Journal of Engineering Sciences

Vol 11, Issue 7,July/2020

ISSN NO:0377-9254

Analysis of Series Active Power Filter for Harmonic Mitigation and Power Factor Improvement under Non-Linear Load Condition

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Abstract:

This work presents a low-cost approach to power factor correction (PFC) of single-phase diode rectifiers using a series active filter. Comparing with the traditional PFC, the proposed PFC has lower requirements of power device ratings, which leads to lower cost, higher efficiency, and lower electromagnetic interference. It also can eliminate the bulky inductor needed in the traditional PFC. The topology, operation principle, and application issues of the proposed PFC are analyzed in this paper. The control strategy is discussed in detail and simulation results are provided.

Keywords: Adjustable-speed drive, heating, ventilating, and air conditioning (HVAC), power factor correction (PFC), series active filter.

I. Introduction

IN the recent years, more and more variable speed motor drives fed by single-phase utility power are used in residential heating, ventilating, and air-conditioning (HVAC) systems. Most of them are using diode rectifiers with smoothing dc capacitors as the front-end. The diode rectifier draws

pulsed current from the utility line, which leads to low power factor, low efficiency, and high rating requirements to the switching devices. As a result, some standards such as IEC 1000-3-2 have been brought forward to limit the harmonic current of the utility line. To comply with these standards, power factor correction (PFC) is needed. So far, a variety of passive and active PFC techniques have been proposed [1]–[5]. While the passive PFC may be the simplest way in the low power applications, the active PFC are used in the majority of applications for their high performance, compact size, and light weight[6].

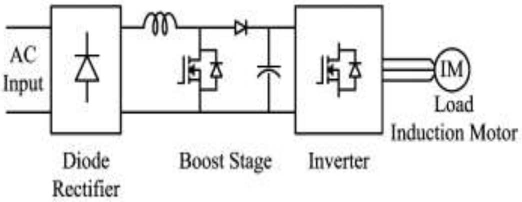

Fig 1: Traditional power factor correction

Fig. 1 shows the most common approach to signal-phase active PFC, where a boost circuit with an additional filter inductor is used to shape the line current[7]. The boost stage forces the dc bus current to follow the line voltage, which results in a nearly sinusoidal line current without phase difference. However, it brings in high dc bus stress, high switching device ratings, high switching losses, and high electromagnetic interference (EMI). In this paper, a new compact, low-weight, low-cost PFC using a series active filter is proposed. Comparing with the traditional PFC, it has lower device ratings, lower cost, lower EMI, and higher efficiency. The inductor needed in the proposed series PFC is also much smaller than those in the traditional PFC, and in the most cases, the line impedance of the utility line is enough for its normal operation[8]-[9]. A hysteresis control strategy, which is simple and easy to implement, is presented to eliminate line harmonics[10]. Simulation and experimental results are given to verify the analysis and demonstrate the control performance.

II. PROPOSED CONVERTERTOPOLOGY

The diode rectifier with proposed PFC for typical residential HVAC is shown in Fig. 2. Because the ac line is 100 V and low, a voltage doubler is used for rectification, i.e., two capacitors are charged alternatively over one cycle. The output voltage is doubled, resulting in an approximate 250 V dc link voltage (V). The PFC circuit, implemented by a full bridge inverter with an optional inductor, connected in series with the diode rectifier. Since the diode rectifier and the full bridge inverter behave like voltage sources, the line current is determined by the difference among these three voltage sources and the loop inductance, which includes the line impedances and the inductance of the optional inductor.

Although four switching devices are used in this topology, each power device only needs to sustain a low capacitor voltage, , which is limited below 50 V. Thus low-cost, high-efficiency 60-V metal-oxide semiconductor field effect transistors (MOSFETs) can be employed. The voltage rating of each device is only 20% of the voltage rating of the switching device that are used in the boost stage of the traditional PFC. Therefore, even though four MOSFETs are used in the proposed topology, its total cost of switching devices is still less than the cost of the high voltage device in the traditional topology. In addition, the gate drive circuit of the proposed topology can draw power directly from the dc capacitor of the inverter without isolation. A simple charge-pump gate drive circuit powered by the inverter dc capacitor can be easily implemented for each MOSFET. Compared with the high transfer ratio and isolated power supply needed in the gate drive circuit of the traditional boost PFC, the proposed topology can also reduce the complexity and cost of the gate drive signal tremendously.

