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A Novel Hysteresis Current Control Strategy with Fuzzy Bandwidth for Active Power Filter

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Introduction

In recent years, with the rapid growth of power electronic devices and widely use of non-linear loads, harmonic contamination and reactive power unbalance problems became more and more serious in power system, on the other hand for a long time users started to require better and better quality electric energy [1]. As an important core device in FACTS (Flexible AC Transmission System), APF (Active Power Filter) has become an efficient fixture in harmonic suppressing, and due to the fast development in power electronic technology and digital signal processing technique, as well as increasing in power level of power devices and improving in control method, APF are more widely used in today's power system [2].

To realize the suppression of harmonic, it's required that APF device can dynamically trace the detected current signal, which is quite concerned with the part of current control [3]. Two regular methods of current control in engineering are triangle-wave PWM and current hysteresis comparison, both of which have some disadvantages [4-5]. When considering hysteresis method, it's a problem worthy of study how to choose the loop width H, which determines the whole current tracking efficiency of APF device. Generally, bigger bandwidth H, lower switching frequency, but more high harmonics contained; while smaller bandwidth H, higher switching frequency, more switching loss, but higher tracking precision [6]. In traditional hysteresis method, fixed bandwidth presents changed switching frequency of device, which will bring about some problems as that, when the gap between command and sampled current signal is big, it'll be not safe for the device working in such a high switching frequency; when the gap is small, it'll bring down the precision of current tracking. To solve these problems, some control methods were proposed aimed to dynamically change the loop width H, and some progresses have been already made. Hysteresis control methods based on voltage space vector are proposed in [7], which allow output voltage control and minimization of harmonic components, limit the current tracking error in hysteresis bandwidth; besides, a novel SVPWM approach to control DC rail resonant inverters is proposed in [8]. And based on these researches, a constant switching frequency hysteresis controller is proposed in [9], whose controller differs from prior art hysteresis controllers by having a second integrator inserted in the controller loop's forward path; and a bi-directional real and reactive power control method is presented in [10], which makes switching frequency of power devices almost constant by adjusting hysteresis loop width. However, both control methods above didn't take consideration of the combination use with FACTS devices; they cannot solve the problems of dynamically tracking the distorted current or voltage and output the time-varying compensating harmonic signals, and no practical field test experiment result is illustrated to demonstrate their conclusion.

In this paper, a new control method that can dynamically adjust the bandwidth of hysteresis with the use of fuzzy logic [11] is proposed. Firstly, the structure and traditional hysteresis principles of APF are presented, and variation of switching frequency in this model is also analyzed; then based on works above, fuzzy control strategy is adopted to dynamically get the hysteresis loop width in any moment, so self-tuning of parameters of hysteresis comparator is realized; finally the efficiency of the method above is further demonstrated by simulation and field test experiment. As a conclusion, this paper not only solves the consistent problem that switching frequency varies too severely due to fixed hysteresis bandwidth, but also protects the power switches in order to ensure the APF device to operate safely.

Structure and basic principle

A. Structure of APF. The structure diagram of an active power filter is shown in Fig. 1. The APF is connected to power grid at the point of common coupling (PCC) through three phase inductors, which takes responsibility for compensating harmonics or reactive power caused by nonlinear loads.

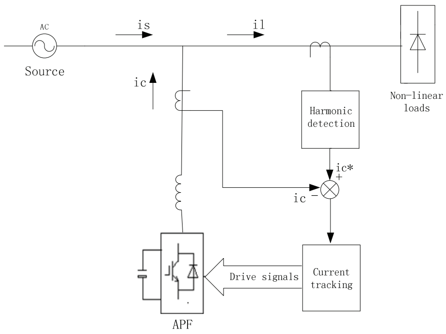


Fig. 1. The structure of APF

B. Traditional hysteresis current control principle. The principle of the traditional hysteresis current tracking control method is shown in Fig. 2, which takes Δi_c (the deviation of reference current i_c^* and sensed actual current i_c) as input, produces PWM switching signals through a hysteresis comparator device, accordingly regulates the compensating current.

