A COMPARATIVE STUDY OF SAPF WITH TWO DIFFERENT CURRENT CONTROL STRATEGIES

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ABSTRACT

In this study, the adaptive-band hysteresis and the triangular carrier current controllers are compared for three-wire SAPF. The generation of the reference current part is based on the well-known p-q theory with the fundamental positive-sequence voltage detector. Performance evaluation of the controllers is carried out through dynamic simulations using Matlab/Simulink.

I. INTRODUCTION

Shunt active power filter (SAPF) is a feasible solution to the harmonic problems created by nonlinear loads [1]. There are variety of proposed control techniques for SAPF to generate and inject a suitable current to the mains so that it cancels the harmonic content of the distorted mains current and obtain a waveform of sinusoidal shape with the requested amplitude and phase [2-6]. The characteristics of harmonic compensation are strongly dependent on the algorithms of reference current calculation and current control techniques that impress this calculated current harmonics to point of common coupling (PCC).

The block diagram of shunt active power filter system is given in Fig. 1. The shunt APF control design is carried on by two steps: derivation of the compensating signals in terms of current and voltage signals, and generating the gating signals for the inverter switches by current controller circuit.

For the active filter design, the instantaneous reactive power (p-q) theory was often applied as the main paradigm for calculating the required amount of compensation current. In the calculation process of this theory, the mains voltages were assumed as ideal. However, in most industrial power systems, the mains voltages are often unbalanced and/or distorted, so the assumption is not valid for those cases. By adding fundamental positive-sequence voltage detector to original p-q theory, the mains current after the compensation is expected to be sinusoidal in spite of variations in mains voltages [3, 7].

The main task of the active filter's current controller is to force the inverter currents to follow the reference currents by generating the switching states for the inverter which decrease the current errors. Ideal tracking over a wide output frequency range, low harmonic content, limited or constant switching frequency, very fast response are the basic requirements of a current control techniques for SAPF's.

Among the current control techniques, the hysteresis control, the dead-beat control and the linear control are the most popular ones for active power filter applications. The comparison of the current control techniques of APF were discussed in [8, 9, 10] under certain switching frequency. In [11], the validity of the adaptive hysteresis band current controller for 3-phase 4-wire shunt active power filters is demonstrated under constant switching frequency of 12 kHz. On the other hand, this paper is aimed at investigating the effect of the chosen switching frequency to the SAPF's performance.

In the study, the overall SAPF scheme is simulated under the MATLAB environment using SimPowerSystem toolbox to compare the effectiveness of the adaptive-band hysteresis control scheme and the triangular carrier control scheme.

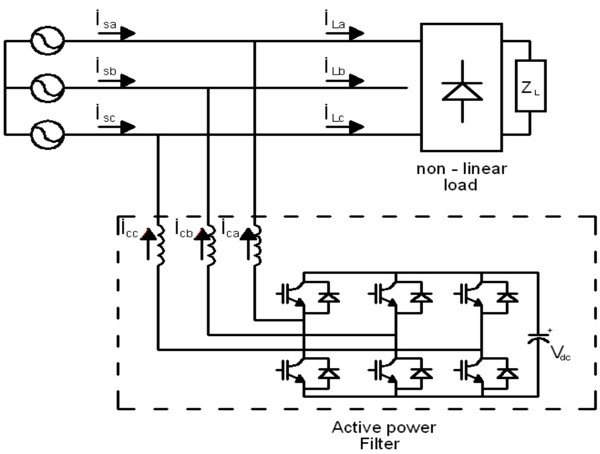


Figure 1. System diagram of a VSI-SAPF

II. MODIFIED P-Q THEORY

The well known p-q theory is not effective under the distorted and unbalanced mains voltage conditions since it compensates the load current to guarantee constant instantaneous real power drained from the network. Therefore, under distorted and unbalanced mains voltage conditions, a fundamental positive-sequence voltage detector is needed to guarantee the decoupling of the currents and distorted voltages at PCC. The fundamental positive-sequence voltage detector will produce fundamental positive sequence voltage that is orthogonal to the fundamental positive sequence currents for SAPF to prevent generating active power. In the fundamental positive-sequence voltage detector shown in Fig. 2(a), the dual of the p-q theory is used for the voltage compensation. The important part of it is the phase-locked-loop (PLL) circuit tracking continuously the fundamental frequency of the voltage. This technique is the best option to guarantee the decoupling of the current and distorted voltages at the PCC [3].

