, harmonic injection and reactive power burden in the power system. They result in poor power factor and lower efficiency of power system. Conventionally, passive filters were the choice for the elimination of harmonics and the improvement of power factor. These passive filters have the disadvantages of large size, resonance and fixed compensation.

In the last couples of decades the concept of active power filters has been introduced and many publications have appeared on this subject. A comprehensive review of active power filters configurations, control strategies, selection of components and other related issues are given in [1-4].

Most APF's are based on voltage source inverters due to its higher efficiency. According to PWM control laws, the DC link voltage of inverter must be kept constant in order that APF can compensate harmonics and reactive power effectively. Because of simple arithmetic and high reliability in steady state, PI controller gains extensive application in the DC-link voltage control system. But PI controller depends on exact mathematical model of system and has poor robustness in transient state. It tends to cause DC voltage overshoot and

inrush source current, which will lead to protection or even damage when APF is plunged into. The voltage overshoot and inrush current have been the bottleneck which restricts the development of APF [6]. However conventional PI controllers were used to generate reference current template. The PI controller requires precise linear mathematical models, which are difficult to obtain and fails to perform satisfactorily under parameter variations, nonlinearity, load disturbance, etc.

Recently, Fuzzy logic controllers (FLCs) have generated a good deal of interest in certain applications. The advantages of FLCs over conventional controllers are that they do not need an accurate mathematical model, they can work with imprecise inputs, can handle non-linearity, and they are more robust than conventional nonlinear controllers [5-8].

The concept of type-2 fuzzy sets (T2FSs) was first introduced by Zadeh [9] as an extension of the concept of well known ordinary fuzzy sets, type-1 fuzzy sets. Typically, T2FSs have the characteristics of grades of membership fuzzy themselves [10]. Very similar to a T1FLC structurally, a T2FLC also contains the components as: fuzzifier, rule base, fuzzy inference engine, and output processor which comprises type reducer and defuzzifier as shown in fig. 1.

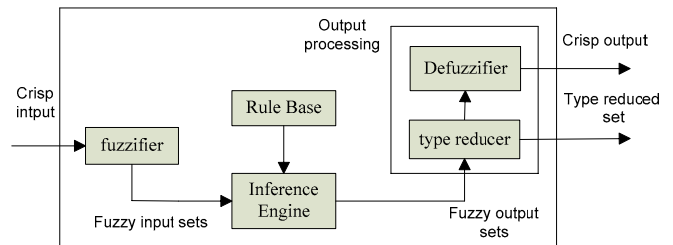


Fig. 1 The architecture of interval type-2 (IT2) fuzzy logical system (FLS)

Similar to T1FLC, the fuzzifier in a T2FLC maps inputs into type-2 fuzzy sets. The output processor includes the type-reducer and the defuzzifier; while the former outputs T1 FS and the latter outputs a crisp number. T2FLCs can be used at the uncertain circumstances when the membership grades can not be determined exactly. As a type-2 fuzzy set is characterized by a fuzzy membership function, i.e., the membership grade for each element also is a fuzzy set in [0,1], unlike a type-1 fuzzy set, where the membership grade is a crisp number in [0,1] [10].

The membership functions of type-2 fuzzy sets are three dimensional and include a footprint of uncertainty (FOU), which is the new third dimension of type-2 fuzzy sets and the footprint of uncertainty provides an additional degree of freedom to make it possible to directly model and handle uncertainties [11]. Normally, T2FLCs have characteristics of intensive computation due to heavy computational load at the step of type reducing process. To simplify the computation the secondary membership functions can be set to either zero or one and called interval type-2 FLSs [12].

The type reduction method that is most commonly used in conjunction with IT2 FLSs is the Karnik-Mendel (K-M) iterative algorithm. Recently several modifications to the K-M type reducer have been proposed [13]. The enhancements resulted in a 39% reduction in the computation time. Another type reduction strategy is the uncertainty bounds method [14]. Inner and outer bound sets are introduced to estimate the uncertainty in an IT2 FLS, resulting in an approximated type reduced set. In spite of the recent research results there is still room for reducing the computing power needed to implement time reduction. Furthermore theoretical analysis of IT2 FLS is challenging because the existing type reduction algorithm can't be expressed in closed form.

