Design and Implementation of Hybrid Active Power Filter

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ABSTRACT
This paper deals with a hybrid active power filter with injection circuit (IHAPF). 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,.The generalized integrator is used for dividing frequency integral control, while fuzzy arithmetic is used for adjusting proportional-integral coefficients timely. The simulation results shows that the new control method is not only easy to be calculated and implemented, but also very effective in reducing harmonics.

Keywords
Hybrid active power filter(HAPF), frequency control, fuzzy adjustor

1. INTRODUCTION
Hybrid active filters for harmonic-current filtering Two types of hybrid active filters for harmonic-current filtering of nonlinear loads were proposed in 1988 and in 1990, respectively. Figure 1.8 and Fig. 1.9 show the simplified circuit configurations of the hybrid active filters. The two hybrid filters are based on combinations of an active filter, a three-phase transformer (or three single-phase transformers), and a passive filter consisting of two single tuned filters to the 5th- and 7th-harmonic frequencies and a second-order high-pass filter tuned around the 11th-harmonic frequency. Although these hybrid filters are slightly different in circuit configuration, they are almost the same in operating principle and filtering performance. Such a combination with the passive filter makes it possible to significantly reduce the rating of the active filter. The task of the active filter is not to compensate for harmonic currents produced by the thyristor rectifier, but to achieve "harmonic isolation" between the supply and the load As a result, no harmonic resonance occurs, and no harmonic current flows in the supply. comparison control using a proportional-integral (PI) regulator has a long history of use. When the reference current is a direct signal, as in the dc motor drive, zero steady-state error can be secured by using a conventional PI controller. When the reference current is a sinusoidal signal, as in the ac motor drive, however, straightforward use of the conventional PI controller would lead to steady-state error due to the finite gain at the operating frequency. This drawback can be solved if the current control is executed in a synchronous-coordinate reference frame. However, it is more complex and requires more hardware\ or software for implementation because it demands transferring the measured currents to a synchronous frame, and subsequently transforming the output of the PI regulator back to a stationary frame to drive the ramp comparison controller. Sinusoidal internal model control also requires more hardware or software for implementation.

2.Topology of the Novel Hybrid Active Power Filter
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. To reduce the power of APFs, a PPF has been designed for some certain orders of harmonics. As in Fig.1, and 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.

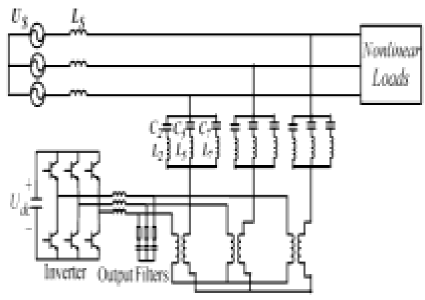


Fig.1 Topology of the Shunt Hybrid APF

The branch is tuned at the fundamental frequency, so the reactance of and should be

$$X_{L1} - X_{c1} = \omega_0 L_1 - \frac{1}{\omega_0 C_1} = 0 \quad \text{….(1)}$$

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 tuned at the th order, the th injection rate can be represented as

$$K_n = \frac{(n^2-1)X_{L1}}{(n^2-1)X_{L1}-X_{CF}} = \frac{n^2-1}{m^2-1} \quad \text{…..(2)}$$

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.

through APF. To further decrease the power of APF, a novel configuration of the hybrid APF is proposed as shown in Fig. And tune at the fundamental frequency, and then compose the injection branch with . 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 power, 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.

injection capacitor, fundamental resonance capacitor, fundamental resonance inductor, and the PPF capacitor and inductor respectively.

