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The Research on Hybrid Shunt Active Power Filter

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***Abstract*—This paper presents a method for the harmonic and the reactive power compensation with an adaptive hysteresis band current controller and a control algorithm for hybrid shunt active power filter (HSAPF) to eliminate the harmonic and compensate the reactive power in three-phase thyristor bridge rectifier. The adaptive hysteresis band current controller can change the hysteresis bandwidth according to modulation frequency, supply voltage, dc capacitor voltage and slope of the $u_i(i = a,b,c)$ reference compensator current wave. Until now, all of the studies have been carried out through detail digital dynamic simulation with the MATLAB Simulink Power System Toolbox. The results of simulation study of the new HSAPF control technique and algorithm presented in this paper certificate this kind of APF has perfect harmonics compensation characteristics in utility current.**

***Index Terms*—Hysteresis band current controller, Hybrid shunt active power filter, Harmonic current compensation.**

I. INTRODUCTION

The recent wide spread of power electronic equipment has caused an increase of the harmonic disturbances in the power Systems. The active power filter (APF) can solve the problems of harmonic and reactive power simultaneously.

In SHAPF design and control, the instantaneous power theory may be complicated for the application of compensation current for the unbalanced and distorted mains voltage in most of time and most of industry power systems[1][2][3]. Thus, the variable structure control (VSC) theory, since its proposal, has been applied in the control of three-phase hybrid shunt active power filters. The proposed control algorithm gives an adequate compensating current reference even for non ideal voltage system. Thus this paper presents the technique with the variable structure control theory (VSC theory) as a suitable method to the analysis of SHAPF control in the non-linear three-phase systems. The control of switching frequency is described with introducing an adaptive hysteresis band current control algorithm. Then, the simulation results are presented followed by the conclusion. The proposed scheme has been found feasible and excellent to the variable structure control algorithms.

II. HYBRID SHUNT ACTIVE POWER FILTER

The hybrid shunt active power filter (SHAPF) is a device which is connected in parallel with and can compensate the reactive and harmonic currents from a nonlinear load. The resulting total current drawn from the ac main is sinusoidal. Ideally, the HSAPF needs to generate just enough harmonic current to compensate the nonlinear loads in the line.

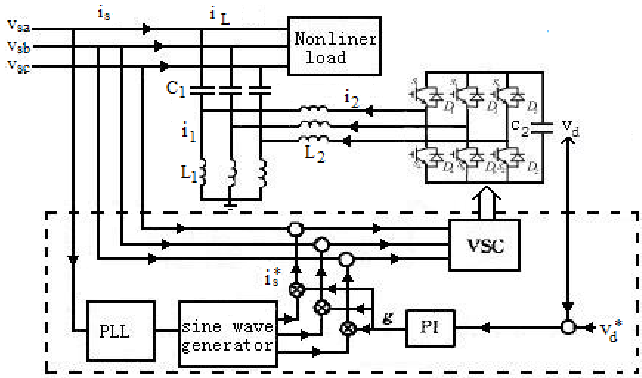

Figure 1. Basic Principle Block Diagram of SHAPF

In an SHAPF depicted in Fig. 1, a current controlled by voltage source inverter is used to generate the compensating current (i_2) and is injected into the utility power source grid. This cancels the harmonic components drawn from the nonlinear load and let the utility line current (i_L) sinusoidal. A voltage-source inverter with IGBT switches and an energy storage capacitor on dc bus is implemented as a hybrid shunt APF. The capacitor C_1 and the inductor L_1 in the main circuit compose the PPF in Fig. 1. And the C_1 is designed on the need of the load reactive power compensation. C_1 and L_1 constitutes the circuit of 5 harmony to compensate the reactive power and low harmony.The APF , which is composed of L_2 and voltage source inverter, is linked between C_1 and L_1. It is used to compensate the other higher harmony that PPF cannot compensate. And the part in the broken line of box is variable structure control system.

III. The Proposed Control Method

According to the main circuit structure in Fig.1, the vector equation of HAPF is derived .