In this paper a new type reduction method called Nie-Tan method was used to reduce the order of the type of IT2 fuzzy sets which gives a closed form expression for the output of an IT2 FS. The main idea of this method is to reduce the order of an IT2 FS by using the vertical slice, instead of the wavy representation [15].

This paper is organized as follows. In section II the shunt active filter was modeled and simulated and comparison was made between PI and fuzzy controllers. In section III an IT2FC was designed step by step in detail. In section IV the simulation results of IT2FC and type-1 fuzzy controllers was presented. The conclusions are drawn in section V.

## II. CONTROL OF SAPF USING PI AND FUZZY CONTROLLERS

The compensation characteristics of shunt active power filter are based on injecting current of the same magnitude with reversed phase of the load harmonics and/or the reactive components at the point of connection to cancel them. The compensation capabilities of shunt active power filter include:

- Current harmonics injection.
- Reactive power production.
- Resonance damping.
- Unbalanced load current compensation.

The synchronous reference frame (SRF) is chosen to compare the performance of the PI and fuzzy controllers due to its higher efficiency because the SRF based controller is almost insensitive to supply voltage distortions, since any non dc components in the SRF can be attributed to harmonics in steady state.

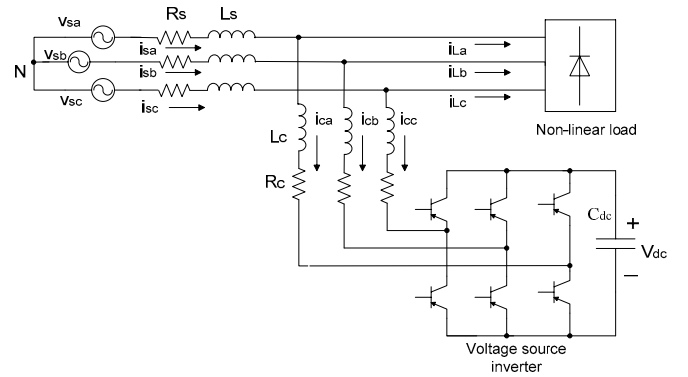


Fig. 2 Shunt active power filter with a voltage source inverter

### A. Modeling of SAPF using PI controller

The shunt active filter shown in fig. 2 is modeled in the stationary  $abc$  frame as described in [16-18]:

$$\frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ v_{dc} \end{bmatrix} = \begin{bmatrix} \frac{-R_c}{L_c} & 0 & \frac{-d_{na}}{L_c} \\ 0 & \frac{-R_c}{L_c} & \frac{-d_{nb}}{L_c} \\ \frac{2d_{na} + d_{nb}}{C} & \frac{d_{na} + d_{nb}}{C} & 0 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ v_{dc} \end{bmatrix} + \frac{1}{L_c} \begin{bmatrix} v_a \\ v_b \\ 0 \end{bmatrix} \quad (1)$$

Where:

$i_a, i_b$ : Two of the three phase inverter currents.

$v_{dc}$ : DC link voltage.

$R_c, L_c$ : The resistance and inductance of the filter.

$d_{na}, d_{nb}, d_{nc}$ : The three phase switching state functions.

$v_a, v_b, v_c$ : Three phase supply voltages.

$C$ : The capacitance of the DC link.

In order to convert quantities from the stationary  $abc$  frame to the rotating  $dq$  frame the transformation matrix is necessary:

$$T_{dqo}^{abc} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\omega t) & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t - \frac{4\pi}{3}) \\ -\sin(\omega t) & -\sin(\omega t - \frac{2\pi}{3}) & -\sin(\omega t - \frac{4\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (2)$$

A phase locked loop (PLL) scheme is used to determine the angle for the dq reference frame orientation such that

$v_q = 0$  and  $v_d = \sqrt{\frac{3}{2}} \hat{V}$  assuming the supply voltage is given by (3).

$$\begin{aligned} v_a &= \hat{V} \cos(\omega t) \\ v_b &= \hat{V} \cos(\omega t - 2\pi/3) \\ v_c &= \hat{V} \cos(\omega t - 4\pi/3) \end{aligned} \quad (3)$$

In steady state conditions the fundamental components of dq quantities is constant. To impose the harmonics on the inverter of fig. 2 it is necessary to separate the constant current component from the oscillating component. This oscillating component with reverse phase is the reference of the controller.