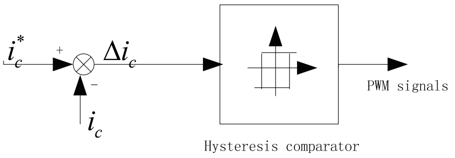


Fig. 2. Schematic diagram of hysteresis

C. Switching frequency in traditional hysteresis. Traditional hysteresis current control technique has comparatively higher precision and faster response, however, it also brings about bigger fluctuation in switching frequency, which makes difficulty to satisfy both the maximum switching frequency restraint and higher regulating current precision.

Fig. 3 shows the structure diagram of a single-phase APF, now the switching frequency variation will be analyzed. Suppose that the reference current $i_c^* = I\sin(n\omega t)$ keeps constant during one switching period; and assume that the voltage of DC-capacitor is u_{dc} and the source voltage is u_s.

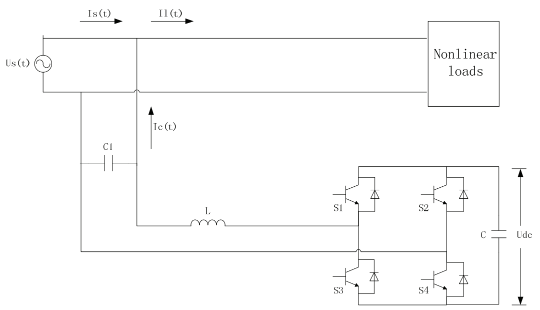


Fig. 3. Structure diagram of single-phase APF

To simplify the analysis, the dead time between upper and lower bridge arms is ignored. When S_1 and S_4 are in working, Eq.(1) can be obtained from the structure diagram of APF inverter

$$u_{dc} - u_s = L\frac{di_c}{dt}. \tag{1}$$

According to the working principle of hysteresis comparator, the turn-on time can be calculated as following

$$T_{on} = \frac{2H}{\left(\dfrac{di_c}{dt}\right)} = \frac{2HL}{u_{dc} - u_s}. \tag{2}$$

When S_2 and S_3 are in working, S_1 and S_4 are turned off, current commutates in upper and lower bridges of converter, Eq.(3) can be obtained from the structure diagram of APF inverter

$$-u_{dc} - u_s = -L\frac{di_c}{dt}. \tag{3}$$

According to the working principle of hysteresis comparator, the turn-off time can be calculated as following

$$T_{off} = \frac{2H}{\left(\dfrac{di_c}{dt}\right)} = \frac{2HL}{u_{dc} + u_s}. \tag{4}$$

Therefore, the switching period of power switches can be expressed as the sum of turn-on and turn-off time

$$T_0 = T_{on} + T_{off} = \frac{4HLu_{dc}}{u_{dc}^2 - u_s^2}. \tag{5}$$

Then the switching frequency is

$$f_0 = \frac{1}{T_0} = \frac{u_{dc}^2 - u_s^2}{4HLu_{dc}}. \tag{6}$$

Actually, the source voltage u_s is a time-varying sinusoidal variable during one working period, while the DC-capacitor voltage u_{dc} almost stays constant. Therefore, the switching frequency is changed all the time during one sinusoidal period. Make deviation of f_0 to the time

$$\frac{df_0}{dt} = -\frac{u_s\left(u_s'\right)}{2HLu_{dc}}. \tag{7}$$

From (7), conclusion can be drawn that the maximum switching frequency occurs at the zero-crossing point of source voltage, and minimum-switching frequency occurs at the peak-value point of source voltage. In traditional hysteresis control method, there's great gap between maximum and minimum switching frequency value during one sinusoidal period due to the constant value of bandwidth H of hysteresis comparator device.

Control algorithm

A fuzzy threshold mutative bandwidth hysteresis current tracking control method is presented in this paper, in order to solve the big switching frequency fluctuation problem in traditional hysteresis method, the hysteresis comparator bandwidth H is designed to be dynamically changed. Fuzzy control logic has good dynamic characteristics and strong robustness, it isn't sensitive to the change of process parameters and can overcome some effects brought by nonlinear factors, so it not only has fuzzy control's advantages like flexible and adaptive characteristics, but also has hysteresis' advantages in high precision and fast response.

