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Harmonics Compensation of HAPF with Adaptive Fuzzy Dividing Rule

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ABSTRACT: This paper deals with a hybrid active power filter with injection circuit (IHAPF). It shows great promise in reducing harmonics and improving the power factor with a relatively low capacity active power filter. This paper concluded that the stability of the IHAPF based on detection supply current is superior to that of others. To minimize the capacity of IHAPF, an adaptive fuzzy dividing frequency-control method is proposed by analysing the bode diagram, which consists of two control units: a generalized integrator control unit and fuzzy adjustor unit. The generalized integrator is used for dividing frequency integral control, while fuzzy arithmetic is used for adjusting proportional-integral coefficients timely. And the control method is generally useful and applicable to any other active filters. Compared to other IHAPF control methods, the adaptive fuzzy dividing frequency control shows the advantages of shorter response time and higher control precision. It is implemented in an IHAPF with a 100-kVA APF installed in a copper mill in Northern China. The simulation results implemented, but also very effective in reducing harmonics.

Keywords: hybrid active power filter, adaptive fuzzy dividing frequency-control, generalized integrator control

I. Introduction

Filters are often the most common solution that is used to mitigate harmonics from a power system. Unlike other solutions, filters offer a simpler inexpensive alternative with high benefits. There are three different types of filters each offering their own unique solution to reduce and eliminate harmonics. These harmonic filters are broadly classified into passive, active and hybrid structures. The choice of filter used is dependent upon the nature of the problem and the economic cost associated with implementation.

A passive filter is composed of only passive elements such as inductors, capacitors and resistors thus not requiring any operational amplifiers. Passive filters are inexpensive compared with most other mitigating devices. Its structure may be either of the series or parallel type. The structure chosen for implementation depends on the type of harmonic source present. Internally, they cause the harmonic current to resonate at its frequency. Through this approach, the harmonic currents are attenuated in the LC circuits tuned to the harmonic orders requiring filtering. This prevents the severe harmonic currents travelling upstream to the power source causing increased widespread problems.

An active filter is implemented when orders of harmonic currents are varying. One case evident of demanding varying harmonics from the power system are variable speed drives. Its structure may be either of the series or parallel type. The structure chosen for implementation depends on the type of harmonic sources present in the power system and the effects that different filter solutions would cause to the overall system performance. Active filters use active components such as IGBT-transistors to inject negative harmonics into the network effectively replacing a portion of the distorted current wave coming from the load. This is achieved by producing harmonic components of equal amplitude but opposite phase shift, which cancel the harmonic components of the non-linear loads.

Hybrid filters combine an active filter and a passive filter. Its structure may be either of the series or parallel type. The passive filter carries out basic filtering (5th order, for example) and the active filter, through precise control, covers higher harmonics.

II. Topology of the Novel HAPF

The parallel HAPF has the advantages of easy installation and maintenance and can also be made just by transformation on the PPF installed in the grid. Fig.1 shows a PHAPF that is in use now [3]. To reduce the power of APFs, a PPF has been designed for some certain orders of harmonics. As in Fig. 1, C_2,L_2; C_5,L_5 and C_7 and L_7 make up a PPF to compensate the second, fifth, and seventh harmonic current, while the APF is just used to improve the performance of PPF and get rid of the resonance that may occur. So the power of the filter can be reduced sharply, usually one-tenth of the power of the nonlinear load, which enables the APF to be used in a high-power occasion. HAPF is expected to compensate for reactive power as well as damp harmonics in the grid, and all of the reactive power current will go through APF. To further decrease the power of APF, a novel configuration of the hybrid APF is proposed as shown in Fig.2 [7]. L_1 and C_1 tune at the fundamental frequency, and then compose the injection branch with C_F. The APF, shunted to the fundamental resonance circuit, is directly connected in series with a matching transformer. Therefore, the novel HAPF (IHAPF) is formed. The PPF sustains the main grid voltage and compensates for the constant reactive powe r, while the fundamental resonance circuit only sustains the harmonic voltage, which greatly reduces the APF power and minimizes the voltage rating of the semiconductor switching device. So it is effective to be used in the 6-kV/10-kV medium-voltage grid.