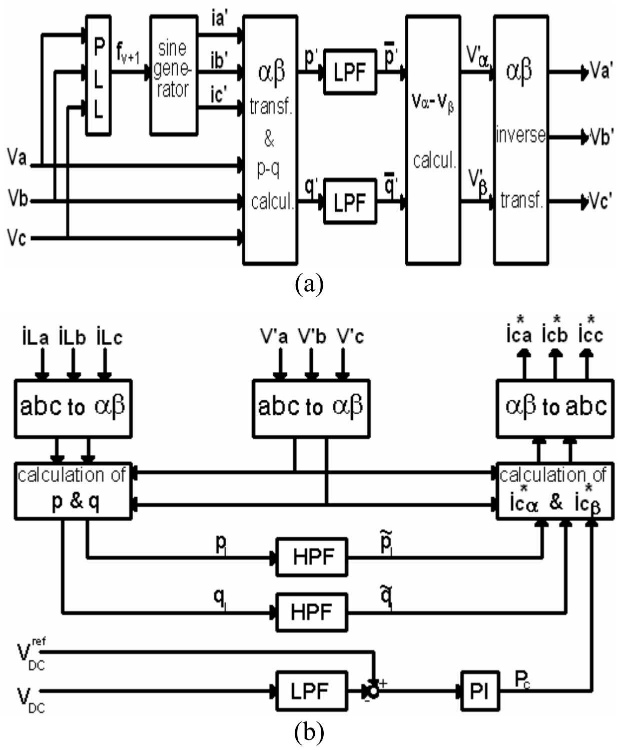


Figure 2. Reference current generation algorithm block diagrams: a-positive sequence voltage detector, b-generation of reference current with p-q theory.

The instantaneous real power p and the instantaneous imaginary power q consumed by the nonlinear load are written in matrix form as in (1).

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} + \begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \quad \textbf{(1)}$$

To obtain a sinusoidal current with unity power factor, the oscillating term of p and all terms of q have to be removed. The compensation currents in α-β quantities are given by (2) using the fundamental positive sequence part of the mains voltage.

$$\begin{bmatrix} I_{c\alpha} \\ I_{c\beta} \end{bmatrix} = \frac{1}{{v'_\alpha}^2 + {v'_\beta}^2} \begin{bmatrix} v'_\alpha & -v'_\beta \\ v'_\beta & v'_\alpha \end{bmatrix} \begin{bmatrix} -\tilde{p} \\ -\tilde{q} \end{bmatrix} \quad \textbf{(2)}$$

By performing the inverse transformation, the three-phase compensation currents in a-b-c frames are obtained by (3).

$$\begin{bmatrix} i_{ca} \\ i_{cb} \\ i_{cc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}^T \begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} \quad \textbf{(3)}$$

The overall procedure is graphically illustrated in Fig. 2.

III. CURRENT CONTROL BY ADAPTIVE-BAND HYSTERESIS

Conventionally for APF, the fixed band hysteresis current control is popularly used because of simplicity of implementation, fast response, inherent peak current limiting capability, and needless of information on system parameters. But, it has the disadvantage that the switching frequency is not constant and varies within a wide range [12, 13]. In principle, the higher the inverter operating frequency leads to get a better compensating waveform. However, because of the switching device, increasing the switching frequency causes more switching losses than before, thereby distorting SAPF performance. It also leads to EMI related problems and audible noise. Therefore the range of switching frequencies should be based on a compromise between these factors. Bose [14] has proposed a programmable hysteresis-band current control to force the switching frequency at a fixed predetermined frequency. It changes the bandwidth according to instantaneous compensating current variation and dc voltage to minimize the influence of current distortion on modulated waveform. The proposed expression of hysteresis bandwidth for phase-a of three phase inverter with isolated neutral is given in (4).

$$HB = \frac{k^I V_{DC}}{4 f_c L}\left[1 - \left(\frac{L}{\left(k^I V_{DC}\right)}\left(\frac{di_a^*}{dt} + \frac{v_{sa}}{L}\right)\right)^2\right] \quad \textbf{(4)}$$

k^I will typically vary between 1/3 and 2/3, and the latter is the worst case [14].

