A SIMPLE HARMONIC COMPENSATION METHOD FOR NONLINEAR LOADS USING HYSTERESIS CONTROL TECHNIQUE

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ABSTRACT

In this paper the elimination of the current harmonics of AC mains injected by nonlinear loads is investigated. The active power filter proposed in this study is a single-phase voltage source inverter (VSI) connecting to the AC mains through an inductor. The hysteresis current controller is used to control the operation of the switches of the inverter. The simulation results show that how well the filter eliminates the harmonics of the source current.

I. INTRODUCTION

Harmonic distortion is a serious problem in power systems due to increase of the usage of solid state devices. Power electronic devices generate harmonic and reactive current in the utility systems. The harmonic and reactive currents lead to low power factor, low efficiency and harmful disturbance to neighborhood appliances, as well as heating of transformers [1-4]. The passive L-C filters can be used to remove these problems but they have many disadvantages such as large size, resonance, fixed compensation, noise, etc. In passive filters, the absorbed filter current is not controllable so, it does not provide a complete solution [5].

Using active power filter (APF) is an efficient solution for all these problems. APFs can be connected to the circuit in series or parallel [6]. The series APF is normally used to eliminate voltage harmonics, spikes, sags, notches, etc. while the parallel APF is used to eliminate current harmonics and reactive power components. The converter used in APFs can be either a current source inverter (CSI) with inductive energy storage or a voltage source inverter (VSI) with capacitive storage [7]. The APF behaves like non-sinusoidal current source to cancel the current harmonics generated by the nonlinear load. Power factor compensation and redistribution of power to keep the system balanced are some of other advantages of the APF.

II. CIRCUIT DESCRIPTION

Some of single-phase loads, such as domestic lights, ovens, furnaces, TVs, computer power supplies, air conditioners, printers and adjustable speed drives behave as nonlinear loads. The used nonlinear load and parallel active power filter circuit configuration is shown in Figure 1. The load consists of an uncontrolled bridge rectifier and a parallel connected capacitor and resistor. The proposed active power filter is a single-phase full-bridge inverter.

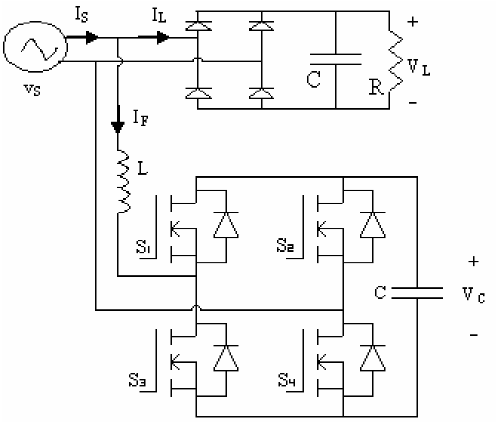


Figure 1 The circuit diagram of the system

The input of APF is parallel with the load and its output is connected to a capacitor. This model is well-known in UPS applications, in the presence of utility source voltage, the same inverter can be used as an active power filter to eliminate the harmonics of nonlinear load.

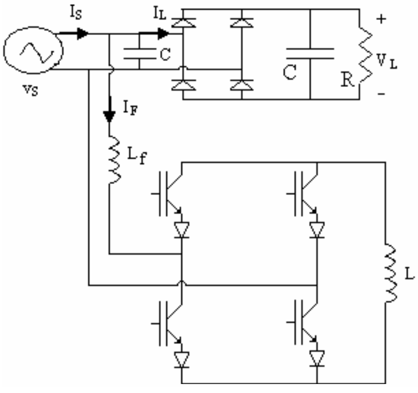


Figure 2 The parallel active power filter with CSI

Nonlinear single-phase loads cause power quality problems. Single-phase (two wire) active power filters have many different configurations such as series, parallel or hybrid and control techniques**.** APF is power electronic equipment containing switching devices and passive elements such as energy storage capacitor or inductor on dc side of inverter. Figure 2 shows a system using current source type active power filter.

II-a MATHEMATICAL MODEL OF THE LOAD

The operation modes of rectifier based on conduction states of diodes are as follows:

Mode 1: D_1, D_4 are turned on and the capacitor C_L is charging.
Mode 2: D_2, D_3 are turned on and the capacitor C_L is charging.
Mode 3: D_1, D_2, D_3, D_4 are turned off and the capacitor C_L is discharging. In this mode the rectifier is disconnected from the ac mains.