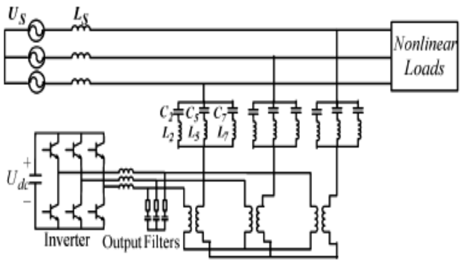


Fig.1 Topology of the Shunt Hybrid APF

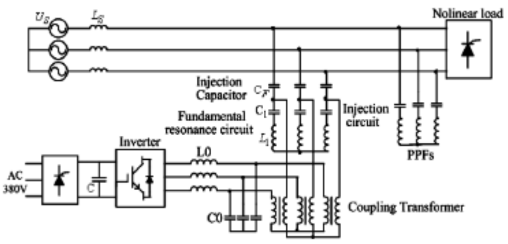


Fig.2 Topology of the Novel HAPF

As shown in Fig.2, the novel HAPF has two advantages.

1) The branch is tuned at the fundamental frequency, so the reactance of and should be the supply voltage is almost applied across the injection capacitor and does not appear on the inverter output terminals, which greatly reduces current

2) The active part of HAPF cannot compensate neighbouring frequency components, but it can eliminate most of the harmonic, especially the main harmonic components, the 5th, 7th, 11th, and 13th order one. By neglecting the system impedance, when the injection circuit is tun

$$X_{L1}-X_{C1}=0 \tag{1}$$

ed at the n_{th} order, the n_{th} injection rate can be represented as

$$K_n=\frac{(n^2-1)X_{L1}}{(n^2-1)X_{L1}-X_{CF}} \tag{2}$$

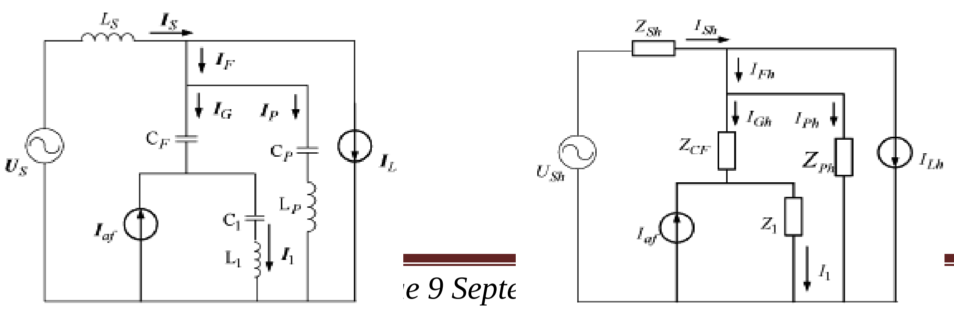
Due to these advantages, it is effective to eliminate the harmonic current and to compensate reactive power for the 6-kV/10-kV/35-kV high-voltage distribution grid.

In order to clarify the compensation principle of IHAPF, a single-phase equivalent circuit is shown in Fig.3, where APF is considered a controlled current source I_{af} , and the nonlinear load is considered to be a harmonic current source I_L. In Fig.3, U_s and L_s are the supply voltage and equivalent inductor of the grid C_F, and C_1,L_1,C_p and L_p are the injection capacitor, fundamental resonance capacitor, fundamental resonance inductor, and the PPF capacitor and inductor respectively.

Fig. 3(b) is the equivalent circuit of the IHAPF only considering the harmonic component of the system. Z_{sh}, Z_{ph}, Z_{cF} and Z_1 represent system impedance, PPF impedance, the impedance of the injection capacitor, and the fundamental resonance impedance.

From Fig.3(b), the equations can be written as

$$\begin{aligned}
&I_{Sh}=I_{Fh}+I_{Lh}\\
&U_{Sh}-I_{Sh}Z_{Sh}=I_{Ph}Z_{Ph}\\
&I_{Fh}=I_{Ph}+I_{Gh}\\
&I_1=I_{Gh}+I_{af}\\
&I_{Gh}Z_{Gh}+I_1Z_1=I_{Ph}Z_{Ph}
\end{aligned} \tag{3}$$



(a) (b)

Fig. 3 (a) Single-phase equivalent circuit. (b) Single-phase equivalent circuit with the effect of a harmonic source

III. ADAPTIVE FUZZY DIVIDING FREQUENCY-CONTROL METHOD

The conventional linear feedback controller (PI controller, state feedback control, etc.) is utilized to improve the dynamic Response and/or to increase the stability margin of the closed loop system. However, these controllers may present a poor steady-state error for the harmonic reference signal.

An adaptive fuzzy dividing frequency control method is presented in Fig.4, which consists of two control units:

1) a generalized integrator control unit and 2) a fuzzy adjustor unit.

