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Digital controller for hybrid filter in HVDC based on approximate inverse system

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Abstract In order to eliminate the characteristic harmonics in high voltage direct current (HVDC) transmission systems and to simplify the analog controller structure, this paper proposes a new digital controller by adopting an approximate inverse system control strategy according to the frequency response characteristic of the hybrid power filter. The proposed digital controller is implemented with a TMS320C32 DSP, including a series of parallel digital band-pass filters, phase shifters and amplifiers. The results of both simulations based on PSCAD and experiments on a 30 kVA HVDC system prove that the proposed digital control system is stable and efficient for eliminating the harmonics.

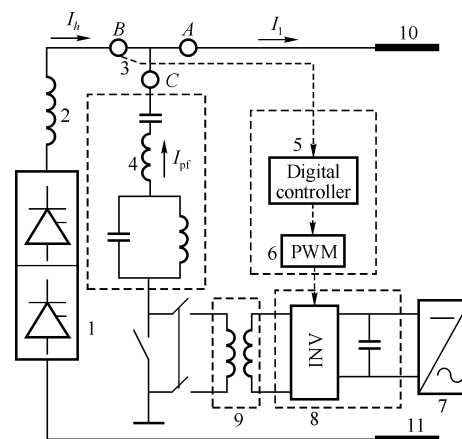
Keywords HVDC, digital controller, active power filter (APF), digital filter

1 Introduction

In HVDC transmission systems, $12n$ characteristic harmonic currents (mostly 12th and 24th) caused by 12 pulse converters used in system can disturb adjacent communication lines, decrease the capability of transmission lines and be detrimental to the security of converter devices. Therefore, handling the harmonics properly is of great significance to HVDC system.

Passive filters (PFs) have been widely used to suppress the harmonics for years. PFs have relatively simple structures and are easy to realize, but they are limited by substantial cost and space requirements, and are sensitive to other facts,

such as temperature and variation of system configuration. Compared with PF, APF is highly controllable, and can suppress several harmonic components simultaneously, thereby offering a more economical approach when the number of harmonic components that need to be cancelled increases. In addition, APF has more flexibility in tuning its control scheme to adapt to the changes of the system frequency and impedance. Recently, hybrid passive-active filter, consisting of a PF and an APF in series, has been adopted to suppress harmonics on the DC side of HVDC projects, as shown in Fig. 1. The hybrid filter can take full advantage of PF in handling large power harmonics with a simpler structure and of APF in eliminating wide range of harmonics simultaneously with less power.



1–converter, 2–smoothing reactor, 3–optical current transducers, 4–passive filter, 5–digital controller, 6–PWM, 7–auxiliary power supply, 8–inverter, 9–coupling transformer, 10–protector, 11–transmission line, I_h –the harmonic current in the HVDC converter station, I_{pf} –the compensating current, I_1 –the harmonic current in the HVDC transmission line

Fig. 1 HVDC and filtering Equipment

In existing ADF control systems, the load current at spot “A” is usually adopted as feedback signal, which is made up of a simple closed-loop system, and the controllers are commonly designed as comb filter or notch filter. When the

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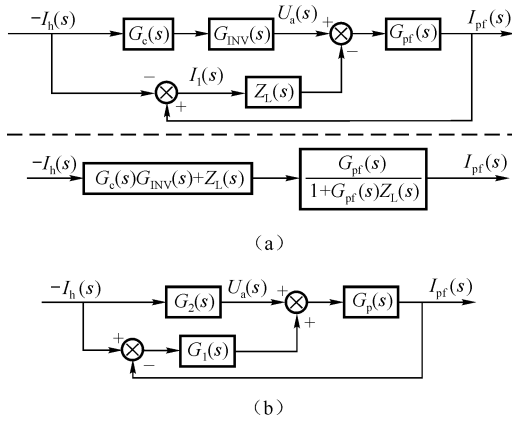
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filter runs, the feedback current would decrease and be more sensitive to the noise and interference. In addition, the absolute value of the feedback current is much less than that of DC in line. Thus, a difficult problem of extracting the tiny feedback current from the line arises. To solve the problem and enhance the performance of system, this paper proposes a novel method based on the pseudo-inverse technique by using digital controller.

2 Control principles

In this control method, current at spot "B" is selected as the main signal and current at spot "C" is selected as the feedback signal; these are greater than that at spot "A" and do not decrease with the compensation. Thus, the difficulty of extracting tiny signal is relieved, and the accuracy of system can be improved.

