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Harmonics Reduction in Three Phase System Using Current Injection Technique for Adjustable Speed Drive

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ABSTRACT

This paper presents a new approach to mitigate harmonics and to improve the power factor of a three phase front-end uncontrolled rectifier. A high-power-factor could be achieved by injecting high-frequency triangular current from the output of the three-phase inverter. The HF current modulates the rectifier input voltage resulting in conduction of diodes into each switching cycle. The resulting ac input line current is continuous and sinusoidal in shape with significant reduction in current harmonics. All the switches are operated at zero-voltage switching (ZVS). The diodes of the rectifier are also operated with soft switching at turn-on as well as at turn-off. Varying switching frequency with a fixed duty ratio regulates the output voltage. The main feature of the circuit is that it does not require any additional active devices for current injection. Results that are presented shows that improved power quality at AC mains.

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INTRODUCTION

Power converters are widely used in industrial applications due to the remarkable progress made in the high power electronic devices. In most of the AC-to-DC power converters, pulse width modulated voltage source inverters supplied from a smooth DC link voltage, are used. Most electronic equipment's are supplied with 50 Hz utility power in which 50% is processed through some power converters. These power converters use simple and conventional diode bridge rectifier followed by a DC capacitor. Since these power converters absorb energy from the AC line only when the line voltage is higher than the DC voltage, the input line current contains rich harmonics which pollute the power system and interfere with other electronics equipment's (M. A. Amin, 1997). Hence, these converters have a low power factor of 0.65. International concerns of power quality problems and pollution have brought the use of PFC converters to feed Induction motor which is used in numerous low power applications because of its high efficiency and wide range of speed (Hiralal M. Suryawanshi, 2008) and harmonic spectra shown in Fig 1. The filters composed of capacitors and inductors have been used for eliminating current harmonics and improving the system power factor. These filters are costly, bulky and sensitive to the line frequency. The scheme of HF current injection, proposed in having a high component count and switch stresses are also high as they have to carry load current as well as HF injection current. In this paper, the converter which comprises of an active power factor correction circuit (APCC) and HF front-end three-phase diode rectifier is proposed. The paper presents the high-power-factor operation of AC-to-DC converter (D.-C. Lee and Y.-S. Kim, 2011). The high-power-factor is obtained by injecting high-frequency (HF) current, at the input of the front-end three-phase rectifier, from the HF inverter. All the switches of the inverter show zero voltage switching. The converter is made to operate in continuous conduction mode and uses a current multiplier approach with average current control.

A high-power-factor is achieved by injecting high frequency triangular current from the output of the three-phase inverter. The HF current at the same switching frequency is injected into the input of a front-end rectifier from the output of an HF inverter. The main feature of the circuit is that it does not require any additional active devices for current injection. The inverter driving the induction motor is operated using a sinusoidal pulse width-modulation technique. These converter topologies can be of potential interest for future work in this area as they have lower switching losses however, (S. Kim, 1997) the additional control circuitry is required for their operation. Detailed modeling and performance analysis is presented in this paper.

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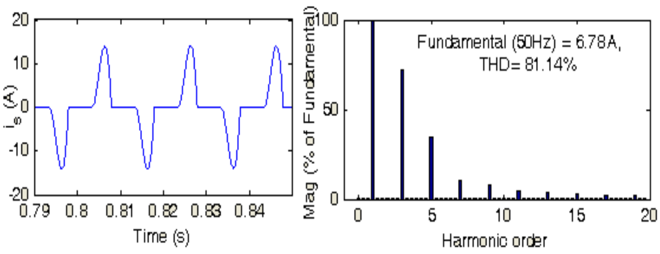

Fig. 1: Current waveform at AC mains and its harmonic spectra for the Adjustable Speed drive without Current Injection.

2. Proposed topology:

The simplified functional block diagram and circuit diagram of the proposed scheme are shown in Fig. 2 (a) and (b), respectively. It consists of a three-phase diode bridge rectifier with source inductors L_s, a DC-link capacitance C_{rect}, and a three-phase full-bridge inverter. The HF inverter output is fed to the three-phase induction motor through small LC filters. The HF current from the inverter output is also fed back to the input of the diode bridge rectifier through an HF current injection network. The current injection network consists of three sets of inductor L_f and capacitor C_f. The inverter is operated using a sinusoidal PWM (SPWM) technique with a reference frequency of 50 Hz and a high carrier frequency. This off time period is not sufficient for the inverter output current to reset to zero. Hence, an anti parallel diode of the device does not conduct before the conduction of the main switch, as the main switch continues to conduct also in the next switching cycle.