The AF can be modeled in the  $dq$  reference frame from (1) with the aim of reducing control complexity if compared with modeling in the stationary  $abc$  reference frame. The dynamic model which is described in [16-19] is obtained from equations (1) and (2) resulting in:

$$\frac{d}{dt} \begin{bmatrix} i_d \\ i_q \\ v_{dc} \end{bmatrix} = \begin{bmatrix} -\frac{R_c}{L_c} & w & -\frac{d_{nd}}{L_c} \\ -w & -\frac{R_c}{L_c} & -\frac{d_{nq}}{L_c} \\ \frac{d_{nd}}{C} & \frac{d_{nq}}{C} & 0 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ v_{dc} \end{bmatrix} + \frac{1}{L_c} \begin{bmatrix} v_d \\ v_q \\ 0 \end{bmatrix} \quad (4)$$

Where  $d_{nd}$  and  $d_{nq}$  are the switching state functions of the system in the  $dq$  reference frame and  $w$  is the supply angular frequency. The first and second lines can be written as:

$$L_c \frac{di_d}{dt} + R_c i_d = L_c w i_q - v_{dc} d_{nd} + v_d \quad (5)$$

$$L_c \frac{di_q}{dt} + R_c i_q = -L_c w i_d - v_{dc} d_{nq} + v_q \quad (6)$$

Let  $u_d$  and  $u_q$  be the right side terms of equations (5) and (6):

$$u_d = L_c w i_q - v_{dc} d_{nd} + v_d \quad (7)$$

$$u_q = -L_c w i_d - v_{dc} d_{nq} + v_q \quad (8)$$

The terms  $u_d$  and  $u_q$  are the respective outputs of the two current PI controllers:

$$u_d = k_p \tilde{i}_d + k_i \int \tilde{i}_d dt \quad (9)$$

$$u_q = k_p \tilde{i}_q + k_i \int \tilde{i}_q dt \quad (10)$$

Where  $\tilde{i}_d = i_d^* - i_d$  and  $\tilde{i}_q = i_q^* - i_q$  are the current errors.

With equations (7) and (8) the switching state functions (11) and (12) can be found.

$$d_{nd} = \frac{v_d + L_c w i_q - u_d}{v_{dc}} \quad (11)$$

$$d_{nq} = \frac{v_q - L_c w i_d - u_q}{v_{dc}} \quad (12)$$

The terms  $\frac{v_d + L_c w i_q - u_d}{v_{dc}}$  and  $\frac{v_q - L_c w i_d - u_q}{v_{dc}}$  in (11) and

(12) are called compensation parts and can be added or not to the output of the PI controllers.

The third equation of the model (4) is given by:

$$C \frac{dv_{dc}}{dt} = d_{nd} i_d + d_{nq} i_q \quad (13)$$

This equation can be written as:

$$u_{dc} = d_{nd} i_d + d_{nq} i_q \quad (14)$$

In order to control the DC voltage, a PI controller is used:

$$u_{dc} = k_{pv} \tilde{v}_{dc} + k_{iv} \int \tilde{v}_{dc} dt \quad (15)$$

Where  $\tilde{v}_{dc} = v_{dc}^* - v_{dc}$  is the voltage error. The control effort is obtained from equation (16).

$$i_{do}^* = \frac{u_{dc} - d_{nq} i_q}{d_{nd}} = \frac{u_{dc} v_{dc} - d_{nq} i_q v_{dc}}{d_{nd} v_{dc}} \quad (16)$$

Assuming that the current loop is ideal, the following properties hold:

$$d_{nq} v_{dc} \approx v_q \quad (17)$$

$$d_{nd} v_{dc} \approx v_d$$

Assuming the supply voltage is given by equation (3) the transformation of  $v_a$  and  $v_b$  to  $dq$  coordinates yields

$$v_d = \sqrt{3/2} \hat{V} \text{ and } v_q = 0.$$

As a result:  $d_{nq} v_{dc} \approx v_q = 0$ ,  $d_{nd} v_{dc} = v_d = \sqrt{3/2} \hat{V}$ .