Hysteresis band given by (4) is modeled as a function of supply voltage and slope of the compensating current waveform so that modulation frequency remains nearly constant and is given in Fig. 3. While modeling the switching pattern for each phase, the calculated hysteresis bandwidth and the current error are used as inputs through the s-function of Matlab\Simulink.

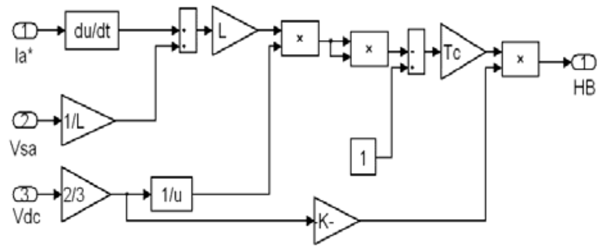


Figure 3. Matlab/Simulink model of the variable hysteresis band

IV. CURRENT CONTROL BY TRIANGULAR CARRIER

In this method, the three phase current errors are compared with a common fixed amplitude and frequency triangular wave [8, 15]. The purpose of introducing the triangular carrier waveform is to stabilize inverter switching frequency, forcing it to be constant and equal to the frequency of the triangular waveform.

For considering one phase, if the current error signal is larger than the triangular wave, the upper inverter switch is activated. However, if the current error signal is smaller than the triangular wave, the lower inverter switch is activated as shown in Fig. 4.

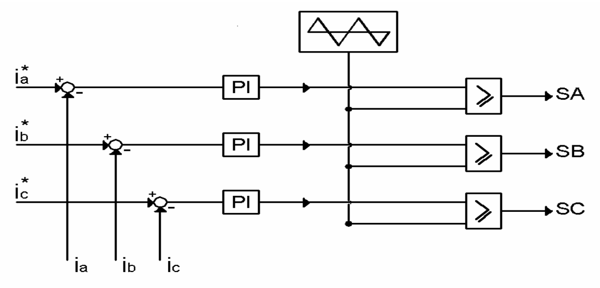


Figure 4. Matlab/Simulink model of of the improved triangular carrier current control

V. SIMULATION RESULTS

The purpose of the simulation is to investigate the effectiveness of adaptive-band hysteresis current control method over the triangular carrier current control method for maintaining sinusoidal source currents when the source supplying a nonlinear load. Two criteria, the measurement of the total harmonic distortion (THD) of the line current waveform and the measurement of the tracking error vector (e_{rms}) are taken into account for the evaluation of two current control methods.

The nonlinear load being compensated by the SAPF is chosen as the three phase diode rectifier with resistive load that's phase current waveform under balanced line voltage obtained with Matlab/Simulink is shown in Fig. 5.

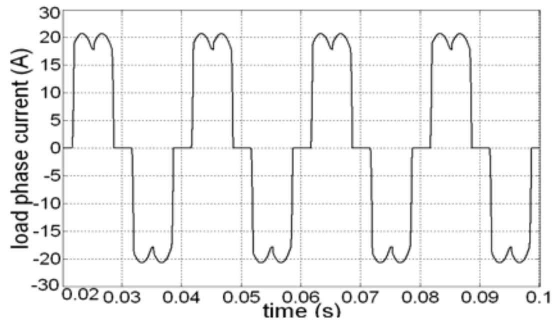


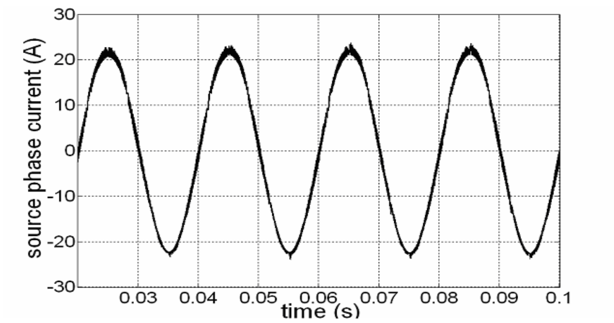
Figure 5. Phase-a load current waveform

Phase-a source current waveform obtained with simulation study related to the examined two current control methods are presented in Fig. 6 and Fig. 7 with respect to high switching frequency, and low switching frequency cases.