The purpose of the controller is as follows: $I_{pf}(s) = -I_h(s)$ which ensures $I_1 \rightarrow 0$. Figure 2 depicts the controller.



G_c – transfer function of the controller of APF, $G_{INV}(s)$ – transfer function of the inverter, $Z_L(s)$ – equivalent resistance of transmission line, G_1 – the transfer function of the feedback loop, $G_{pf} = 1/Z_{pf}$ – transfer function of the PF

Fig. 2 APF control diagram. (a) Feed forward control diagram; (b) Integrated control diagram

Define the feed forward transfer function as follows:

$$G_2(s) = G_c(s)G_{INV}(s) + Z_L(s) \quad (1)$$

The object transfer function is as follows:

$$G_p(s) = \frac{G_{pf}(s)}{1 + Z_L(s)G_{pf}(s)} \quad (2)$$

Given $G_2(s) = 1/G_p(s)$, the output current can track the input current. However, the ability of anti-jamming of the open-loop controlling strategy mentioned earlier is not good enough. In order to decrease the effect of interference, an integrated strategy is proposed as the Fig. 2(b), which combines the feedback controlling and open-loop controlling. The tracking ability of this strategy mainly depends on

function G_2 , while the sensitivity to noise and interference is related to G_1 . So, conventional proportional-integral (PI) controlling strategy can be used for G_1 , and inverse controlling strategy for G_2 . The tracking ability depends on the following function:

$$G_{yr}(s) = \frac{I_{pf}(s)}{I_h(s)} = \frac{G_p(s)G_1(s) + G_p(s)G_2(s)}{G_1(s)G_p(s) + 1} \quad (3)$$

To attain the goal that G_{yr} is close to 1: $G_2(s) = 1/G_p(s)$ which is $G_c(s) = 1/G_{pf}(s) = Z_{pf}(s)$ or $G_c(j\omega) = 1/G_{pf}(j\omega)$

In this paper, the PF is a double-tuned filter whose resistance is as follows:

$$\begin{aligned} Z_{pf}(s) &= R_1 + sL_1 + \frac{1}{sC_1} + \frac{R_2 + sL_2}{s^2L_2C_2 + sR_2C_2 + 1} \\ &= \frac{a_4s^4 + a_3s^3 + a_2s^2 + a_1s^1 + a_0}{b_3s^3 + b_2s^2 + b_1s^1 + b_0} \end{aligned} \quad (4)$$

The numerator's order is one more than the denominator's order, thus the system requires a first-order differentiator, which is sensitive to high-frequency signals and hard to realize. Therefore, it is seldom used in real systems.

Considering the character of harmonics in HVDC, a pseudo-inverse system, which consists of a group of band-pass filters for characteristic harmonics, is proposed. The compensating signal engendered by such an inverse system is close to the input signal and can be modulated through PWM more easily.

Based on the result that the characteristic harmonic currents in this system are 12th, 24th, 36th and 48th, the filter group can be designed as:

$$G_c(z) = \sum H_i P_i K_i; \quad i = 12, 24, 36, 48 \quad (5)$$

where $H_i(z)$ is the transfer function of i th band-pass filter; $P_i(z)$ is the phase shifter; and K_i is the amplifier.

3 Digital controller design and implementation

To extract the harmonic component, there are two kinds of filters to choose, i.e., analog filter (AF) and digital filter (DF). The former is realized by hardware components such as R , L , C and so on, which has complicated configurations. The latter, which is realized by software, is more flexible and easy to realize. There are two major types of DF: the finite impulse response (FIR) filter, and the infinite impulse response (IIR) filter. FIR digital filter has linear phase-frequency characteristic, but it requires quite a high-order filter in order to achieve good frequency selectivity, which will bring on heavy calculation. On the other hand, IIR digital filter can achieve good frequency selectivity with lower order, but the phase-frequency characteristic is nonlinear. To achieve the same frequency selection, the order of FIR filter required is much higher than that of the IIR filter. IIR filter is

IIR filter is adopted in this paper. Figure 3 shows the frequency characteristic of a second-order band-pass IIR digital filter.