The control effort can be approximated by:

$$i_{do}^* = \sqrt{\frac{2}{3}} \frac{v_{dc}}{\hat{V}} u_{dc} \quad (18)$$

The instantaneous active power is:  $p = v_d i_d$ .

In order to maintain the DC link voltage, the d-axis current in (18) must be added to  $i_d^*$  because the  $i_q$  current doesn't contribute for the active power to maintain the DC link voltage.

### B. Modeling of SAPF using Fuzzy Controller

The PI controllers are replaced by fuzzy controllers as shown in fig. 4. The internal structure of the fuzzy controller is shown in fig. 3.

The fuzzy controller is characterized as follows:

- 1) Seven fuzzy sets for input and output.
- 2) Triangular membership functions for simplicity.
- 3) Fuzzification using continuous universe of discourse.
- 4) Defuzzification using the height method.

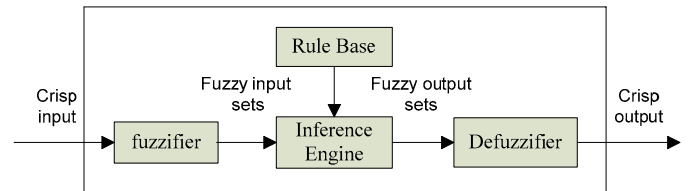


Fig. 3 The architecture of type-1 (T1) fuzzy logical system (FLS)

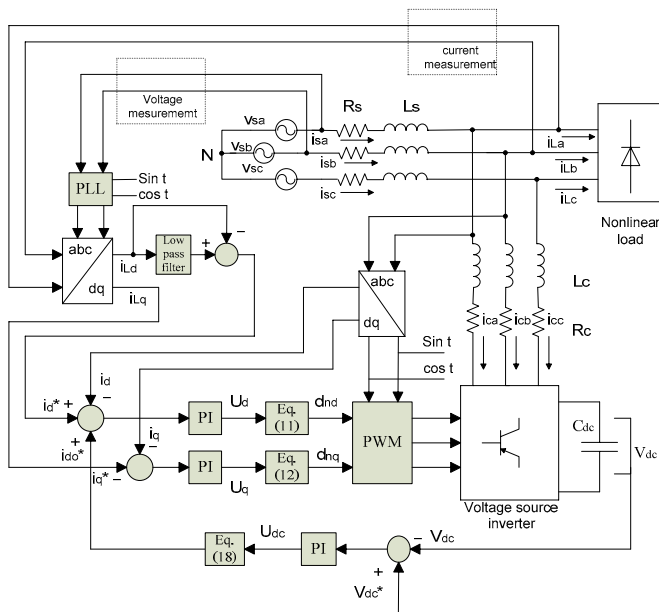


Fig. 4 Schematic diagram of SAPF with SRF based PI controller

The membership functions are chosen to be triangular because the parametric functional description of triangular MF is most economic one. Triangular MF are preferred because of their striking simplicity, solid theoretical basis and ease of computation, since they are symmetrical and have zero value at some point away from their centre. For this work seven unequal spaced triangular membership functions have been chosen for representing each linguistic variable NB, NM, NS, Z, PS, PM, PB.

The number of linguistic variables is directly related to the accuracy of approximating functions and plays an important role for approximating the nonlinear input output mapping. As the number of linguistic variables increases the output of the fuzzy controller becomes a linear function of the input.