The EMI problem due to the while switching is also a big concern of the PFC system. In the proposed PFC, the voltage stress on the switching devices is only , which is less than 50 V, while the switching device in the traditional boost PFC needs to switch on and off the whole dc bus voltage, 250 V. Therefore, the EMI interference during switching will be reduced significantly. The voltage distortion brought into the acgrid by the proposed circuit also can be neglected because 1) the inverter dc voltage is relatively low (V) and 2) the line impedance, with the inductance of the optional inductor, are normally far greater than the source impedance, . The simplified equivalent circuit is shown in Fig. 3, where is the total line impedance, . The relationship between the output voltage of the inverter and the state of each switch can be summarized by

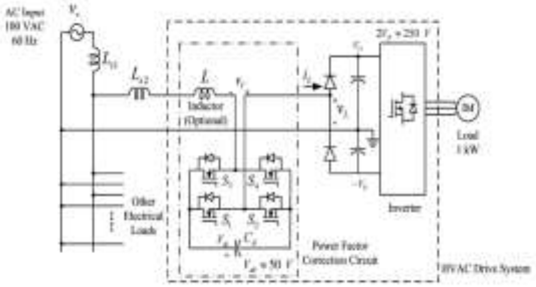

Fig2: Proposed power factor correction converter (PFC).

$$v_C = kV_{\mathrm{dc}}$$

--→(1)

where k is defined as

$$k = \begin{cases} +1, & \text{for } S_1 \text{ is ON and } S_3 \text{ is OFF} \\ 0, & \text{for both } S_1, S_3 \text{ are ON or OFF simultaneously} \\ -1, & \text{for } S_1 \text{ is OFF and } S_3 \text{ is ON.} \end{cases}$$

--→(2)

III. CONTROL STRATEGY

The easiest way to control the proposed topology is to use the hysteresis control, as shown in Fig. 4(a). In this control, the harmonic component of the line current, is extracted by a notch

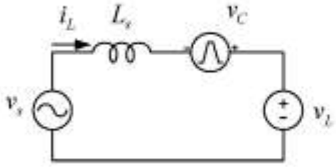

Fig. 3. Equivalent circuit of proposed PFC.

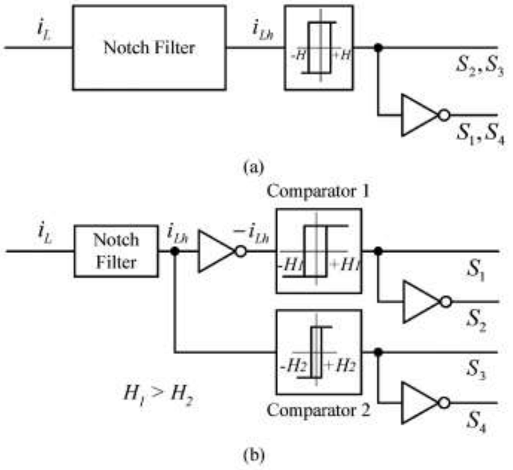

Fig. 4. Hysteresis control.

filter, and fed into a hysteresis comparator. The output of the inverter will switch between and to limit the harmonic current within the hysteresis band. In this control strategy, the zero voltage of the inverter is not utilized, which results in higherswitching frequency and higher switching ripples. In order to reduce the switching frequency and the voltage ripple, the zero voltage has to be utilized.

Fig. 4(b) shows the proposed double hysteresis control, which utilizes the zero voltage output of the inverter. In this control strategy, two hysteresis comparators with different hysteresis widths, H1 and H2, are used. Since the two-phase legs of the full-bridge inverter are symmetrical, we can assume that H1 is greater than .H2

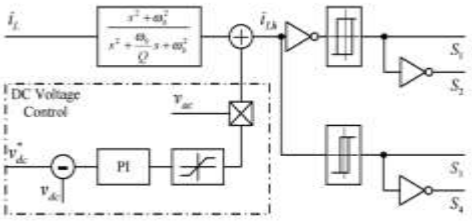

Fig 5: Block diagram of Hysteresis control with PI control

In this control strategy, switches S1 and S2 only switch three times per fundamental cycle. The switching frequency of switches S3 and S4 is approximately half that of the single hysteresis control with the same hysteresis width. Therefore, the double hysteresis control strategy tremendously reduces the switching frequency.