The generalized integrator, which can ignore the influence of magnitude and phase, is used for dividing frequency .integral control, while fuzzy arithmetic is used to timely adjust the PI coefficients. Since the purpose of the control scheme is to receive a minimum steady-state error, the harmonic reference signal is set to zero. First, supply harmonic current is detected. Then, the expectation control signal of the inverter is revealed by the adaptive fuzzy dividing frequency controller.

The stability of the system is achieved by a proportional controller, and the perfect dynamic state is received by the generalized integral controller. The fuzzy adjustor is set to adjust the parameters of proportional control and generalized integral control. Therefore, the proposed harmonic current tracking controller can decrease the tracking error of the harmonic compensation current, and have better dynamic response and robustness

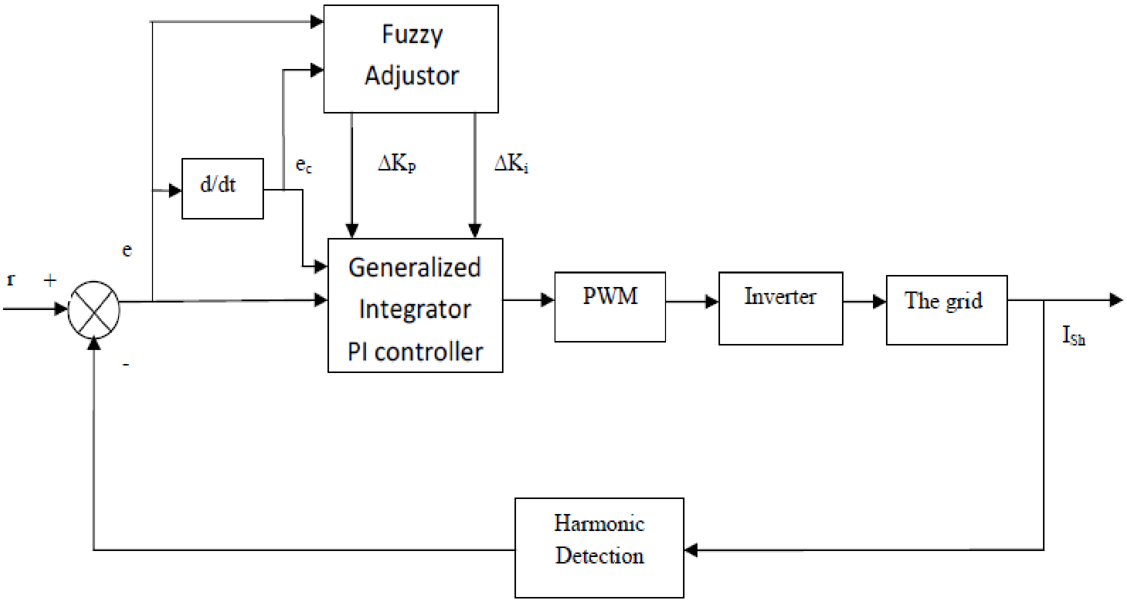


Fig.4 Configuration of the adaptive fuzzy dividing frequency controller

Generalized Integral Controller:

The generalized integral PI controller carries out the dividing frequency control of the sinusoidal signal. Similar to the direct signal case, the generalized integrator just works on the amplitude of a sinusoidal signal e(t)=Asin(ωt+φ), but has no effect on its frequency and phase. So the amplitude integration of this signal can be written as y(t)=Atsin(ωt+φ). Further defining an auxiliary signal y(t)=Atsin(ωt+φ), the Laplace transforms of the three signals are

$$X(s) = \frac{As\cos\varphi}{s^2+\omega^2} - \frac{A\omega\sin\varphi}{s^2+\omega^2}$$

$$E(s) = \frac{A\omega\cos\varphi}{s^2+\omega^2} + \frac{As\sin\varphi}{s^2+\omega^2} \quad (5)$$

$$Y(s) = \frac{S}{S^2+\omega^2}\left(\frac{A\omega\cos\varphi + AS\sin\varphi}{S^2+\omega^2}\right) + \frac{S}{S^2+\omega^2}\left(\frac{A\omega\cos\varphi - AS\sin\varphi}{S^2+\omega^2}\right) \quad (6)$$