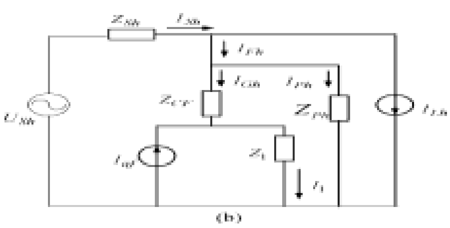


Fig. 2 Single-Phase equivalent circuit

Fig. (2) is the equivalent circuit of the IHAPF only considering the harmonic component of the system. Zsh,Zph,ZcF and Z1 represent system impedance, PPF impedance,theimpedance of the injection capacitor, and the fundamental resonance impedance. From Fig.2, we can see that

$$I_{sh} = I_{Fh} + I_{Lh}$$

$$U_{sh} = I_{sh}Z_{sh} = I_{ph}Z_{ph}$$

$$I_{Fh} = I_{ph} + I_{Gh} \quad \text{……………..(3)}$$

$$I_1 = I_{Gh} + I_{af}$$

$$I_{Gh}Z_{Gh} + I_1Z_1 = I_{ph}Z_{ph}$$

2.1 Control Strategy Based on Load Current Detection: This method detects the load harmonic current , and the APF is controlled as

$$I_{af} = KI_{Lh} \quad \text{…………….(4)}$$

From (2.3) and (2.4) and when only harmonic current is considered,

the supply harmonic current should be

$$I_{sh} = \frac{(Z_{CF}+Z_1-KZ_1)Z_{ph}I_{Lh}}{(Z_{CF}+Z_1)(Z_{ph}+Z_{sh})+Z_{ph}Z_{sh}} \quad \text{…….(5)}$$

Equation (5) can be written as

$$\frac{I_{sh}}{I_{Lh}} = \frac{(Z_{CF}+Z_1-KZ_1)Z_{ph}}{(Z_{CF}+Z_1)(Z_{ph}+Z_{sh})+Z_{ph}Z_{sh}} \quad \text{……………….(6)}$$

It can be seen that the characteristic of PPFs is optimized and the harmonic

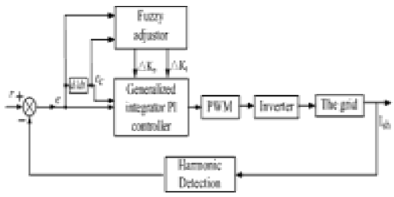


Fig. 3 Configuration of the adaptive fuzzy dividing frequency controller

impedance of the grid is increased, which improves the performance of harmonic elimination. However, the possibility of resonance between the IHAPF and the grid cannot be avoided, and it increases the difficulty of parameter design. Moreover, it is not suitable to be used in the situation where the impedance of the grid changes at high frequency.

2.2 Control Strategy Based on the Supply-Current Detection:

This method detects the supply harmonic current , and the APF is considered as a controlled current source

$$I_{af} = KI_{sh} \quad \text{………………(7)}$$

Where k is the controlled gain of . From (2.3) and (2.7), the supply current should be

$$I_{sh} = \frac{(Z_{CF}+Z_1)Z_{ph}I_{Lh}+(Z_{CF}+Z_1+Z_{ph})U_{sh}}{(Z_{CF}+Z_1+Z_{ph})Z_{sh}+(Z_{CF}+Z_{sh}+kZ_1)Z_{ph}}$$

…………………………(8)

Equation (2.8) indicates that it is possible to eliminate the influence of the load harmonic current and supply harmonic voltage as low as possible if is large enough. Moreover, if the supply harmonic voltage is not considered, that is

$$\frac{I_{sh}}{I_{Lh}} = \frac{(Z_{CF}+Z_1)Z_{ph}}{Z_{sh}(Z_{CF}+Z_1+Z_{ph})+(Z_{CF}+Z_{sh}+KZ_1)Z_{ph}}$$

………………….(9)

. According to Fig.2, the APF of the IHAPF tends to be a harmonic resistance, which is in series with the . When large enough, the harmonic current flowing into the grid is is nearly zero. Thus, it has a good performance in harmonic elimination. At the same time, it can restrain the possibility of parallel resonance between the IHAPF and the grid. As stated before, it can be found that for the sake of compensating harmonic current, the control strategy based on the detection of load harmonic current is a good choice. But the possibility of resonance between the IHAPF and the grid cannot be avoided, and it increases the difficulty of the IHAPF parameter design. If the control strategy based on supply current detection is used, IHAPF can eliminate not only the harmonic current, but also the possibility of parallel resonance between IHAPF and the grid will be restrained. So the control strategy based on the supply current detection is applied

3. 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. 3.2, 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.