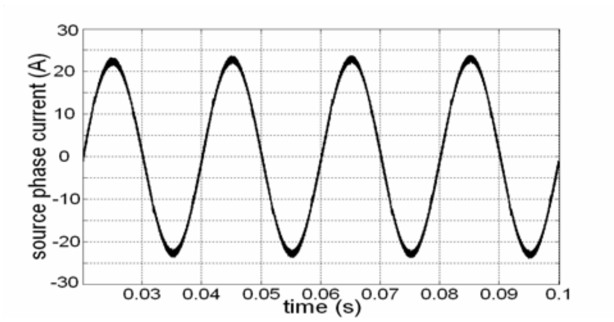
The ratings of the simulated system used for the performance comparison are reported in Table 1.

TABLE 1- Ratings of the Simulated System

Line Voltage	380 Vrms, 50Hz
Rectifier Input Inductor	0.3 mH
Rectifier Resistance	26 Ω
Interface Filter	3.3 mH
Filter dc-side capacitance	2 mF
Filter dc-side voltage	750 V

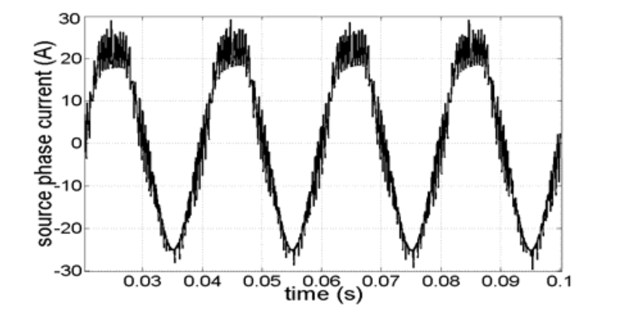


(a) with adaptive-band hysteresis

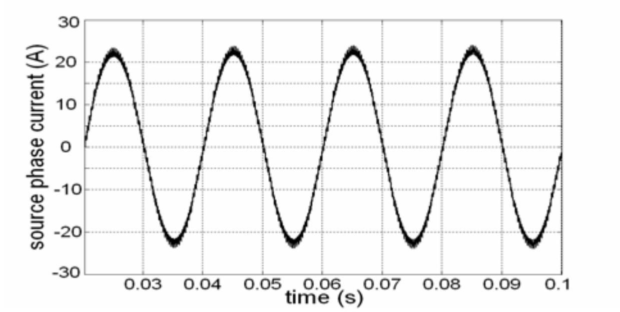


(b) with triangular carrier

Figure 6. Phase-a source current waveform under $f_{switching,high}$



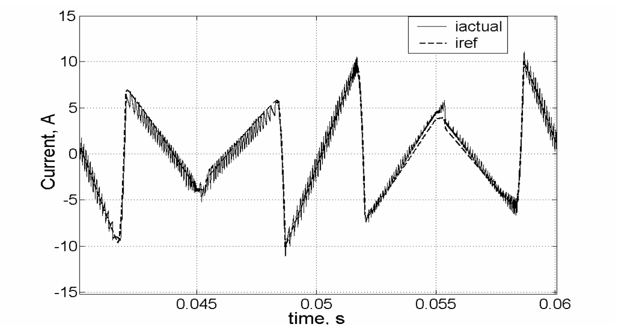
(a) with adaptive-band hysteresis



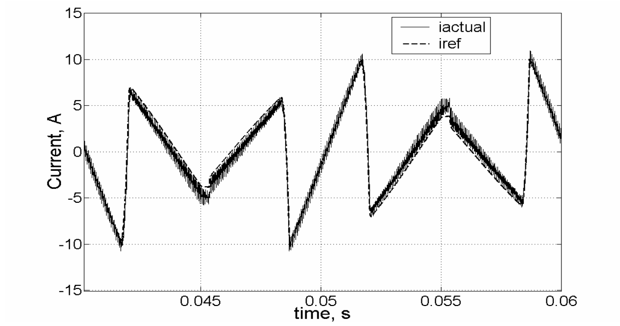
(b) with triangular carrier

Figure 7. Phase-a source current waveform under $f_{switching,low}$

The current tracking performances of these methods with low and high switching frequency cases are also can be observed in Fig. 8 and Fig. 9 respectively.