So,

$$Y(s) = \frac{s}{s^2+\omega^2}E(s) + \frac{\omega}{s^2+\omega^2}X(s) \tag{7}$$

When the frequency of the sinusoidal signal has a deviation Δω

$$e^{'}(t) = A\sin[(\omega+\Delta\omega)t+\varphi] \tag{8}$$

The auxiliary signal and integration signal can be shown as

$$x^{'}(t) = A\cos[(\omega+\Delta\omega)t+\varphi] \tag{9}$$

$$y^{'}(t) = At\sin[(\omega+\Delta\omega)t+\varphi] \tag{10}$$

And then

$$\frac{S}{S^2+\omega^2}E^{'}(s) + \frac{S}{S^2+\omega^2}X^{'}(s) = L(A\sin[(\omega+\frac{\Delta\omega}{2})t+\varphi]\frac{\sin\frac{\Delta\omega}{2}t}{\frac{\Delta\omega}{2}}) \tag{11}$$

where L(*) is the Laplace transform of the signal *. When the frequency deviation Δω is small, there is

$$\sin\frac{\Delta\omega}{2}t \approx \frac{\Delta\omega}{2} \tag{12}$$

so (5.8) can be written as,

$$Y^{'}s) = \frac{s}{s^2+\omega^2}E^{'}(s) + \frac{\omega}{s^2+\omega^2}X^{'}(s) \tag{13}$$

From (12), it can be seen that (7) comes into existence all the same even when the frequency of the sinusoidal signal has a small deviation. When Δω is far bigger than 1, there is

$$\sin\frac{\Delta\omega}{2}\frac{t}{\frac{\Delta\omega}{2}} \approx 0 \tag{14}$$

As for Y'(s)

$$\frac{s}{s^2+\omega^2}E^{'}(s) + \frac{\omega}{s^2+\omega^2}X^{'}(s) \approx 0 \tag{15}$$

So when the frequency deviation is large, the amplitude integration will be zero. And so, for the three sinusoidal signals

$$y_n(t) = A_n t\sin(\omega_n t+\varphi_n) \tag{16}$$

$$e^{''}(t) = e_n(t) + \sum_{m=0,m\neq n}^{\infty} A_m\sin(\omega_m t+\varphi_m) \tag{17}$$

$$x^{''}(t) = x_n(t) + \sum_{m=0,m\neq n}^{\infty} A_m\cos(\omega_m t+\varphi_m) \tag{18}$$

Where

$$x_n(t) = A_n \cos(\omega_n t + \varphi_n)$$
$$e_n(t) = A_n t \sin(\omega_n t + \varphi_n) \qquad (19)$$

According to the previous analysis, when $|\omega_m-\omega_n|>>1$, their Laplace transforms can be written as

(20)

$$Y_n(s) = \frac{s}{s^2+\omega_n{}^2}E^{"}(s) + \frac{\omega_n}{s^2+\omega_n{}^2}X^{"}(s) \qquad (21)$$

From (22), it can be seen that (7) has a selectivity of frequency. It indicates that the integration signal $y_n(t)$ of a sinusoidal signal $e_n(t)$with the frequency can be obtained based on (22).

At the same time, it can see that

$$L\left(\frac{A\sin\varphi\sin\omega t}{\omega}\right) = \frac{s}{s^2+\omega^2}E(s) - \frac{\omega}{s^2+\omega^2}X(s) \qquad (22)$$

According to (22) and (7),then

$$L\left(y(t) + \frac{A\sin\varphi\sin\omega t}{\omega}\right) = \frac{2s}{s^2+\omega^2}E(s) \qquad (23)$$

Relative to y(t), Asinφsinωt/ω is negligible; thus, the transfer function of the generalized integrator, which has a function of dividing frequency, is

$$G_n(s) = \frac{2s}{s^2+\omega_n{}^2} \qquad (24)$$

In terms of the analysis from before, the block diagram of the generalized integrator PI controller can be obtained by the characteristic of the generalized integrator, shown in Fig.5.

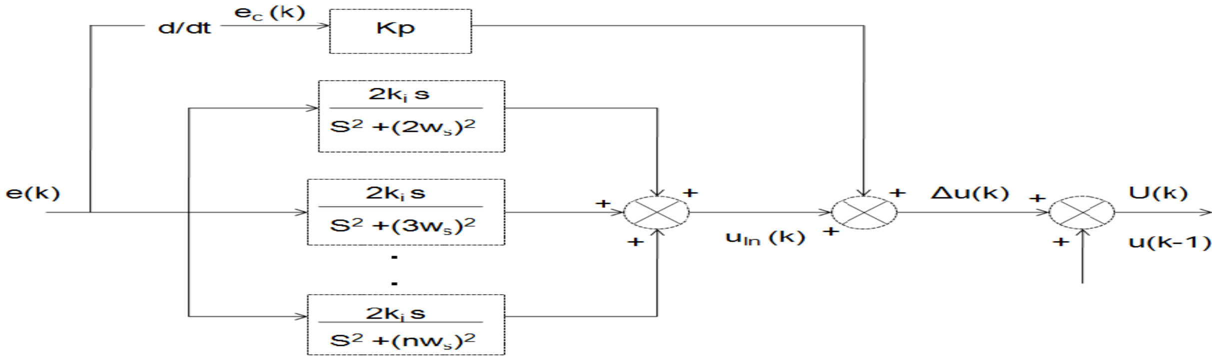


Fig. 5 Configuration of the generalized integrator PI controller

To reduce count quantity and improve the real time, the incremental iteration algorithm is applied. On the principle of the control quantity of the previous two-control cycle, the output of the generalized integrator is expressed as