The circuit connection of the nonlinear load including a single-phase uncontrolled rectifier is shown in Figure 3. The state variables of the rectifier are chosen to be i_L and V_L. The conditions governing the states of diodes are related to diode bias voltages and currents.

$$i_L' = \delta i_L; \qquad (1)$$

where the the switching function (δ) is given by

$$\delta = \begin{cases} +1 & \text{D1 } \textbf{AND} \text{ D4 are } \textbf{ON} \ \ \textbf{AND} \text{ D2 } \textbf{AND} \text{ D3 are } \textbf{OFF}, \\ 0 & \text{D1 } \textbf{AND} \text{ D2 are } \textbf{OFF} \ \textbf{AND} \text{ D3 } \textbf{AND} \text{ D4 are } \textbf{OFF}, \\ -1 & \text{D2 } \textbf{AND} \text{ D3 are } \textbf{ON} \ \ \textbf{AND} \text{ D1 } \textbf{AND} \text{ D4 are } \textbf{OFF}, \end{cases} \qquad (2)$$

The state space equations of the rectifier can be written as:

$$\frac{di_L}{dt} = -\frac{R_s}{L_s} i_L + \frac{1}{L_s}(V_s - \delta V_L) \qquad (3)$$

$$\frac{dV_L}{dt} = \frac{-1}{R_L C_L} V_L + \frac{\delta}{C_L} i_L \qquad (4)$$

The state space model is derived as;

$$\frac{d}{dt}\begin{bmatrix} i_L \\ V_L \end{bmatrix} = \begin{bmatrix} -\frac{R_S}{L_s} & -\frac{\delta}{L_s} \\ \frac{\delta}{C_L} & \frac{-1}{R_L C_L} \end{bmatrix} \begin{bmatrix} i_L \\ V_L \end{bmatrix} + \begin{bmatrix} \frac{1}{L_S} \\ 0 \end{bmatrix} V_S \qquad (5)$$

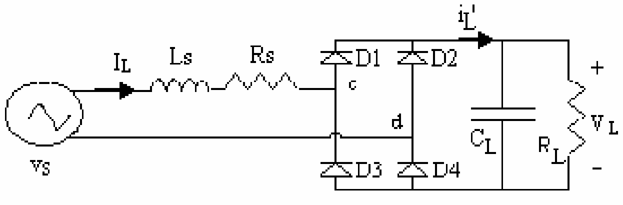
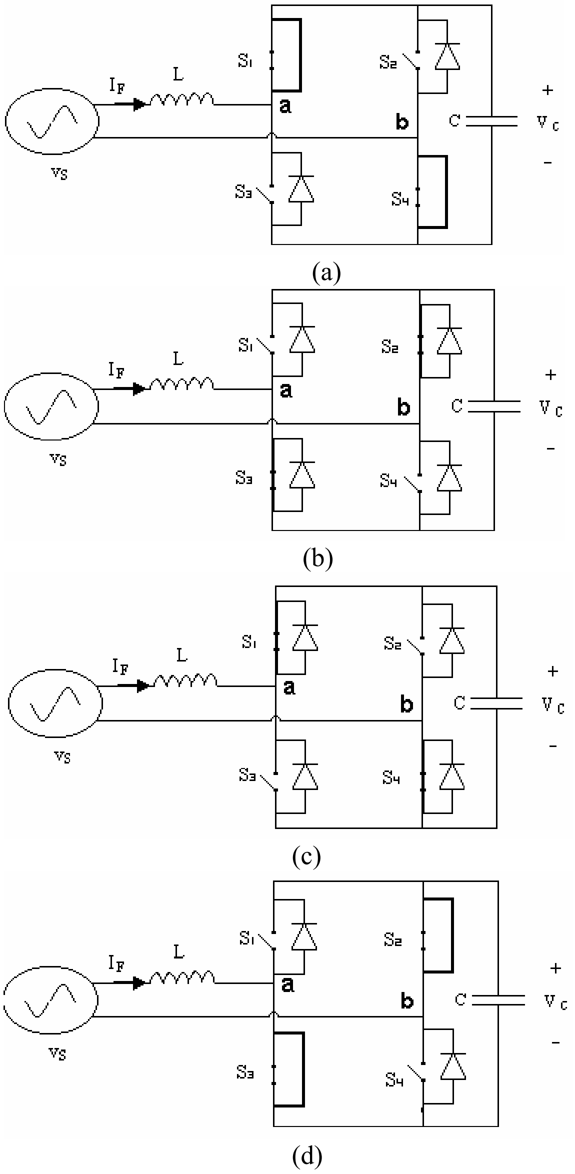


Figure 3 A typical nonlinear load

II-b MATHEMATICAL MODEL OF THE FILTER

Active power filter consists of a H-bridge inverter and an energy storage capacitor. This H-bridge inverter operates as a voltage source inverter converting ac signal into dc. The operation of an active power filter is similar to that of a boost chopper.