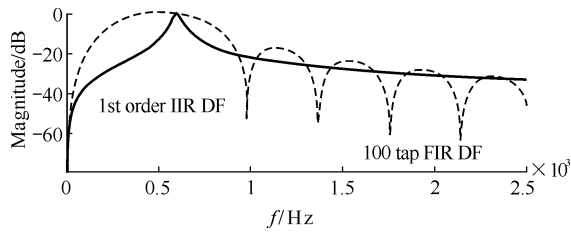
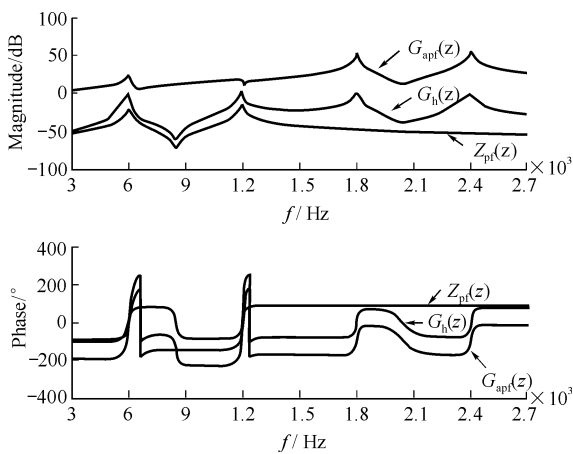


Fig. 3 IIR DF frequency character

Figure 3 shows that the magnitude at the central frequency is one, while magnitudes at other characteristic frequencies decrease quickly; thus it can work well in extracting characteristic harmonics. Similarly, band-pass filters for other three characteristic harmonics (24th, 36th and 48th) also can be designed suitably for extracting corresponding signals.

Based on such a digital controller, the filter system performs well in tracking signals and eliminating harmonics. Figure 4 shows the frequency responses of PF, APF, where the responses of filters at four characteristic frequencies, with magnitudes close to one and phase differences near zero, meet the requirement of system.



$G_{apf}(z)$ —the response of APF, $G_h(z)$ —the response of hybrid filter.

Fig. 4 Frequency responses of PF and APF

To realize the controller, A TMS320C32 chip, a floating DSP chip processor produced by TI Corporation, is adopted in the system. The chip produced the reference signal for PWM circuit after a series of arithmetic such as harmonic signals calculation and signal controlling. The signal controlling program, including input, processing and output, is implemented in interrupting mode. Figure 5 shows the program diagram in DSP.

In the program, harmonic current I_h , as the object to be eliminated, is put into DSP after a modulating circuit and a

conversion to digital signal, which is transformed into floating mode, and then processed through the band-pass filters group. Take 12th harmonic signal, for example—the signal passes through a second-order Butterworth IIR filter, next magnitude and phase regulator. Other three harmonic signals undertake similar processes. The results of four channels are added together, and then regulated by a PI controller as the reference signal, which is transformed into analog signal for PWM.

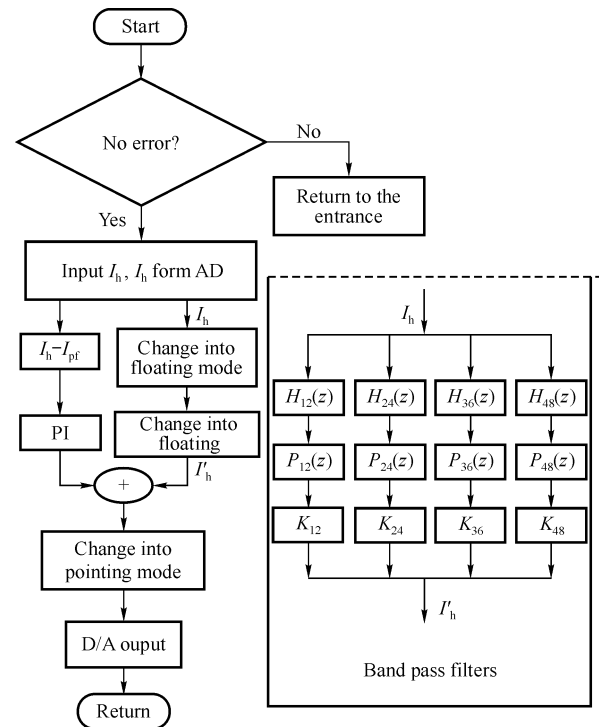


Fig. 5 DSP program diagram

4 Simulation and experiments

In order to verify the effect of the proposed method, we designed a system; the system consists of a three-phase AC source, a 12-pulse converter with rated DC output voltage +800 V and a hybrid filter, which is composed of a double-tuned filter and an APF. The load impedance is composed of a 75 Ω resistor and a 36 mH reactor representing the transmission line and the remote inverter station. The system has been simulated by simulation software electro-magnetic transient of DC/power system computer aided design (EMTDC/PSCAD). Figure 6 shows the result of simulation. In addition, the compensating efficiency (defined as $\eta = 1 - (I_{in} / I_{hn}) \times 100\%$) of 12th, 24th, 36th and 48th are, respectively, 99.5%, 98.1%, 96.6%, 95.9%.