$$u_{In}(k) = \frac{2K_I e_C(k) + 2u_{In}(k-1) - u_{In}(k-1)}{1+(n\omega_s)^2}$$
$$\Delta U_C(k) = K_p e_C(k) + \sum_{n\subset H} u_{In}(k)$$
$$U_C(k) = U_C(k-1) + \Delta U_C(k) \qquad (26)$$

where k is the sampling value of the current time, k-1 is the sampling value of the previous cycle, K_P and K_I are the proportional coefficient and integrator coefficient of the PI controller, respectively, and H is a set of harmonic orders that need to be eliminated. In order to eliminate disturb efficiently, the discrete differential coefficient $e_c(k)$ can be obtained as eq.(27)

$$e_C(k) = \frac{e(k) = 3e(k-1) - 3e(k-2) - e(k-3)}{6}$$

Fuzzy Adjustor:

The fuzzy adjustor is used to adjust the parameters of proportional control gain and integral control gain.

$$\begin{aligned} K_p &= K_P^* + \Delta K_P \\ K_I &= K_I^* + \Delta K_I \end{aligned} \qquad (28)$$

where K_P*and K_I* are reference values of the fuzzy-generalized integrator PI controller. K_P* and K_I* are calculated offline based on the Ziegler–Nichols method. In a fuzzy-logic controller, the control action is determined from the evaluation of a set of simple linguis development of the rules requires a thorough understanding of the process to be controlled, but it does not require a mathematical model of the system.

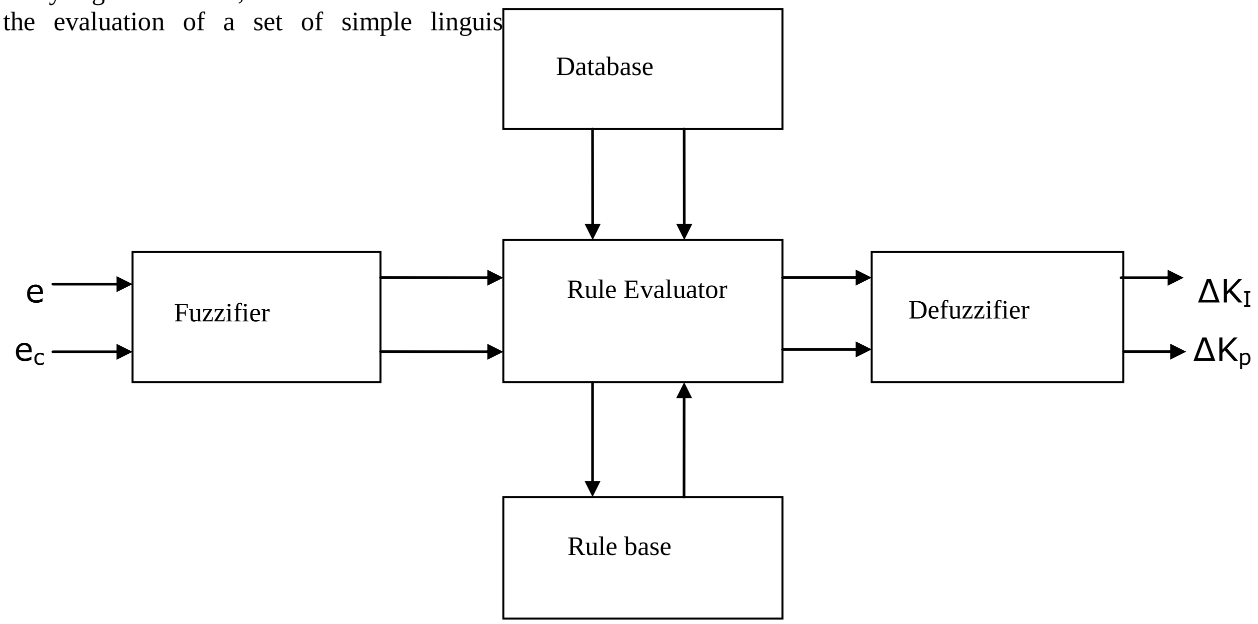
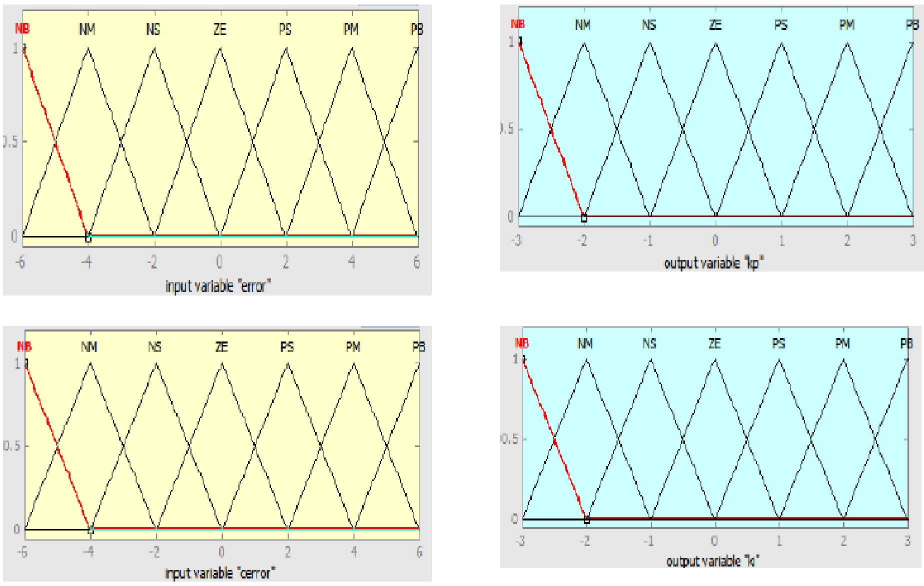