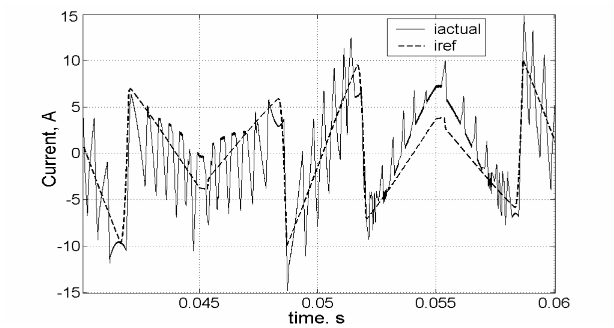


(a) with adaptive-band hysteresis

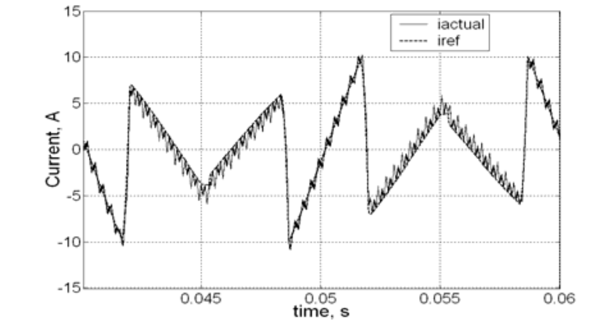


(b) with triangular carrier

Figure 8. Current tracking performances under $f_{switching,high}$



(a) with adaptive-band hysteresis



(b) with triangular carrier

Figure 9. Current tracking performances under $f_{switching,low}$

In the adaptive-band hysteresis control, the switching frequency is nearly constant with respect to the system parameters and defined switching frequency. However, at low switching frequency case, the tracking is not as good as in high switching frequency one. Obviously, a decrease in switching frequency results in an increase in the hysteresis bandwidth that causes the free operation of current error in a wider range. This higher low-frequency error, in turn, will lead to higher low order harmonics in the source current, therefore, higher THD. Based on the above facts, the switching frequency should be kept as high as possible for better performances of adaptive-band hysteresis current control.

In the triangular carrier method, the output current ripple is fed back and influences the switching times. It entails the advantage of a fast response, provided that the modulator can react on instantaneous changes of its reference by keeping the switching frequency constant. For the achievement of the best filter capability, the choice of the parameters for proportional-integral (PI) controller are important. If the current error signal exceeds the amplitude of the triangular waveform, a smaller proportional gain is to be chosen. On the other hand, integral gain should be chosen as big enough so that the generated current will be able to follow the reference current closely. The current error will be kept in the memory of the integrator until it is brought to near to zero. Therefore, it is good choice to take the time constant of the integrator in the range of the switching period.

Current control by the triangular carrier current control is also affected from the chosen switching frequency but it has still acceptable performance. It is worthwhile to note that in many industrial applications, an impressed current is required, but every modulation process produces instantaneous deviations in the reference current.

The simulation results given in the previous figures are summarized in Table 2. However, for the low switching frequency case, as the reason mentioned before, the performance of the adaptive-band hysteresis current control become worst.

TABLE 2- Source current THD and RMS current error

Current Control Method	High $f_{switching}$	Low $f_{switching}$
THD (%), I_{load}	27.47	27.47
Adaptive-Band Hysteresis *THD (%)*, I_{line} $e_{rms\ (A)}$	 3.71 1.81	 17.24 5.52
Triangular Carrier *THD (%)*, I_{line} $e_{rms\ (A)}$	 2.52 1.14	 3.38 1.57

$$\left(e_{rms} = \sqrt{\frac{1}{T}\int \left(e_{\alpha}^{\ 2} + e_{\beta}^{\ 2}\right) dt} \right)$$

In high switching frequency operation, the simulated SAPF is able to compensate up to the 25 th harmonic successfully that causes the better compensated current waveform. However, in practical applications, increasing the switching frequency causes increased switching losses and EMF- related problems. Besides, higher frequency operation may require a faster embedded controller. On the other hand, increasing the switching frequency of power inverters will decrease the output harmonic and the cost of filter circuits.

VI. CONCLUSION

This paper illustrates comparative study of two current control techniques applied for SAPF. In both of the investigated current control techniques, the switching frequency remains constant in contrast to conventional hysteresis current control method. In addition to this, in adaptive-band hysteresis control, the hysteresis bandwidth, which is unknown in the fixed-band case, can be determined from these parameters. However, the switching frequency should be kept as high as possible for better performance of adaptive-band hysteresis current control. In the overall simulation study, the triangular carrier method has certain superiority with respect to the adaptive-band hysteresis current control.

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