3.1 Fuzzy Inference System

Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. The mapping then provides a basis from which decisions can be made, or patterns discerned. The process of fuzzy inference involves all of the pieces that are described in the previous sections: membership functions, fuzzy logic operations, and if-then rules.

These are two types of fuzzy inference systems that can be implemented in the fuzzy logic toolbox: Mamdani-type and sugeno-type. These two types of inference systems vary in the way outputs are determined.

Basically a fuzzy inference system is composed of five functional blocks as shown in the fig4.1.

rule base containing a number of fuzzy if-then rules;

A data base, which defines the membership functions of the fuzzy sets used in the fuzzy rules;

Fuzzification interference to fuzzify the inputs;

A decision making unit which performs the crisp inputs into degrees to match with linguistic values;

A defuzzification interface which

transforms the fuzzy results of the

interference into a crisp output.

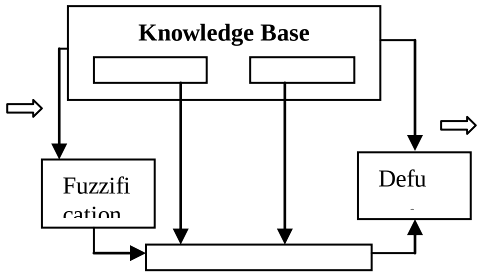


Fig 4. Block Diagram of fuzzy Inference system The steps performed by fuzzy inference systems are:

Step 1.Fuzzify inputs:

Resolve all fuzzy statements in the antecedent to a degree of membership between 0 and 1. If there is only one part to the antecedent, this is the degree of support for the rule.

Step 2.Apply fuzzy operator to multiple part antecedents:

If there are multiple parts to the antecedent, apply fuzzy logic operators and resolve the antecedent to a single number between 0 and 1. This is the degree of support for the rule.

Step 3.Apply implication method:

Use the degree of support for the entire rule to shape the output fuzzy set. The consequent of fuzzy rule assigns an entire fuzzy set to the output. This fuzzy set is represented by a membership function that is chosen to indicate the qualities of the consequent. If the antecedent is only partially true, (i.e., is assigned a value less than 1), then the output fuzzy set is truncated according to the implication method.

Step 4. Aggregating the output across all rules:

Steps 1, 2, 3 occur for all rules so each rule has fuzzy set to contribute to each output. Joining all these sets into a single output membership function is known as aggression and the aggression operator mediates it.

Step 5. Defuzzification:

The input to the defuzzification process is a fuzzy set (the aggregate output fuzzy set) and the output is a single number. The most popular defuzzification method is the centroid calculation, which returns the center of the area under the curve. The other methods are the

bisector method, middle of maximum (the average of the maximum value of the output set) largest of maximum and the smallest of the maximum.

In the fuzzy logic toolbox, which is available with the MATLAB package there are five primary graphical user interface (GUI) tools for building, editing and observing the fuzzy interface systems. The toolbox contains the fuzzy inference system (FIS) Editor, the membership function Editor, the rule Editor, the rule viewer and the surface viewer. These different GUI's are all effectively siblings in that we can have any or all of them open for any given system.

The FIS Editor handles the high level issues for the system: How many input and output variable? What are their names? The membership function associated with each variable. The rule editor is for editing the list of rules that defines the behavior of the system. The last two GUI's are used for looking at, as opposed to editing, the FIS. The rule viewer is a very powerful window full of information. The surface viewer displays how one of the output depends on any one of the outputs depends on any one or two of the inputs that is, it generates and plots an output surface map for the system

3.2 Mamdani-type Inference.

Mamdani's fuzzy inference method is the most commonly seen fuzzy methodology. Mamdani's method was proposed in 1975 by Ebrahim Mamdani and is among the first inference systems built using fuzzy set theory. Mamdani-type inference, expects the output membership functions to be fuzzy sets. After the aggregation process, there is a fuzzy set for each output variable that needs defuzzification. It's possible, and in many cases much more efficient, to use a single spike as the output membership functions rather than a distributed set. This is sometimes known as a singleton output membership function, and it can be thought of as a pre-defuzzified fuzzy set.