Since the hysteresis control is used to control the switching devices, the switching frequency is not constant. However, it is desirable to estimate the average switching frequency for design purposes

In this circuit, the actual dc capacitor voltage is detected and compared with the reference value, and the error is fed into a PI controller. A sinusoidal signal in phase with the line voltage is added to the harmonic currents extracted by the notch filter. The amplitude of the sinusoidal signal is controlled by the PI controller. By adding the sinusoidal offset to the input of the hysteresis comparator, active power flowing into the capacitor will be changed, thus the dc capacitor voltage can be controlled.

IV. COMPARITVE ANALYSIS OF PFC OF WITH SERIES FILTER AND WITHOUT SERIES ACTIVE POWER FILTER

Simulink diagrams:

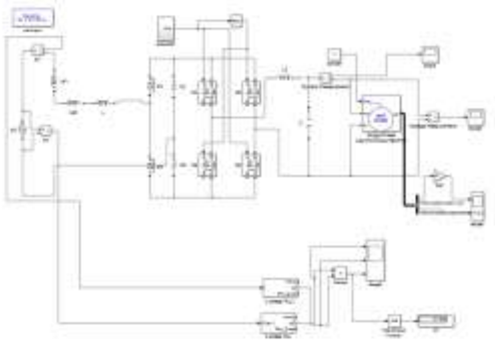

Fig 6: Without Series Filter

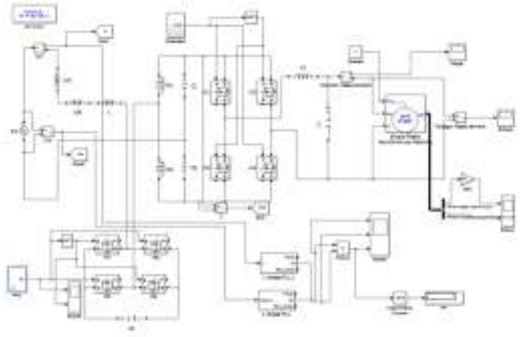

Fig 7: with series filter

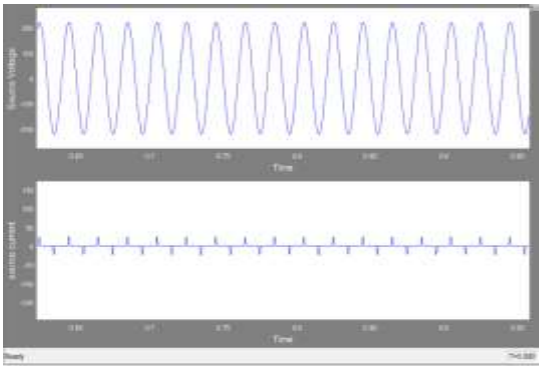