In the lab system, the main circuit of APF adopts single-phase bridge inverter composed of two PM75DSA120 IGBT IPM (intelligent module), with rated value 1 200 V, 75 A, switching frequency upper limit 20 KHz, the effective

operating frequency about 10 KHz. Detecting precision of current transducer LTS6-NP used to detect current is 0.1 %. The digital control algorithm is implemented by a TMS320C32. PWM rectifier uses SG3532, whose carrier-frequency is 12 KHz, about 4 times higher than 48th, and the highest harmonic expected to be eliminated.

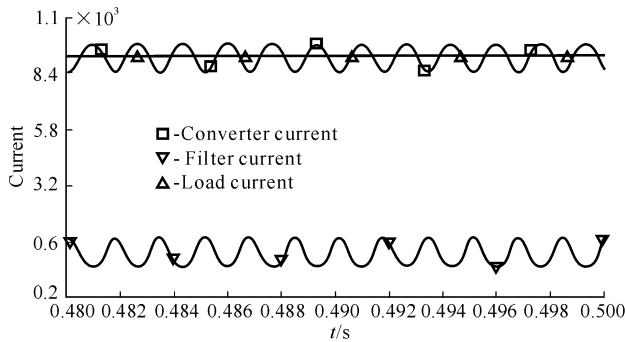
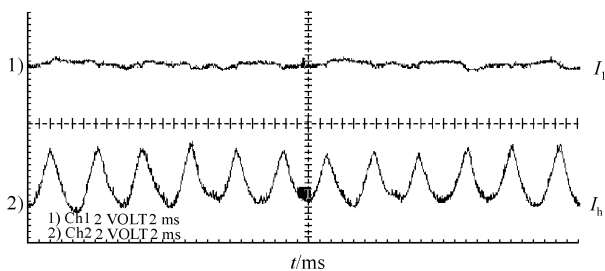


Fig. 6 The simulating result

Experiment results are shown in Table 1. Data in the upper row is the efficiency of the system only using double-tuned PF, and data in the lower row is the efficiency of the system using hybrid passive-active filter.

Table 1 Comparison of compensating efficiency

Efficiency	$\eta / \%$			
Harmonics	I_{12}	I_{24}	I_{36}	I_{48}
PF	85.1	86.3	65.9	64.8
ADF	99.2	96.8	76.5	67.4



x -coordinate represents time, y -coordinate represents current, Ch2- I_h in the front of the filter branch junction, Ch1- I_l of load current after compensation of the hybrid filter

Fig. 7 The experimental results

The data indicates that the compensation effects are improved when the APF is used. The compensating effects of 12th and 24th harmonic currents are obviously good, according to the simulation results. On the other hand, many nonlinear problems, such as the transducer noise and the switching frequency limit, have been ignored in the process of the simulation, so ideal effects can be obtained. In lab. system, the compensating effects of 36th and 48th harmonic currents are not as good, which may be caused by the

performance of the IGBT; the switching frequency of IGBT is only a few times higher than the frequency of the 48th harmonic, which significantly depresses the compensating effect. Experiment shows the compensating effects of APF eliminating 1.8 kHz and 2.4 kHz harmonic components with a 12 kHz carrier wave are limited.

According to the results of simulation and experiment, it is clear that the hybrid filter made of digital controller can perform well in cancellation of the harmonics in DC line. Furthermore, this study still room for improvement such as the inconstancy of the parameters and the limitation of the IGBT, which will hopefully be solved in future research.

5 Conclusions

The paper analyzed the main principle of the APF, discussed the shortage of existing series hybrid filter and proposed an improved method of digital controller based on Pseudo-Inverse filtering technique. The digital controller consists of a feed forward channel composed of a group of digital band-pass filters, magnitude and phase regulators, and a feedback channel composed of a PI controller. In addition, the method avoids the problem of extracting feeble signals by selecting feed forward signal which is much greater than simple feedback signal, so as to improve the ability of anti-jamming. Results of simulation and experiment validate the feasibility and effectiveness of proposed method, lending a solid support for future application in industry. Further research can aim at integrated controlling based on self-adaptive strategy to eliminate disturbance caused by environment.

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