To trade off between accuracy and complexity, through rigorous simulation studies it has been found that seven membership functions are sufficient to produce desired results in required band. Reducing the number of MFs will produce improper results at some band, while increasing the number of MFs will produce a delay due to more computational steps required [20].

### C. Simulation of SAPF Using PI and fuzzy controller

The system of fig. 4 was simulated with MATLAB in SimPower systems environment. The simulation model is shown in fig. 5. Figs. 6-7 show the simulation results of the proposed SAPF using the PI and fuzzy controllers. The parameters selected for simulation studies are:  $V_s = 120$  V (rms),  $R_c = 0.2$  ohm,  $L_c = 2$  mH,  $R_L = 10$  ohm and  $L_L = 20$  mH. It is clear from simulation results that the transient response of the DC voltage is better for the fuzzy controller compared to the PI controller and takes shorter time to reach the steady state. The THD of source current before compensation is 25.8% and after compensation is 4.7% and 4.3% respectively which comply with the IEEE-519 standards.

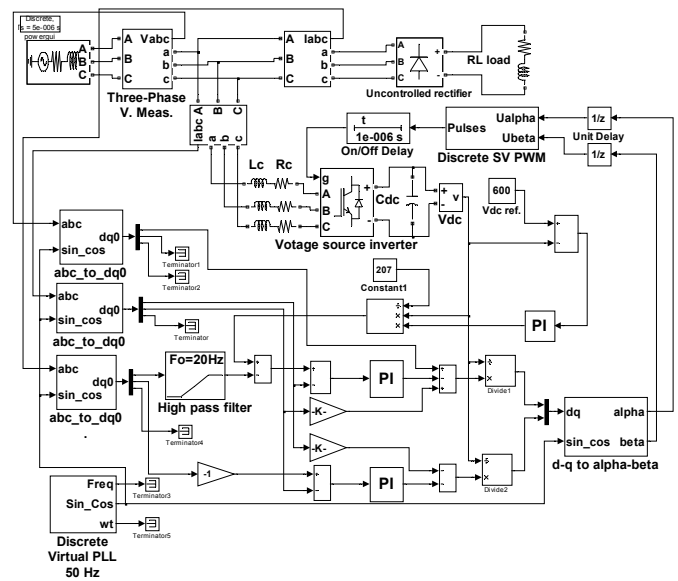


Fig. 5 The simulation model in SimPower systems environment

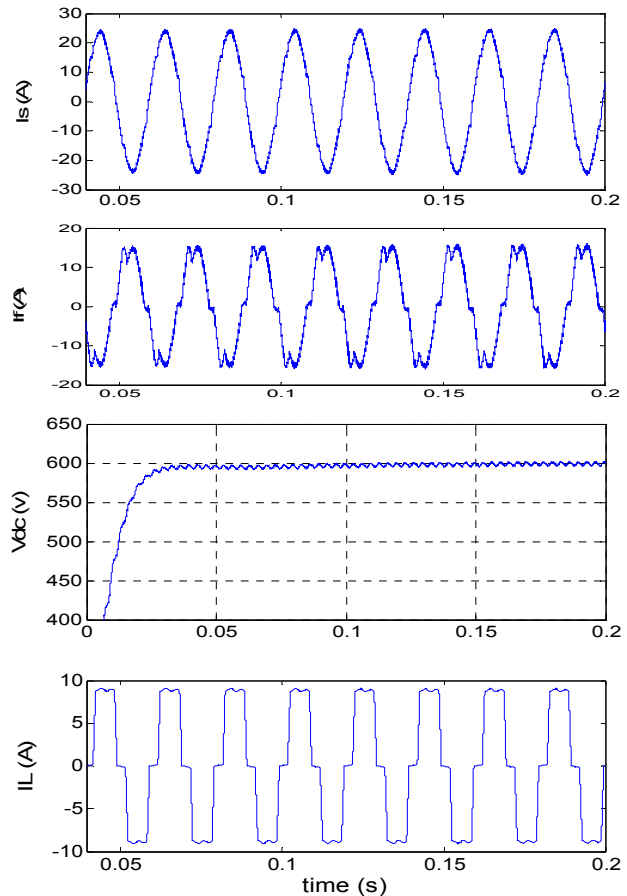


Fig. 6 The response of shunt active power filter using PI controller

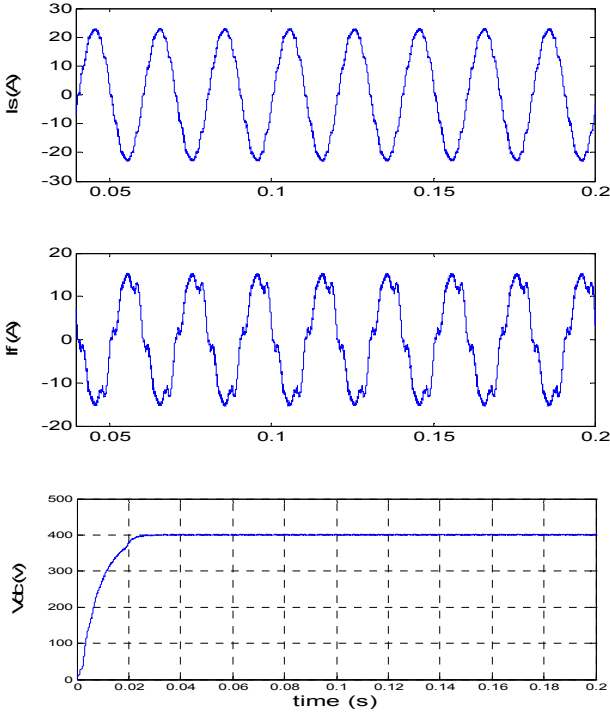


Fig. 7 The response of shunt active power filter using fuzzy controller