The input of fuzzy controller contains two parts: Δi_c, the deviation of reference current and sensed actual current (denoted e); and $\frac{d\Delta i_c}{dt}$, the change rate of deviation Δi_c (denoted ec). Fig. 4 shows the schematic diagram of fuzzy controller.

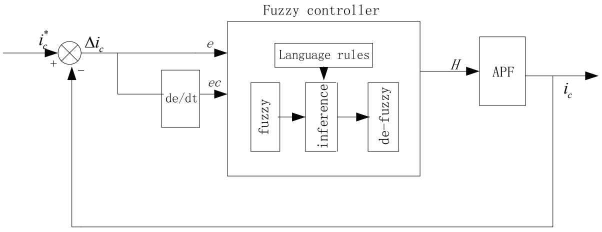


Fig. 4. Schematic diagram of fuzzy controller

Due to that the required output current of APF should compensate all or certain parts of harmonic current, which is time-varying in both frequency and amplitude, the change rate of current should be considered more compared to traditional sinusoidal current inversion. Sample e and ec continuously when device working and regulate these two parameters on the basis of fuzzy rules online dynamically, so as to fit all the conditions with different value of e and ec, and make better static and dynamic characteristics for controlled object. According to the derivation in C of Sec. II, five types of cases can be summarized:

1. $|\Delta i_c|$ is in big value, namely the current is near the zero-crossing point, which represents a high switching frequency, now the loop width H should be increased appropriately;
2. $|\Delta i_c|$ is in small value, namely the current is near the peak-value point, which represents a low switching frequency, now the loop width H should be decreased appropriately;
3. $|\Delta i_c|$ is in middle value, now the loop width H should be also determined by the value of $\left|\frac{d\Delta i_c}{dt}\right|$:
   - $\left|\frac{d\Delta i_c}{dt}\right|$ is in big value, which represents the current value is in rapid change, now the loop width H should be increased appropriately;
   - $\left|\frac{d\Delta i_c}{dt}\right|$ is in small value, which represents the current value is in slow change, now the loop width H should be decreased appropriately;
   - $\left|\frac{d\Delta i_c}{dt}\right|$ is in middle value, the loop width H stays constant.

The fuzzy linguistic variables are two inputs, e and ec, which represent $|\Delta i_c|$ and $\left|\frac{d\Delta i_c}{dt}\right|$; and output is loop width H. In this paper, the three linguistic values for each linguistic variable are considered: Big (B); Middle (M); and Small (S). Triangular function with strong sensitivity is selected as fuzzy variable's membership function, and Mamdani max-min synthetic method as fuzzy inference method, shown as Fig. 5 and Fig. 6. Meanwhile the fuzzy universe is in the form as $H_i = [H_1, H_2, H_3, H_4, H_5]$, where H_1 - H_5 are different values of H corresponding to different types of cases above. The fuzzy rules in conclusion are listed as following:

Rule 1. If $|\Delta i_c| = B$, then $H = H_1$, $\mu_1\left(|\Delta i_c|, \left|\frac{d\Delta i_c}{dt}\right|\right) =$
$= \mu_{aB}\left(|\Delta i_c|\right)$;

Rule 2. If $|\Delta i_c| = M$ and $\left|\frac{d\Delta i_c}{dt}\right| = B$, then $H = H_2$,
$$\mu_2\left(|\Delta i_c|, \left|\frac{d\Delta i_c}{dt}\right|\right) = \mu_{aM}\left(|\Delta i_c|\right) \cap \mu_{bB}\left(\left|\frac{d\Delta i_c}{dt}\right|\right);$$

Rule 3. If $|\Delta i_c| = M$ and $\left|\frac{d\Delta i_c}{dt}\right| = M$, then $H = H_3$,
$$\mu_3\left(|\Delta i_c|, \left|\frac{d\Delta i_c}{dt}\right|\right) = \mu_{aM}\left(|\Delta i_c|\right) \cap \mu_{bM}\left(\left|\frac{d\Delta i_c}{dt}\right|\right);$$