(a)

(b)

(c)

(d)

Figure 4 The equivalent circuits of the APF for different operation modes, Mode1 (a), Mode2 (b), Mode3 (c), Mode4 (d).

There are four switches and four freewheeling diodes employed in the converter. Consequently, it can be either operated as a rectifier to absorb current or an inverter to supply current for harmonic compensation (Figure 4) [8]. In this paper, the operation of switches is bipolar mode. In this mode the polarity of the voltage across a and b nodes, V_{ab} changes during each switching period [9].
Based on the gate signals the following operation modes are derived:

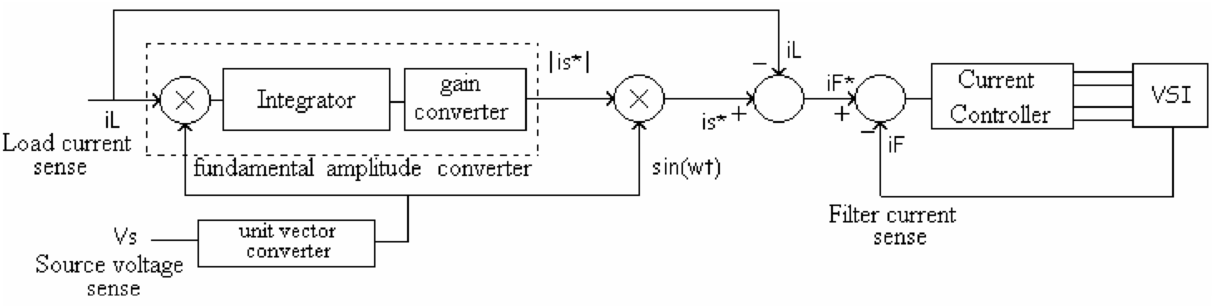


Figure 5 Control strategy of the APF

Mode1: In this mode the source voltage is in the positive cycle. S1 and S4 are in on state, S2 and S3 are off. The states of S1 and S4 in the positive cycle do not affect the system operation and the current passes through their parallel connected diodes.

Mode 2: In this mode the source voltage is in the positive cycle. S1 and S4 are in off state, S2 and S3 are conducting. The current passes through the S2 and S3 switches.

Mode 3: In this mode the source voltage is in the negative cycle. S1 and S4 are in on state, S2 and S3 are off. The current passes through the S1 and S4.

Mode 4: In this mode the source voltage is in the negative cycle. S1 and S4 are in off-state, S2 and S3 are in on-state. The states of the S2 and S3 switches do not affect the system operation and the current passes through their parallel connected diodes.

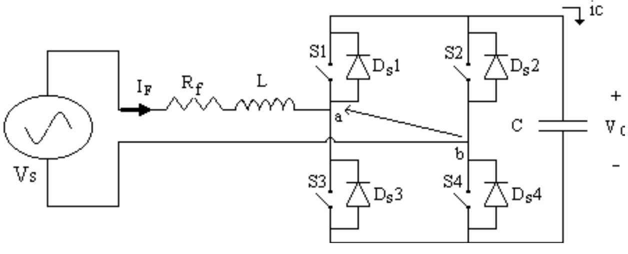


Figure 6 Single-phase voltage source APF circuit

The state variables of the rectifier are chosen to be i_f and V_c. To avoid shorting the output capacitor and destroying the power semiconductors, the two switches of each bridge leg must be in complementary states. The conditions governing the states of the power semiconductors considered in are related to switch drive signals and diode bias voltages and currents [10].

Therefore the voltage across a and b and the capacitor current can be written as;

$$u_{ab} = \delta V_c \tag{6}$$

$$i_c = \delta i_F \tag{7}$$

where the switching function is given by ;

$$\delta = \begin{cases} +1 & \text{S1 AND S4 are ON OR D1 AND D4 are ON} \\ -1 & \text{S2 AND S3 are ON OR D2 AND D3 are ON} \end{cases} \tag{8}$$

Considering the above conditions the state space equations of the filter can be written as:

$$\frac{di_F}{dt} = -\frac{R_s}{L} i_F + \frac{1}{L}(V_s - \delta V_C) \tag{9}$$

$$\frac{dV_C}{dt} = \frac{1}{C} \delta i_F \tag{10}$$

The state space model is derived as;

$$\frac{d}{dt}\begin{bmatrix} i_F \\ V_C \end{bmatrix} = \begin{bmatrix} -\frac{R_S}{L} & -\frac{\delta}{L} \\ \frac{\delta}{C} & 0 \end{bmatrix}\begin{bmatrix} i_F \\ V_C \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_S \tag{11}$$