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$$L_2 \frac{d}{dt} i_s = -R_2 i_s - v + (\frac{L_2}{L_1} + 1)(v_s - v_{C1}) - (\frac{L_2}{L_1} R_1 + R_2)\ i_1 + R_2 i_L + L_2 \frac{d}{dt} i_L \tag{1}$$

The vector control voltage v depends on the inverter switch controlling. In Fig.1, if the on-state of the arm bridge is labeled as $u_i = 1$ and the off-state of the arm bridge is labeled as $u_i = 0$ in each phase ,then the relation between volume control switch $u_i(i = a,\ b,\ c)$ and vector control voltage v can be labeled as the following formula[4]:

$$v = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \frac{v_d}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \tag{2}$$

According to the characteristics of the filter, the phase of supply current i_s can be adjusted into the phase of the power supply voltage v_s , the current can be a purpose of control system. Assuming that the power supply voltage is sine wave and the capacitance C_1 can completely compensate the reactive power, then the initialization of the supply current i_s can be designed as $i_s{}^* = g v_s$, Where, g is a scalar quantity.The size of g is decided by the active power consumed by load and Power Filter, which is regulated by closed-loop control of DC side of capacitor voltage . It is showed in the broken line of box of Fig.1, the capacitor voltage is a given value.So the controlling problem of the power filter translate into that how does i_s make a good track of i_s^*.When adopting VSC, state variable can be defined as follows $\Delta i_s = i_s{}^* - i_s$, It is substituted into the Esq. (1), and neglecting the inductor resistance, the equation of state can be labeled as the following formula:

$$\frac{d}{dt} \Delta i_s = \frac{v}{L_2} - (\frac{1}{L_1} + \frac{1}{L_2})(v_s - v_{C1}) + \frac{d}{dt}(i_s{}^* - i_L) \tag{3}$$

If defining

$$e = (\frac{L_2}{L_1} + 1)(v_s - v_{C1}) - L_2 \frac{d}{dt}(i_s{}^* - i_L) \tag{4}$$

the equation of state can be described into

$$\frac{d}{dt} \Delta i_s = \frac{v - e}{L_2} \tag{5}$$

The Esq. (2) is substituted into the Esq. (5), then the formula can be described into

$$\frac{d}{dt} \begin{bmatrix} \Delta i_{sa} \\ \Delta i_{sb} \\ \Delta i_{sc} \end{bmatrix} = \frac{1}{L_2} \left\{ \frac{v_d}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} - \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \right\} \tag{6}$$

According to the theory of VSC, the switching surface is defined into $S = \Delta i_s = 0$, When the state of system deviate from the switching surface S, the controlled variable $u_i = 1$ or $u_i = 0$. It makes the state of system switch surface S and go along to the original point. According to the conditions of VSC, when S≠0, the choice of u_i must satisfy the condition of VSC.

$$\begin{aligned} \Delta i_{sa} \cdot \frac{d}{dt} \Delta i_{sa} &< 0 \\ \Delta i_{sb} \cdot \frac{d}{dt} \Delta i_{sb} &< 0 \\ \Delta i_{sc} \cdot \frac{d}{dt} \Delta i_{sc} &< 0 \end{aligned} \tag{7}$$

In order to find the VSC control rules conveniently, space vector can be used for analyzing. In Fig.2 (1), the controlled variable u_i of different value have different voltage vector [5][6]. According to Esq. (6) and Fig.2,the area of Δi_s is calculated , and the rules is described in Tab. I.

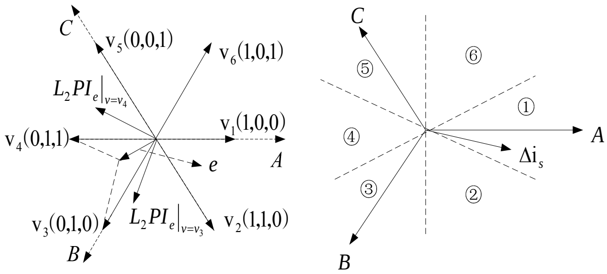


Figure 2. Space Vector Diagram（1）Voltage（2）Current

TABLE. I.
THE PLOT RULE OF CURRENT SPACE VECTOR REGIONS

	①	②	③	④	⑤	⑥
u_c	+	+	-	-	-	-
Δi_{sb}	-	+	+	+	-	-
Δi_{sc}	-	-	-	+	+	+

TABLE. II.
THE RELATION OF REGION Δi_s AND SWITCH u_s

The area of Δi_s	①	②	③	④	⑤	⑥
u_c	0	0	1	1	1	0
Δi_{sb}	1	0	0	0	1	1
Δi_{sc}	1	1	1	0	0	0

In the case of the value of v_d is big enough or neglecting the system disturbance e , according to Esq. (3), the vectorgraph of $d\Delta i_s / dt$ when on the condition of different control voltage vector can be drawn. So when the area of Δi_s is known, $d\Delta i_s / dt$ can be is calculated from Esq. (7). Then the right V can be found. For example, when Δi_s locate in the area of ① in Fig.3, as in Fig.2, In order to satisfy Esq. (7) , equally to satisfy $d\Delta i_{sa} / dt < 0$,