Rule 4. If $|\Delta i_c| = M$ and $\left|\frac{d\Delta i_c}{dt}\right| = S$, then $H = H_4$,
$$\mu_4\left(|\Delta i_c|, \left|\frac{d\Delta i_c}{dt}\right|\right) = \mu_{aM}\left(|\Delta i_c|\right) \cap \mu_{bS}\left(\left|\frac{d\Delta i_c}{dt}\right|\right);$$

Rule 5. If $|\Delta i_c| = S$, then $H = H_5$, $\mu_5\left(|\Delta i_c|, \left|\frac{d\Delta i_c}{dt}\right|\right) =$
$= \mu_{aS}\left(|\Delta i_c|\right)$.

Different value of H_1 - H_5 will make impact on control effect, normally if maximum physical switching frequency of the power switches permits, the smaller bandwidth H, the higher current tracking precision; however, the switching frequency changes rapidly near the zero-crossing point of current, so that the fuzzy controller may not regulate the loop width value relatively in time, since there's always a time-delay in fuzzy inference. Therefore, the safety allowance should be designed to protect power switches as the maximum allowed switching frequency is considered.

Engineering experience always plays an important part in deciding the values of H_i, it's decreasing from H_1 to H_5 ($H_1 > H_2 > H_3 > H_4 > H_5$), when both the switching frequency and current tracking precision are considered. In case of Rule.3, both $|\Delta i_c|$ and $\left|\frac{d\Delta i_c}{dt}\right|$ are near middle linguistic variables, and general middle loop width value is suitable; while in case of Rule.1, maximum loop width value is preferred, which is mainly determined by inherent switching frequency range of power device; and in case of Rule.5, minimum loop width value should be chosen so that can have higher precision and smaller tracking error. In this paper H_1 to H_5 are set to the values of 16, 12, 8, 6, 2, both switching frequency restraint efficiency and current tracking precision are demonstrated by latter simulation and experiment results.

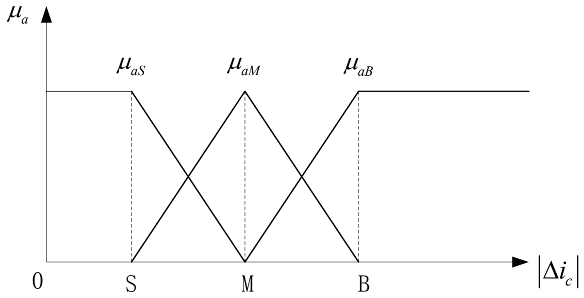


Fig. 5. Membership function of $|\Delta i_c|$

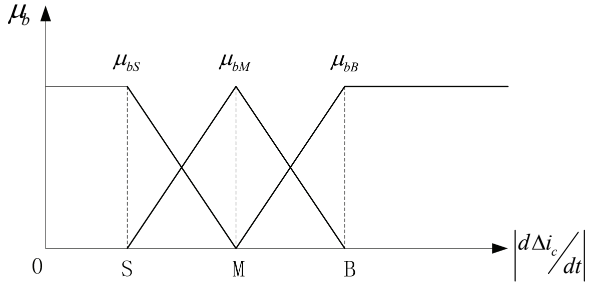


Fig. 6. Membership function of $\left|\frac{d\Delta i_c}{dt}\right|$

In the fuzzy rules, $\mu_a(x)$ and $\mu_b(x)$ are membership functions of $|\Delta i_c|$ and $\left|\frac{d\Delta i_c}{dt}\right|$. Fig. 7 shows the surface picture of fuzzy controller.