Fig. 6 Block diagram of the fuzzy adjustor

A block diagram fuzzy-logic adjustor is shown in Fig. 6. In this way, system stability and a fast dynamic response with small overshoot can be achieved with proper handing of the fuzzy-logic adjustor.

Fuzzification converts crisp data into fuzzy sets, making it comfortable with the fuzzy set representation of the state variable in the rule. In the fuzzification process, normalization by reforming a scale transformation is needed at first, which maps the physical values of the state variable into a normalized universe of discourse.

The error and change of error are used as numerical variables from the real system. To convert these numerical variables into linguistic variables, the following seven fuzzy levels or sets are chosen as [17]: negative big (NB), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM), and positive big (PB).To ensure the sensitivity and robustness of the controller, the membership function of the fuzzy sets for e(k),$e_c(k)$,ΔK_p,and ΔK_I are acquired from the ranges of e, e_c, ΔK_p ,and ΔK_I, which are obtained from project and experience. The membership functions are shown in Fig.7, respectively.



(a) (b)

Fig.7The membership functions

mainly from the intuitive feeling for and experience of the process. The fuzzy control rule design involves defining rules that relate the input variables to the output model properties.For designing the control rule base for tuning and ,the following important factors have been taken into account.

1) For large values of |e| a large ΔK_p is required, and for small values of |e|, a small ΔK_p is required.

2) For $e.e_c > 0$, a large ΔK_p is required, and for $e.e_c < 0$, a small ΔK_p is required.

3) For large values of |e| and $|e_c|$, ΔK_i is set to zero, which can avoid control saturation.

4) For small values of |e|, ΔK_i is effective, and ΔK_i is larger when |e| is smaller, which is better to decrease the steady-state error.

So the tuning rules of ΔK_p and ΔK_I can be obtained as Tables 1 and 2.

deltakp					ec			
		NB	NM	NS	0	PS	PM	PB
	NB	PB	PB	NB	PM	PS	PS	0
	NM	PB	PB	NM	PM	PS	0	0
	NS	PM	PM	NS	PS	0	NS	NM
e	0	PM	PS	0	0	NS	NM	NM
	PS	PS	PS	0	NS	NS	NM	NM
	PM	0	0	NS	NM	NM	NM	NB
	PB	0	NS	NS	NM	NM	NB	NB

deltaki					ec			
		NB	NM	NS	0	PS	PM	PB
	NB	0	0	NB	NM	NM	0	0
	NM	0	0	NM	NM	NS	0	0
	NS	0	0	NS	NS	0	0	0
e	0	0	0	NS	NM	PS	0	0
	PS	0	0	0	PS	PS	0	0
	PM	0	0	PS	PM	PM	0	0
	PB	0	0	NS	PM	PB	0	0

IV. SIMULINK MODEL FOR IHAPF

Simulation results of a 10-kV system have been carried out with software MATLAB. The system parameters are listed in Table 3. The PPFs are turned at the 11th and 13th, respectively. The injection circuit is turned at the 6th. In this simulation, ideal harmonic current sources are applied. The dc-side voltage is 535 V.