$d\Delta i_{sb}/dt > 0$, $d\Delta i_{sc}/dt > 0$ the voltage vector v_4 is chosen uniquely, namely $(u_a, u_b, u_c) = (0,1,1)$ .Thus, the relationship between the area of Δi_s and controlled variable u_i can be calculated as follows, described in Tab. II. The sign of "+" represents the value which is bigger than 0, and the sign of "-" represents the value which is lesser than 0. Compare Table Ⅰ with Table Ⅱ , when $v_d \geq 3max|e|$ is satisfied, three-phase alternating current can be controlled and the VSC control rules which applied in hybrid shunt active power filters is calculated as follows:

$$u_a = \begin{cases} 1 & \Delta i_{sa} < 0 \\ 0 & \Delta i_{sa} > 0 \end{cases} ; \; u_b = \begin{cases} 1 & \Delta i_{sb} < 0 \\ 0 & \Delta i_{sb} > 0 \end{cases} ; \; u_c = \begin{cases} 1 & \Delta i_{sc} < 0 \\ 0 & \Delta i_{sc} > 0 \end{cases}$$

.

The parameter design of PI adjustor , because the size and stabilization of v_d can influence the quality of VSC directly, the system adopts the measure of closed loop control, and it can make v_d track the given v_d^* .

$$P_S = P_L + P_C = 3V_S I_S = 3gV_S^2 \tag{8}$$

If active power is changed, it can be calculated from Esq. (8).

$$\Delta P_S(t) = 3\Delta g(t)V_S^2 = \Delta P_L(t) + \Delta P_C(t) \tag{9}$$

The change of capacitor C_2 in the energy storage can be expressed as

$$\int_0^t \Delta P_C(t)dt = \frac{1}{2}C_2(v_d + \Delta v_d(t))^2 - \frac{1}{2}C_2 v_d^2 \tag{10}$$

Doing laplace transform for Esq. (10) and neglecting the item of $\Delta v_d^2(t)$, it can be calculated as follows:

$$G_C(s) = \frac{\Delta v_d(s)}{\Delta P_C(s)} = \frac{1}{C_2 v_d s} \tag{11}$$

According to Esq. (9) and (11), the transfer function of PI adjustor can be calculated as follows

$$G_{pi}(S) = \frac{K_p(T_i s + 1)}{T_i s} \tag{12}$$

Where K_p is a scale coefficient, T_i is a integral time constant. According to parameters of PI adjustor which used in system design of type Ⅱ, it can be calculated as follows $T_i = 5T_F$, $K_p = v_d C_2 / 5V_s^2 T_F$, T_F is filtering time constant. According to antijamming of type Ⅱ system, the value of C_2 must satisfy the inequation : $C_2 > 1.6T_F \Delta P_L / v_d \Delta v_{max}$.

IV. HYSTERESIS BAND CURRENT CONTROLLER

The actual active power filter line currents are monitored instantaneously, and then compared to the reference currents generated by the control algorithm. In order to get precise instantaneous current control, the current control method must supply quick current controllability, thus quick response. For this reason, hysteresis band current control for active power filter line currents can be implemented to generate the switching pattern the inverter. There are various current control methods proposed for such active power filter configurations, but in terms of quick current controllability and easy implementation hysteresis band current control method has the highest rate among other current control methods such as sinusoidal PWM. Hysteresis band current control is the fastest control with minimum hardware and software but even switching frequency is its main drawback.The hysteresis band current control scheme, used for the control of active power filter line current, is shown in Fig. 3, composed of a hysteresis around the reference line current. The reference line current of the active power filter is referred to as $i_c^{\bullet}$ and actual line current of the active power filter is referred to as i_c . The hysteresis band current controller decides the switching pattern of active power filter[7][8]. The switching logic is formulated as follows:

If $i_{ca} < (i_{ca}^* - HB)$, for leg "a" (SA=1), the upper switch is OFF and the lower switch is ON.

If $i_{ca} > (i_{ca}^* - HB)$, for leg "a" (SA = 0), the upper switch is ON and the lower switch is OFF.

The switching function SB and SC, which are for phases "b" and "c" respectively, are determined similarly, with the corresponding reference, the measured currents and the hysteresis bandwidth (HB).