Fig 8: Without series filter Input a)Voltage

b) current

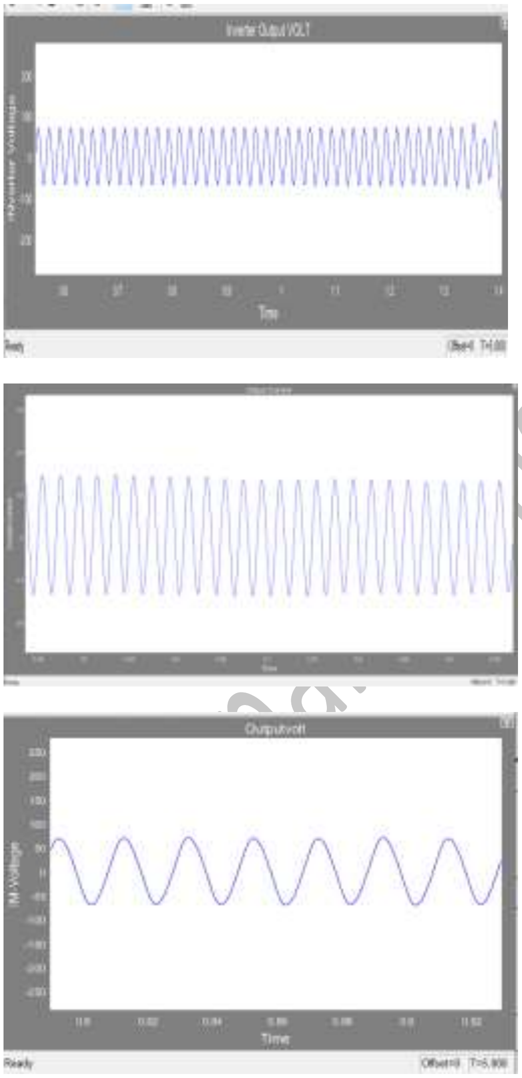

Fig 9) Output voltage a)Inverter b) Induction Motor

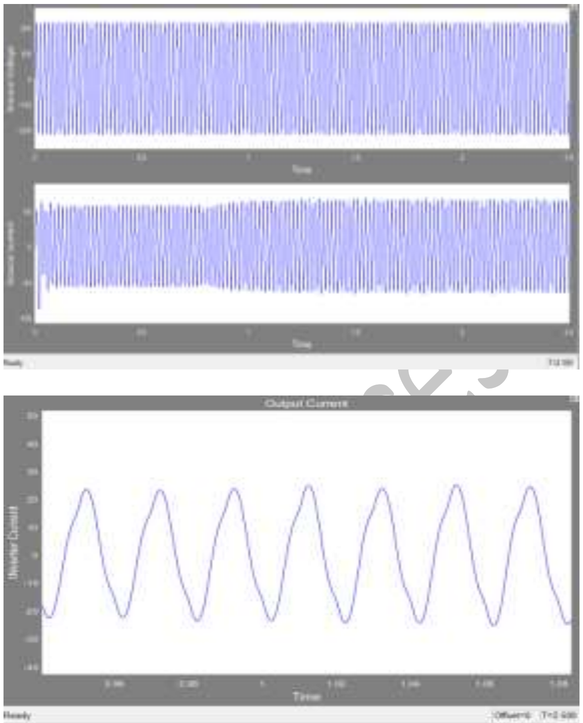

Fig 10) With Series Filter input a) voltage b) Load current c) Inverter Current(after add filter)

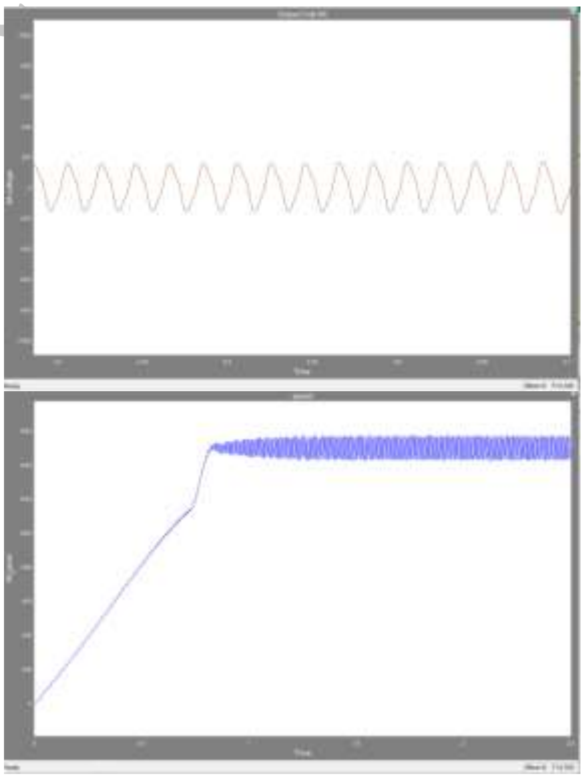

Fig 11) i) with series filter output voltage of IMii) Speed

V. CONCLUSION

A new PFC with double hysteresis control has been presented. The operation principle has been discussed in detail.. It shows that a high power factor has been obtained. Compared with the traditional PFC, the proposed PFC has the following advantages: 1) lower devices rating, which reduces cost, EMI, and switching losses, 2) no additional inductor is required, the line impedance is enough for most cases, and 3) the proposed double hysteresis control reduces the switching frequency significantly, which leads to higher efficiency

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