III. CONTROL STRATEGY

The overall control system has ability to generate the reference current waveforms for APF and also produces the switching signals for VSI. The control system is based on the measurement of load current (I_L). Due to nonlinearity of the load, the load current is not a sinusoidal wave, thus includes harmonics. In this method $i_{L1} \cos \theta_1$ is derived based measurement of the load active power. Assuming a lossless converter the source current peak value to obtain unity power factor will be equal to $i_{L1}\cos\theta_1$. Subtracting load current from the source current gives the reference filter current which is used in the control of the inverter switches. Figure 5 shows the overall control structure of the system.

There is another control strategy method in which the source current is taken as reference instead of filter current. In this method there is no need to subtract the load current from the source current therefore, the mathematical process in this method is less than the first one (Figure 7). This method simplifies the control strategy.

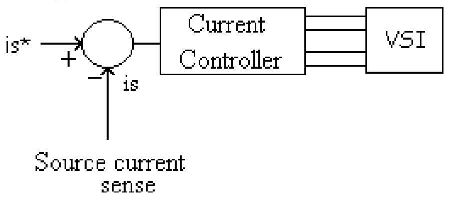


Figure 7 Control strategy using source current

III-a. BASIC CONTROL THEORY

The source voltage is assumed to be pure sinusoidal wave as;

$$v_s(t) = V_p sin(wt) \qquad (12)$$

The nonlinear load current is represented as;

$$i_L(t) = \sum_{n=1}^{\infty} i_n \sin(nwt + \theta_n) \qquad (13)$$

A signal with unity amplitude is obtained from the source voltage using a voltage divider as;

$$u(t) = \sin(wt) \qquad (14)$$

The source current is required to satisfy the controller to operate properly is obtained from Equation (15).

$$i_s(t) = \frac{1}{T}\int_0^T [i_{L1}\sin(wt+\theta_1) + \sum_{n=2}^{\infty} i_n \sin(nwt+\theta_n)]\sin(wt)dt$$
$$= i_{L1}\cos\theta_1 \qquad (15)$$

Equations (16) and (17) give the reference source and filter currents.

$$i_S^{\,*} = i_1 \cos\theta_1 \sin(wt) \qquad (16)$$

$$i_F^{\,*} = i_S^{\,*} - i_L \qquad (17)$$

III-b. CURRENT CONTROL TECHNIQUE

The hysteresis current controller technique is used in both control strategies. In the first method the filter current is taken as reference current and in the second one the source current is taken as reference current [11-13]. This control technique is simple and fast. (Figure 8)