It enhances the efficiency of the defuzzification process because it greatly simplifies the computation required by the more general Mamdani method, which finds the centroid of a two-dimensional function. Rather than integrating across the two-dimensional function to find the centroid, we use the weighted average of a few data points. Sugeno-type systems support this type of model. In general, Sugeno-type systems can be used to model any Inference system in which the output membership functions are either linear or constant.

3.3 Fuzzy Adjustor

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

$$Kp = K_p^* + \Delta K_p \quad \text{………………….(10)}$$

$$K_I = K_I^* + \Delta K_I \quad \text{…………………..(11)}$$

where and are reference values of the fuzzy-generalized integrator PI controller. In this paper, and 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 linguistic rules. The 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. 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 ,and in this paper are acquired from the ranges of and which are obtained from project and experience. And the membership functions are Fig.6 Membership functions of the fuzzy variable.(a) Membership function of e(k) and ec(k). (b) Membership functions of Δk_p and ΔK_I

The core of fuzzy control is the fuzzy control rule, which is obtained mainly from the intuitive feeling for and experience of the process. The fuzzy control rule design involves

Table 1

Adjusting rule of the Δk_p parameter

ΔKp		e_c						
		NB	NM	NS	0	PS	PM	PB
e	NB	PB	PB	NB	PM	PS	PS	0
	NM	PB	PB	NM	PM	PS	0	0
	NS	PM	PM	NS	PS	0	NS	NM
	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

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, a large is required, and for small values of , a small is required.

2) For, a large is required, and for , a small is required.

3) For large values of and, is set to zero, which can avoid control saturation.

4) For small values of, is effective, and is larger when is smaller, which is better to decrease the steady-state error. So the tuning rules of and can be obtained as Tables I and II.

The inference method employs the MAX-MIN method. The imprecise fuzzy control action generated from the inference must be transformed to a precise control action in real applications. The center of gravity method is used to defuzzify the fuzzy variable into physical

Domain

Adjusting rule of the Δk_I parameter

TableII

ΔK_I		e_c						
		NB	NM	NS	0	PS	PM	PB
e	NB	0	0	NB	NM	NM	0	0
	NM	0	0	NM	NM	NS	0	0
	NS	0	0	NS	NS	0	0	0
	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

SIMULATION RESULTS

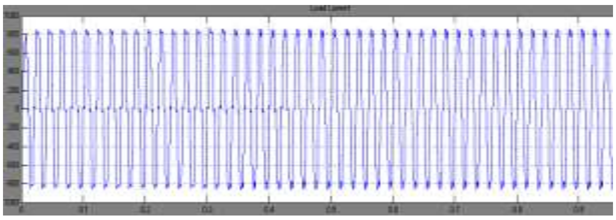
The PPFs are turned at the 11th and 13th, respectively.The injection circuit is turned at the 6th. In this simulation, ideal harmonic current sources are applied. The dc-side voltage is 535 V. Simulation results with the conventional PI controller and the proposed current controller are shown in Figs. 7.1(a) and 7.1.(c)

Table 7.1

Parameters of the IHAPF

	L/mH	C/μF	Q
Out put 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,C_1: 690	

Fig.7.1.(a) Simulation results of dynamic performance with PI controller



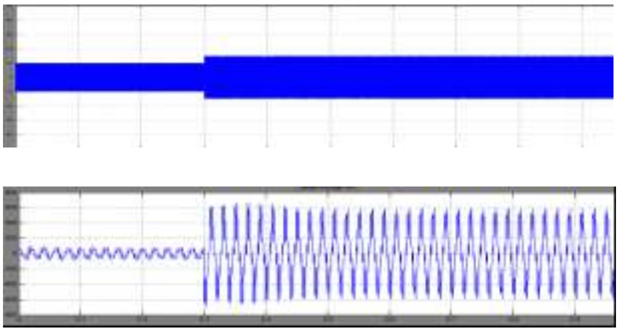


Fig.7.1.(b) Simulation results of dynamic performance with generalized integral controller