Table 3. Parameters of the IHAPF

	L/mH	C/μF	Q
Output filter	0.2	60	
11^{th} turned filter	1.77	49.75	50
13^{th} turned filter	1.37	44.76	50
6^{th} turned filter	14.75	C_F:19.65,C1=690	

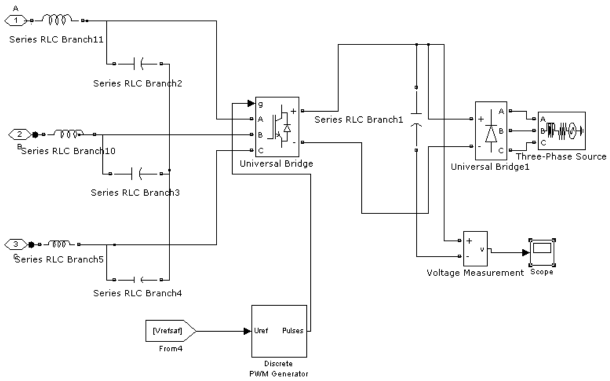


Fig.6.2.Active power filter subsystem

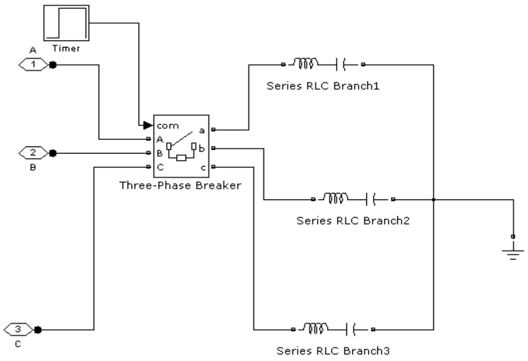


Fig.6.3.Passive power filter subsystem

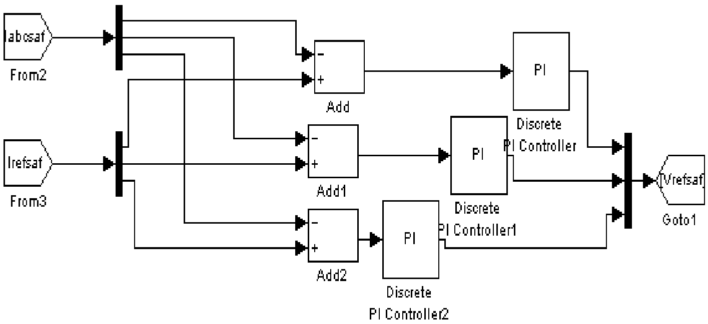


Fig.8. PI controller block

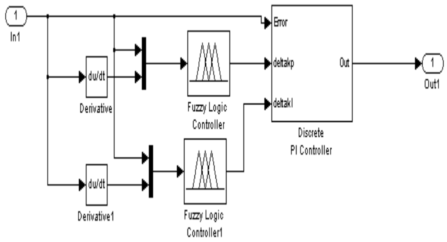


Fig.9.Fuzzy controller block

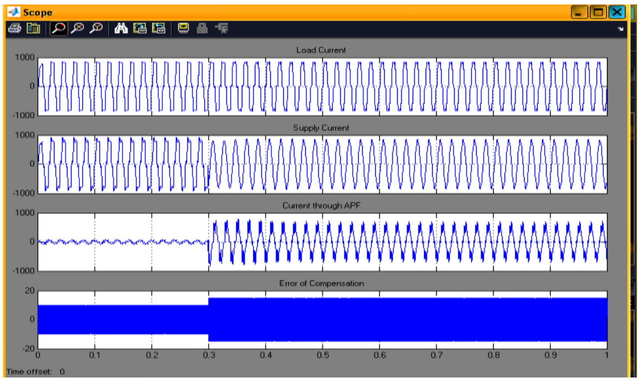


Fig.10 Simulation results of dynamic performance with PI controller

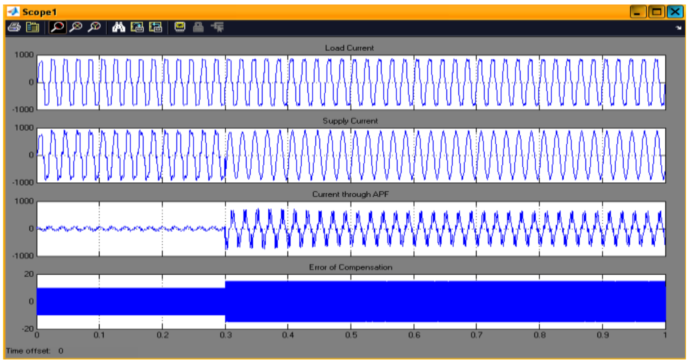
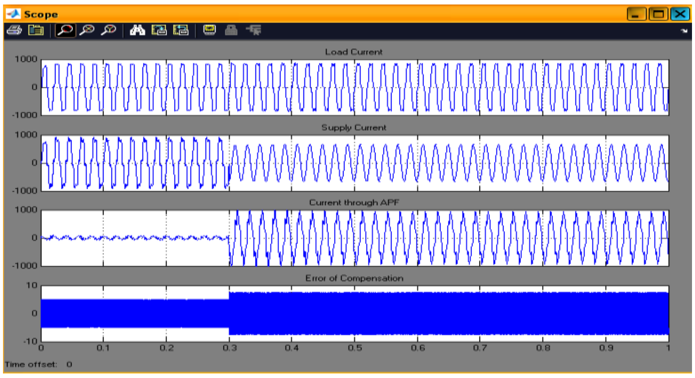


Fig.11 Simulation results of dynamic performance with Generalized integral controller



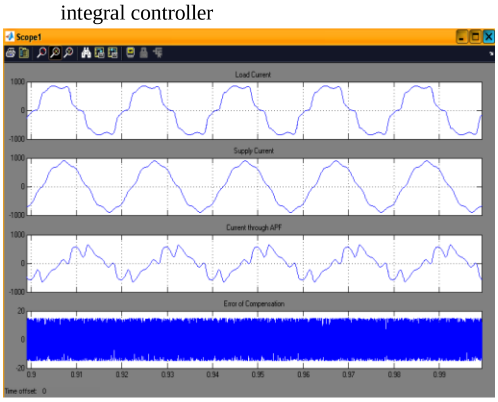
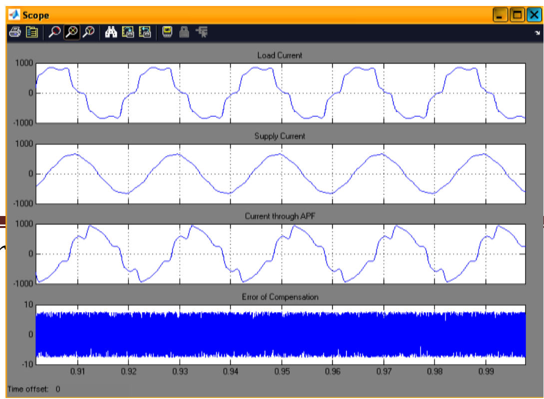


Fig.12 Simulation results of dynamic performance with adaptive fuzzy Controller

Fig.13 Simulation results of steady state performance with PI controller



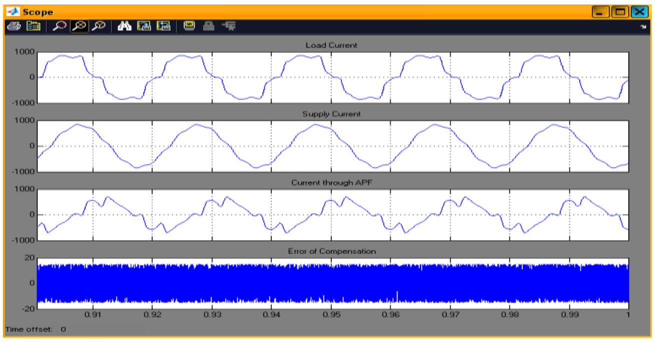


Fig.14 Simulation results of steady state performance with Generalized Integral controller Fig.15 Simulation results of steady state performance with adaptive fuzzy controller

V. CONCLUSION

In the present work the Adaptive Fuzzy Control Schemes are used for the Development of Novel Hybrid Active Power Filter with injection circuit. The proposed adaptive fuzzy-dividing frequency control can decrease the tracking error and increase dynamic response and robustness.

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This control method is also useful and applicable to any other active filters. Simulation and application results proved the feasibility and validity of the hybrid active power filter and the adaptive fuzzy control method. The comparison of supply current Total Harmonic Distortion(THD) and power factor is shown in table 4

Table 4. Comparison of supply current THD and Power factor

	THD	Power factor
With out IHAPF	21.5%	0.69
IHAPF with Adaptive Fuzzy	1.9%	0.94

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