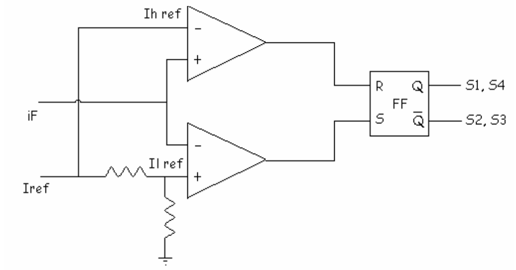


Figure 8 Pratical model of the hysteresis current controller

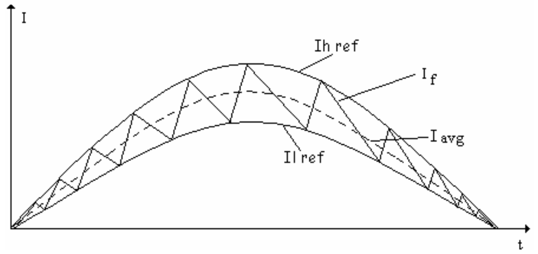
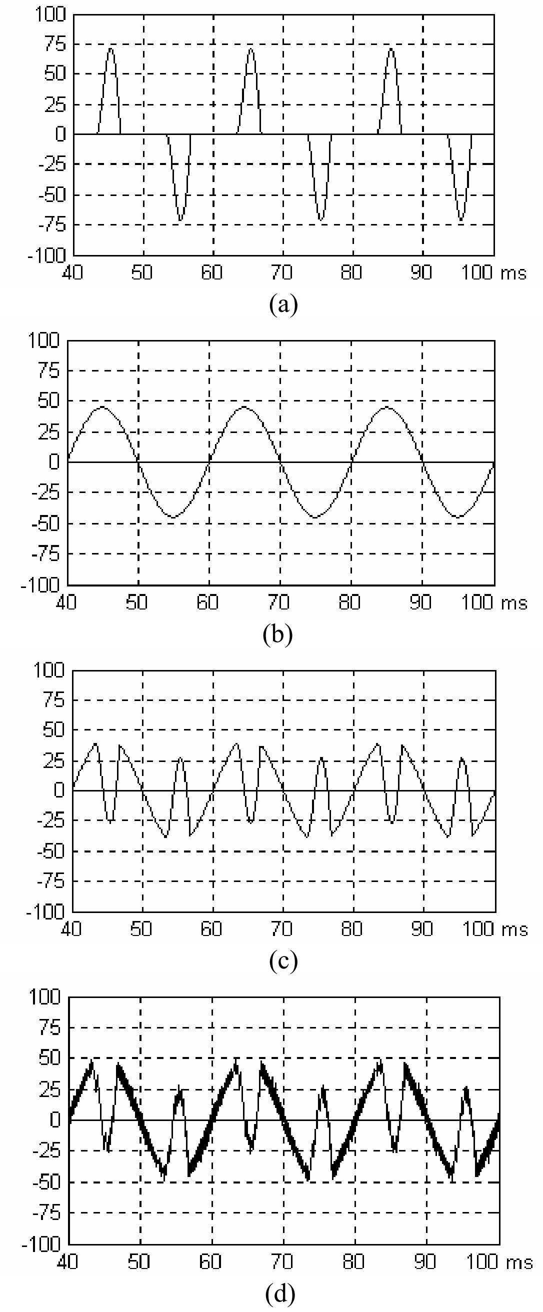


Figure 9 The waveform of hysteresis current controller

The switching frequency is changing in the hysteresis current controller. The error is found between desired and reference current. When the error reaches an upper limit the switches are changed to decrease current. When the current reaches a lower limit, the switches are changed to increase current. So the current tracks the reference current (Figure 9).

IV. SIMULATION RESULTS

The parameters used in simulation of system of Figure 1 are given in Table 1. Figure 10 (a) shows the current waveform of a 5 kW nonlinear load. The load current contains odd harmonics which increase the reactive power drawn from the utility. This causes a reduction in power factor and efficiency of the system. These disadvantages can be removed using active power filter.

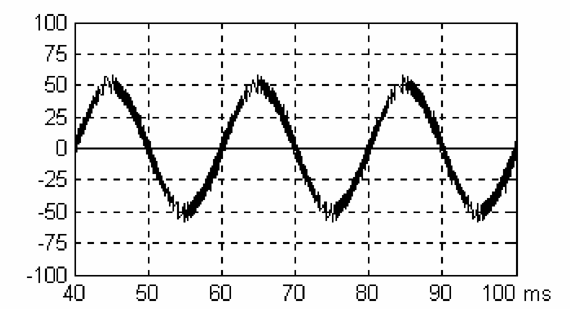


(a)

(b)

(c)

(d)

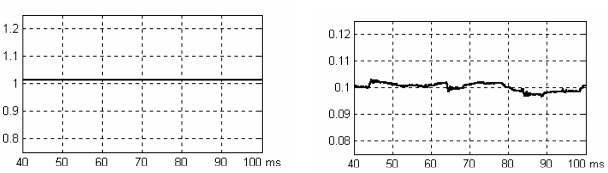


(e)

Figure 10 Nonlinear load current of the active power filter (a), Reference source current (b), Reference filter current (c), Measured filter current (d), Measured source current (e)

The reference source current, reference filter current, measured source current and the measured filter current are shown in Figure 10-b, 10-c, 10-d and 10-e, respectively.

Figure 11-a shows the source current THD for the case there is no filter is used in the system. After connecting the APF to system the THD of the source current decreases as shown in Figure 11-b.



(a) (b)

Figure 11 (a) Source current THD without using APF, (b) Source current THD using APF

Table 1 Simulation Parameters

Source Voltage	V_s	=	220 V (rms)
Frequency	f	=	50 Hz
Power	P	=	5 kW
Load resistance	R_L	=	20 Ω
Load capacitance	C_L	=	2200 µF
Input resistance of rectifier	R_S	=	0.25 Ω
Input inductance of rectifier	L_S	=	0.5 mH
APF resistance	R_F	=	0.1 Ω
APF inductance	L_F	=	2 mH
APF capacitance	C_F	=	440 µF

V.CONCLUSION

In this study, the active power filter was designed and used in eliminating the current harmonics of the AC mains and increasing the power factor of the system. The control strategy is simple and needs reference signals. In this study the reference source current was obtained based on assumption of having a lossless converter. The results obtained from simulation of system using MATLAB program show that the proposed controller effectively cancels the harmonic components of the source current.

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