### III. DESIGN OF IT2 FUZZY LOGIC CONTROLLER

The architecture of interval type-2 (IT2) fuzzy logical system (FLS) as shown in fig. 1:

#### A. Fuzzifier

In this paper we adopt two input one output FLC to introduce the design procedure of IT2 FLC that is we consider error and rate of error scaled to the same range as the inputs of the proposed diagonal type FLC. The triangular membership functions for error and rate of error are shown in fig. 8. The fuzzy labels are negative big (NB), negative medium (NM), negative small (NS), zero (Z), positive small (PS), positive medium (PM), positive big (PB). A singleton fuzzification with minimum t-norm is used in this work.

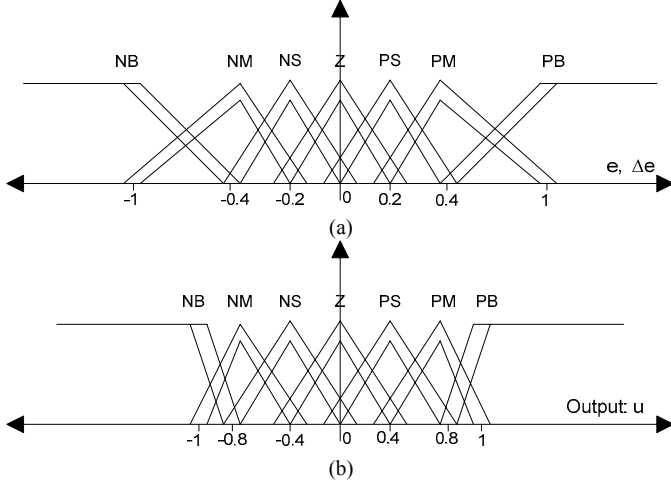


Fig. 8 The membership functions for (a) error and change of error and (b) output (u)

#### B. Rule base

The rules for IT2 FLS are still remained the same as that of T1 FLS. But their antecedents and consequents will be represented by IT2 fuzzy sets. The diagonal rule table is summarized in table I which is constructed for the scenario in which error and change of error approach zero with a fast rise time and without overshoot.

TABLE I  
CONTROL RULE TABLE

$\frac{e}{\dot{e}}$	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. Fuzzy inference engine

The inference engine combines all fired rules and gives a nonlinear mapping from input IT2 FS to output IT2 FS. In the inference engine multiple antecedents are combined using the meet operation.