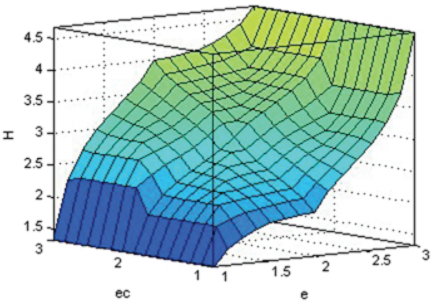


Fig. 7. Surface picture of fuzzy controller

After fuzzy inference, de-fuzzy is needed to get the accurate value of bandwidth H ; this paper adopts centroid method as denazification method to obtain the value of H

$$H=\frac{\sum_{i=1}^{5}\left[\mu_i\left(|\Delta i_c|,\left|\frac{d\Delta i_c}{dt}\right|\right)H_i\right]}{\sum_{i=1}^{5}\mu_i\left(|\Delta i_c|,\left|\frac{d\Delta i_c}{dt}\right|\right)}. \tag{8}$$

Throughout all the process above, loop width of any time can be worked out, set the value of H to be comparator device's threshold and PWM switching signals will be generated.

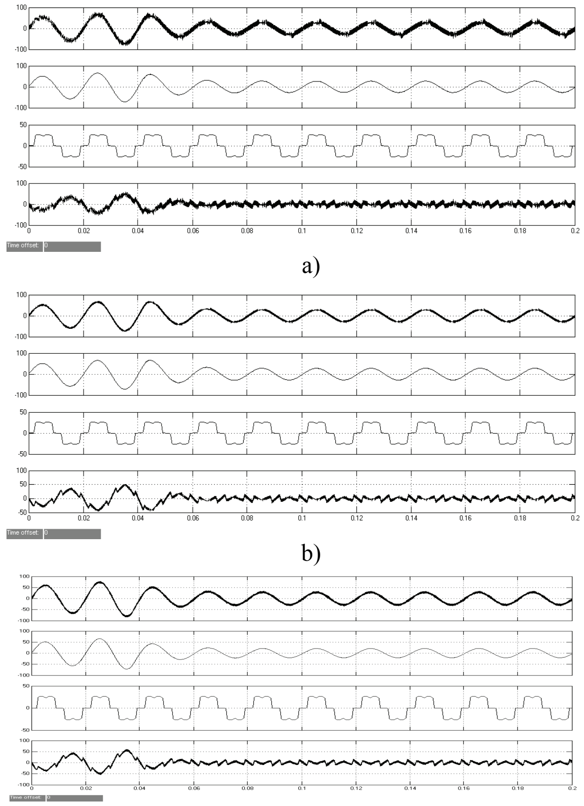
Simulation analysis

Based on three-phase/three-wires transmission system, simulation mode of APF is set up with Matlab in this paper; nonlinear load in the mode is three-phase thyristor Rectifier Bridge, which will generate odd harmonic currents. The simulation parameters are:

1. Rms value of grid source line voltage Us=380V;
2. Incoming line inductor L=1mH;
3. DC-capacitor C=4500μF.

The fuzzy threshold mutative bandwidth hysteresis current tracking control method proposed in this paper is further demonstrated with the simulation model.

Fig. 8 (a) shows the current waveforms in traditional hysteresis method, with bandwidth 2*H*=12; Fig. 8 (b) shows the current waveforms in traditional hysteresis method, with bandwidth 2*H*=6; Fig. 8 (c) shows the current waveforms with the use of the control method proposed in this paper.



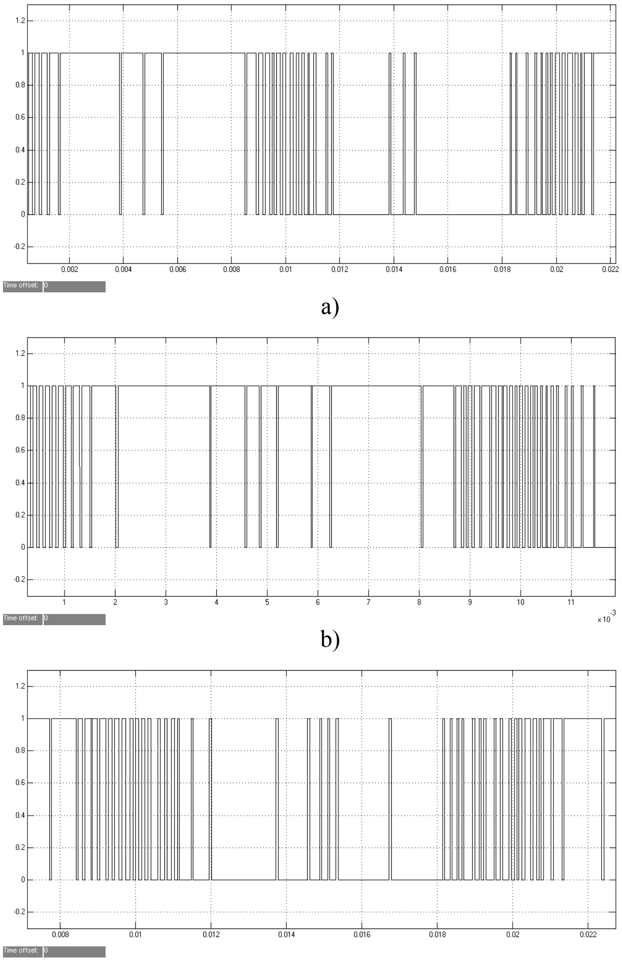
a)