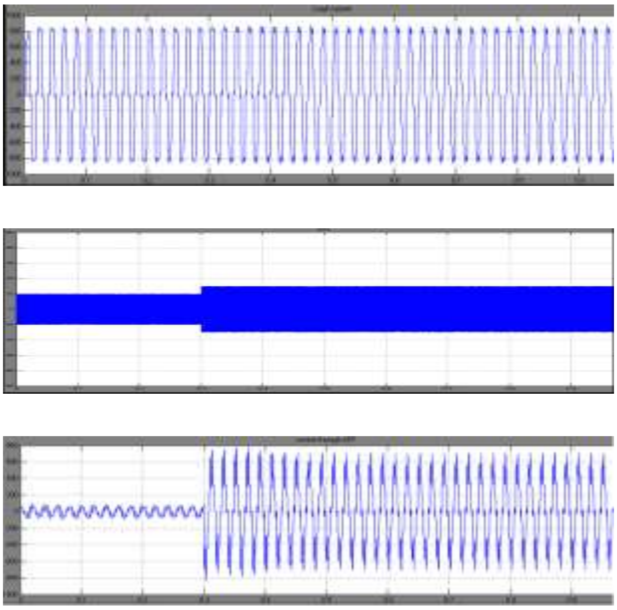
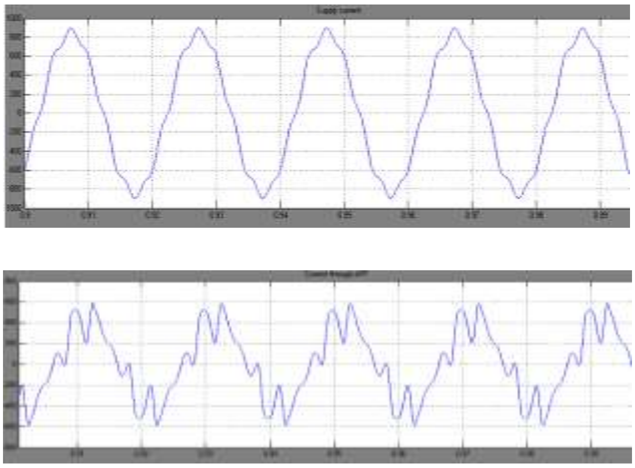
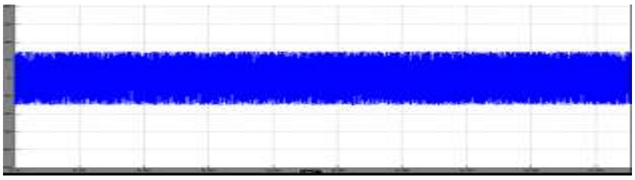
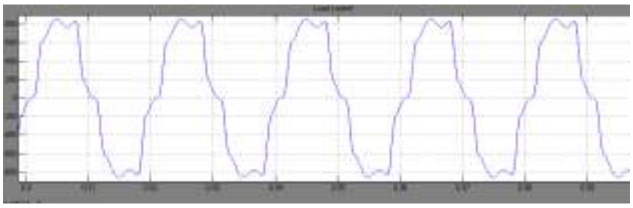


Fig.7.1.(c) Simulation results of dynamic performance with adaptive fuzzy controller







When the conventional generalized integral controller is used, the current THD reduces to 3.3% from 21.8%, while after the IHAPF with the proposed PI controller runs, the current THD reduces to 1.8% from 21.8%. So it can be observed that the proposed current controller exhibits much better performance than the conventional PI controller and the conventional generalized integral controller.

CONCLUSION:

A novel hybrid APF with injection circuit was proposed. Its principle and control methods were discussed. The proposed adaptive fuzzy-dividing frequency control can decrease the tracking error and increase dynamic response and robustness. The control method is also useful and applicable to any other active filters. It is implemented in an IHAPF with a 100-kVA APF system in a copper mill in Northern China, and demonstrates good performance for harmonic elimination.

Simulation and application results proved the feasibility and validity of the IHAPF and the proposed control method.

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