#### D. Type reduction and Defuzzification

The Nie-Tan method is formulated using the vertical slice representation of an IT2 fuzzy set (FS). For an IT2 FS, each vertical slice is an embedded type-1 fuzzy set that can be easily type reduced. This characteristic motivated the proposition that computation overhead can be reduced by first type reducing each vertical slice, before defuzzifying the resulting type-1 fuzzy set to obtain the centroid of the IT2 FS.

The Nie-Tan method supposed that the continuous vertical slice is discretized into  $n$  points, and then the centroid of each vertical slice can be computed as follows:

$$u_j = \frac{\sum_{i=1}^{n_j} u_j^i * 1}{\sum_{i=1}^{n_j} 1} = \frac{1}{n_j} \sum_{i=1}^{n_j} u_j^i \quad (19)$$

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,

$$u_j = \frac{1}{n_j} \sum_{i=1}^{n_j} u_j^i = \frac{1}{2} (\bar{u}_j + \underline{u}_j) \quad (20)$$

Where  $\bar{u}$  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:

$$\begin{aligned}
x_c &= \frac{\sum_{j=1}^N x_j * u_j}{\sum_{j=1}^N u_j} \\
&= \frac{\sum_{j=1}^N x_j * [0.5 * (\bar{u}_j + \underline{u}_j)]}{\sum_{j=1}^N 0.5 * (\bar{u}_j + \underline{u}_j)} \quad (21) \\
&= \frac{\left( \sum_{j=1}^N x_j * \bar{u}_j + \sum_{j=1}^N x_j * \underline{u}_j \right)}{\left( \sum_{j=1}^N \bar{u}_j + \sum_{j=1}^N \underline{u}_j \right)}
\end{aligned}$$

Equation (21) shows that the Nie-Tan formulation of the crisp output of an IT2 FLS depends only on the lower and upper bounds of its foot print of uncertainty. As iterations are no longer needed to calculate the defuzzified value of an IT2 FLS, the computation cost of type reduction may be greatly reduced. Another advantage is (21) is a closed form equation. After that the defuzzification is done by the height method which is mainly based on multiplication, addition and subtraction.

#### IV. SIMULATION RESULTS

The simulation of shunt active power filter is carried in MATLAB/SimPower Systems environment. The simulation model is as shown in fig. 5 but replacing the PI controller with the IT2 fuzzy controller. Figs. 9-10 show the transient response of the DC voltage using IT2 fuzzy controller and T1 fuzzy controller when the uncertainty  $R_C$  and  $L_C$  are introduced with 50 % of the nominal value. The simulation results clearly show that no change in the transient response using IT2 fuzzy controller in spite of the uncertainty while the T1 fuzzy controller has a small steady state error.

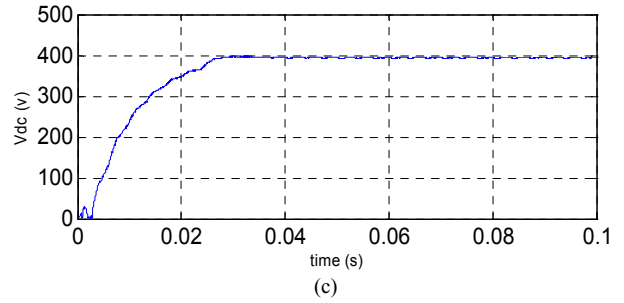
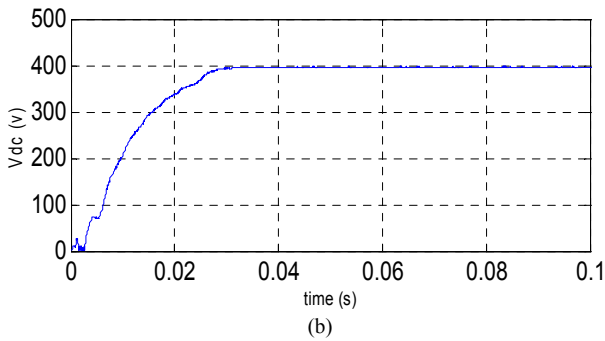
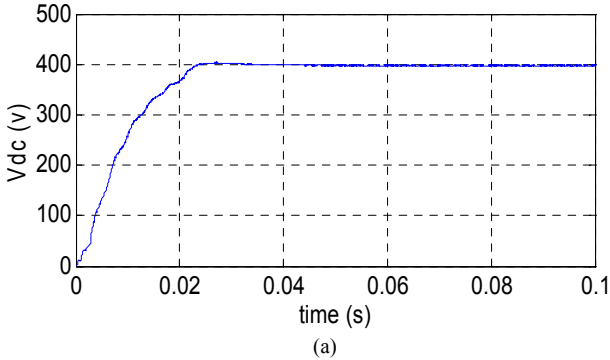