b)

c)

Fig. 8. Simulation waveforms of APF current (a) Traditional hysteresis: 2H=12; (b) Traditional hysteresis: 2H=6; (c) Fuzzy threshold hysteresis method

In each simulation waveform picture, from top to bottom is respectively source current, detected harmonic current, load current, and compensating device current. During the beginning two and a half period, DC-capacitor is charging, with a comparatively large amplitude of active current; and after that it turns to steady state, APF starts to generate current equal to the system harmonic current in amount. Fig. 9 shows the switching signal pulses of phase A in the three cases above.



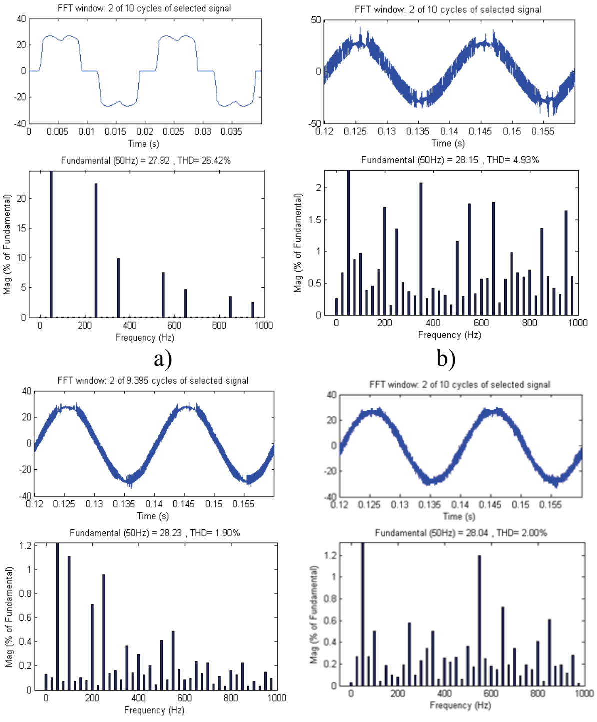
a)

b)

c)

Fig. 9. Simulation waveforms of PWM pulses of phase A (a) Traditional hysteresis: 2H=12; (b) Traditional hysteresis: 2H=6; (c) Fuzzy threshold hysteresis method

It can be seen from Fig. 8 that, in the first two cases of traditional hysteresis, when the bandwidth is big (2H=12), the switching frequency is low, however the current waveform is not good, has much glitch, and can't obtain a good compensating effect (like Fig. 8 (a)); on the other hand, when the bandwidth is small (2H=6), the output current waveform is better, but relatively, the switching frequency is high, probably exceed the maximum switching frequency range of power switches, which will bring danger to the APF device (like Fig. 8 (b)). Compared with traditional hysteresis method, when using fuzzy threshold hysteresis control method presented in this paper, the output current waveform is perfectly smooth, it can be seen from Fig.8 (c) that after compensating, the source current is almost the same as reference sinusoidal current, and current tracking effect almost reaches the level of traditional hysteresis method with small loop width; at the same time, the maximum switching frequency is effectively decreased, with the use of fuzzy controller, the working frequency is basically restrained to the range of maximum allowed switching frequency of power switches. Analyze and compute the frequency of switch pulse in Fig. 9, the result is that in the cases of traditional hysteresis with big loop width, small loop width and fuzzy threshold mutative bandwidth, the maximum switching frequency are comparatively 3.5 kHz, 9.5kHz and 5 kHz.