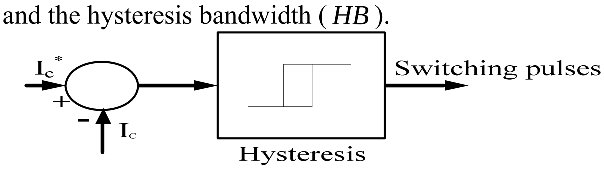


Figure 3. Conventional Hysteresis Band Current Controller

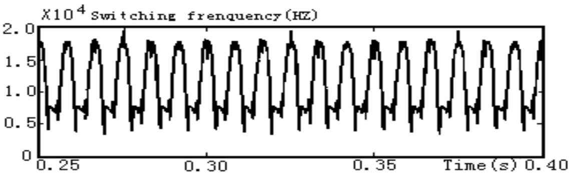
V. SIMULATION RESULTS AND DISCUSSIONS

In the conventional fix band hysteresis current control and adaptive hysteresis band current control method[9] with the variable structure control theory, the instantaneous switching frequencies are shown in Fig. 4, respectively. In the practical application, in order to determine switching device and its switching loses, it is necessary to keep the switching frequency to a certain limits. In the conventional hysteresis band current controller, it is impossible to determine not only hysteresis bandwidth but also switching frequency according to system parameters (L, v_{dc}) . In the adaptive hysteresis band current controller with the variable structure control theory, the switching frequency remains constant respecting the system parameters and defined frequency.

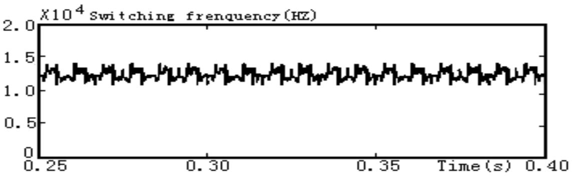
The harmonic current with HSAPF is implemented in a three-phase power system, in which the utility power supplies a voltage of 380V and a current source to a three-phase diode-bridge rectifier with resistive load as the harmonic current compensation object. The design specifications and the circuit parameters used in the simulation are indicated in Table III. The current waveform in a-phase without compensating and with the PPF's compensating is respectively shown in Fig.5 and Fig.6. Then compensation supply current wave with SAPF or HSAPF is respectively shown in Fig.7 and Fig.8.THD (total harmonic distortion) is also computed in load current as well as in supply current. The THD is 20.98% before harmonic compensation in load compensation current and after harmonic current is 3.58%. The performance of the proposed adaptive hysteresis band current controller regarding harmonics suppression is compared with a fixed band current controller.

TABLE. III
PARAMETERS OF THE SYSTEM

Power phase-voltage	220V/50Hz
value of square wave amplitude of load current	40A
burst max of load current	144A/ms
trigger Angle of load current	30°
Capacitors C_1 /inductors L_1	270/1.5mH
Capacitors C_2 /inductors L_2	2000/0.5mH
value of capacitor voltage v_d^*	130V
filtering time constant T_F	1.5ms
parameters of PI adjustor	7.5ms/0.00072



(a) Conventional Fix Band Hysteresis Current Controller



(b) Adaptive Hysteresis Band Current Controller

Figure 4. Instantaneous Frequency

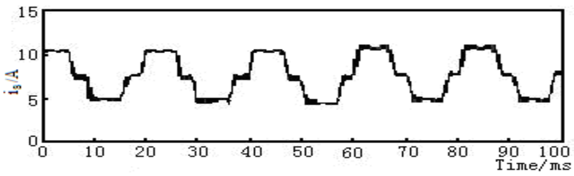


Figure 5. Uncompensating Current Waveforms

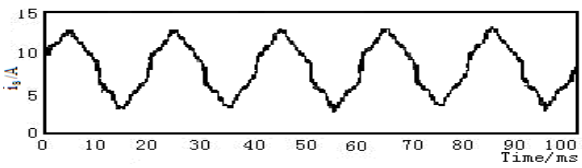


Figure 6. Compensating Current Waveforms of PPF

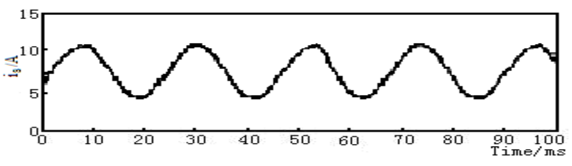


Figure 7. Compensation Supply Current Waveforms with SAPF

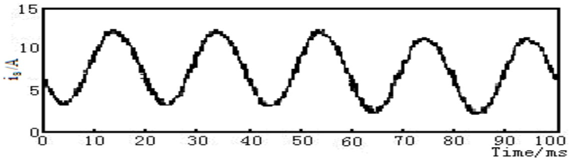


Figure 8. Compensation Supply Current Waveforms with HSAPF

VI. CONCLUSION

This paper demonstrates an adaptive hysteresis band current control PWM technique, in which the bandwidth can be programmed as a function of system parameters to optimize the PWM performance and the validity of the proposed adaptive hysteresis band current controller the variable structure control theory for hybrid shunt active power filters. The results of simulation are found quite satisfactory to eliminate harmonics and reactive power components from utility current. The main difference between the two control methods should be in the high frequency harmonics generated by switching of the IGBT. The instantaneous switching frequency remains constant in the proposed method contrary to conventional fix band hysteresis current control method.

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