Fig. 9 The transient response of DC voltage using IT2 fuzzy controller with (a) uncertain  $L_c$  (b) uncertain  $R_c$  (c) uncertain  $R_c$  and uncertain  $L_c$

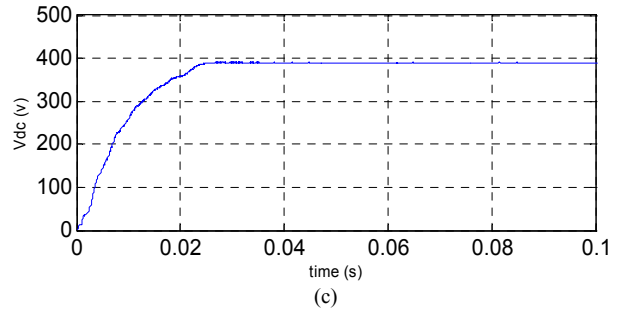
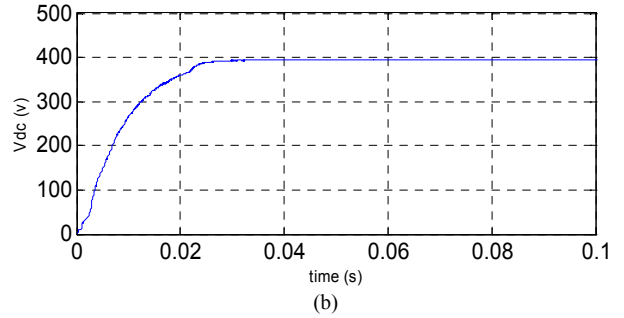
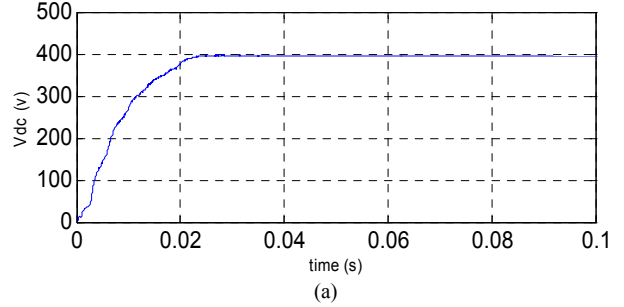


Fig. 10 The transient response of DC voltage using T1 fuzzy controller with (a) uncertain  $L_c$  (b) uncertain  $R_c$  (c) uncertain  $R_c$  and uncertain  $L_c$

## V. CONCLUSION

A shunt active power filter was modeled and simulated in the synchronous reference frame. The simulation results assured that the regulation performance for the fuzzy controller is better compared to the PI controller. The THD of source current before compensation is 25.8% and after compensation is well below 5%, the harmonics limit imposed by the IEEE-519 standards. A new adaptive control technique using IT2 Fuzzy controller is proposed. Simulation results show that IT2FLC is better than the T1 fuzzy controller and is robust against parameter variation and rule uncertainty. Recently, T2FSM (type-2 fuzzy sliding mode control) and T2FNN (type-2 fuzzy neural network) have proposed to minimize the number of rules and reduce the complexity of analysis which will be reported later.

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