a) b)

c) d)

Fig. 10. Spectrum analysis of current waveforms (a) Before compensation; (b) Traditional hysteresis: 2H=12; (c) Traditional hysteresis: 2H=6; (d) Fuzzy threshold hysteresis method

Table 1. Comparison of current frequency content in steady state

Harmonic order	Before compensation	After compensation		
		2H=12	2H=6	Fuzzy H
5	22.40	1.35	0.96	0.58
7	9.91	2.07	0.37	0.50
11	7.56	1.74	0.49	1.20
13	4.71	1.77	0.24	0.73
17	3.50	1.36	0.23	0.61
19	2.49	1.64	0.15	0.28
THD/%	26.42	4.93	1.90	2.00

Fig. 10 shows the spectrum analysis of source current after compensation in the three cases above; Table 1 is the current frequency content comparison in steady state of Fig. 10. It's further demonstrated from the data of Table 1 that the compensating efficiency of fuzzy threshold hysteresis method proposed in this paper is far better than traditional hysteresis method with big bandwidth, nearly as good as traditional method with small bandwidth, and comparatively the switching frequency is decreased obviously.

Conclusions

This paper has presented a novel current control strategy, based on traditional hysteresis method; the novel method takes use of fuzzy controller to dynamically adjust the loop width of hysteresis controller. As the result of this design in current unit, it will bring about two benefits and progresses as following:

I. Restrain the maximum switching frequency of power switches. Compared with traditional hysteresis method, the damage rate due to excessive switching frequency is effectively cut down;

II. Current tracking precision is raised obviously by appropriately decreasing bandwidth in smooth parts of current waveform.

Finally, in order to prove that the method above could be applied in the practical industrial site, this paper has presented the DSP-based hardware and software implementations of the APF. This filter has not only satisfied the demand of control precision and dynamic characteristics, but also performed comparatively strong robust and adaptive capacity. Simulation of the APF performance under a typical but serious non-linear load condition, and experiment validation have been provided.

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This paper presents a novel hysteresis current control strategy with fuzzy bandwidth for Active Power Filter. Based on the structure of traditional hysteresis current unit of APF and with the analysis of the variation of hysteresis bandwidth, an internal fuzzy controller is designed in order to dynamically adjust the loop width of hysteresis comparator device. Compared to traditional hysteresis method, progresses are made not only in limiting the switching frequency of power switches so that protect the APF device, but also in achieving a more excellent dynamic response and precision of compensation. Finally, the harmonic compensating efficiency to the typical non-linear loads of the approach presented is further verified by the simulation and experiment results in this paper. Ill. 10, bibl. 11, tabl. 1 (in English; abstracts in English and Lithuanian).

Xinyang Liu, Jie Wang, Gang Yao. Aktyviojo galios filtro histerezės srovės valdymo strategija // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2012. – Nr. 4(120). – P. 3–8.

Pateikiama aktyviojo galios filtro histerezės srovės valdymo, naudojant neraiškiosios logikos pralaidumo juostos plotį, strategija. Remiantis tradicinių histerezės srovės mazgų aktyviuosiuose galios filtruose (AGF) struktūra ir atlikus histerezės juostos pločio kitimo analizę, suprojektuotas vidinis neraiškiosios logikos valdiklis, leidžiantis dinamiškai koreguoti histerezės kilpos plotį komparatoriuje. Palyginti su tradiciniais histerezės metodais, ne tik geriau ribojamas galios jungiklių persijungimo dažnis, kas saugo AGF įtaisą, bet ir pagerėja kompensavimo dinaminis atsakas ir tikslumas. Kompensavimo efektyvumas esant tipinėms netiesinėms apkrovoms, patikrintas palyginant modeliavimo ir eksperimentinius duomenis. Il. 10, bibl. 11, lent. 1 (anglų kalba; santraukos anglų ir lietuvių k.).