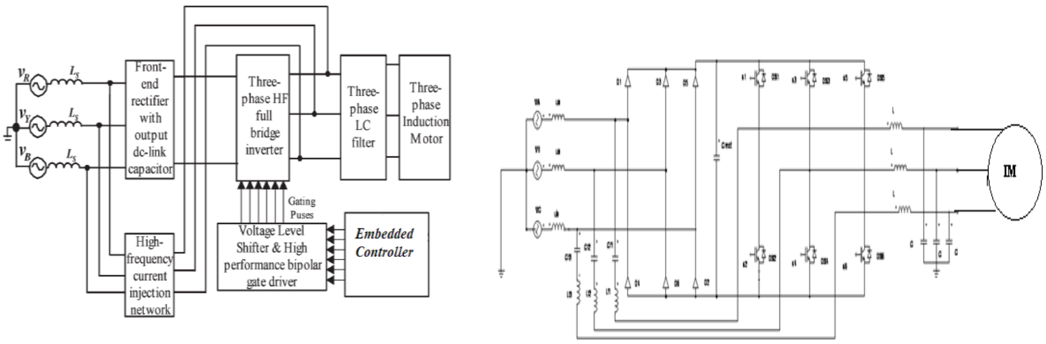

Fig. 2: (a) Simplified functional block diagram. (b) Circuit diagram of the proposed scheme.

Thus, the turn-on losses are reduced to a significant level, but they are not completely eliminated. The non-ZVS period is eliminated by keeping a small modulation index and a maximum duty ratio of about 0.5. The turn-off losses are reduced by connecting a snubber capacitor C_n across each switch.

3. Principle of Operation:

The AC input line current of the three-phase diode bridge rectifier has a discontinuity in periods 0° to 30°, 150° to 210°, and 330° to 360° in one cycle of the phase voltage. The ideal operating wave form at the peak of phase A shown in Fig 3.

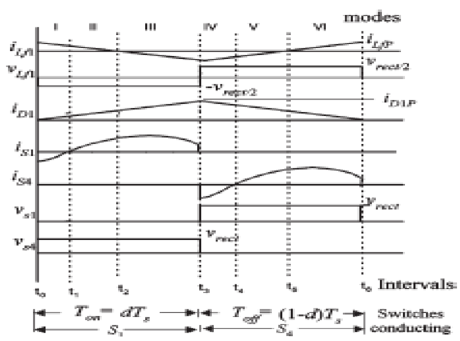

Fig. 3: ideal operating wave form at the peak of phase A.

This is because none of the diodes are forward biased during these periods. It is evident that the diode leg current i_{rectA} is the resultant sum of the line current i_A and the injected current i_{Lf1} (Hiralal M. Suryawanshi, 2008). HF current injection modulates the diode leg voltage V_A at the injected frequency range of kHz. Therefore, the diode bridge rectifier operates at a high frequency. When i_{rectA} is positive, the upper diode conducts, and when i_{rectA} is negative, the lower diode conducts. The modulated voltage also provides a sufficient forward bias to the diodes during the valley period. Each diode turns on and turns off at the switching frequency and conducts a complete 180° period of the input voltage in the discontinuous mode. When none of the diodes on a leg of the input diode bridge rectifier is in conduction, the input AC line current through that phase is equal to the injected current (P. Pejovic, 1998). It can be seen that the operation of the front-end rectifier of the converter is similar to that of the (J. Huppunen, 1949) and (J. A. M. Blejis, 2005) three-phase PWM boost rectifier operating with continuous input currents.

It can be seen that the operation of the front-end rectifier of the converter is similar to that of the three-phase PWM boost rectifier operating with continuous input currents. The diodes D_1 and D_4 of the input three-phase diode bridge rectifier's turn on and turn off at the rate of the switching frequency during the positive and negative half-cycles of the AC input supply voltage of phase A, respectively. When switch S_1 turns on, the current through diode D_1 linearly increases from 0 to its peak value I_{D1p}. Similarly, when switch S_4 turns on, the current through D_1 linearly decreases from its peak value I_{D1p} to 0. The current i_{D1} becomes zero at the end of the switching cycle. Thus, the current through the input rectifier is the HF triangular waveform in a sinusoidal envelope of the supply frequency, as shown in Fig. 4 (a). The current through the switched inductor L_{f1} is also a triangular waveform. It linearly decreases from $+I_{Lf1p}$ to $-I_{Lf1p}$ during the time interval Ton = dTs and linearly increases from $-I_{Lf1p}$ to $+I_{Lf1p}$ during the time $T_{off} = (1 - d)$ Ts, where d is the duty ratio, and T_{on} and T_{off} are the on and off periods of the switching device of the HF inverter, respectively.

In a conventional switch-mode rectifier, the inverter is controlled to obtain a nearly sinusoidal input current at a high PF. However, to control the ASD, an additional inverter is required to feed the drive. In this paper, high PF operation of a three phase rectifier for an ASD is presented. A high-frequency (HF) current is injected from the output of an HF inverter into the input of a front-end rectifier (T.Chandra Sekar, 2014) and (M. Cross, 2003). Thus, the power transistors of the active front-end rectifier are eliminated. Due to the HF current injection, the rectifier input voltage is modulated at a high frequency. The HF current is injected through the branch consisting of three sets of inductor L_f and capacitor C_f.

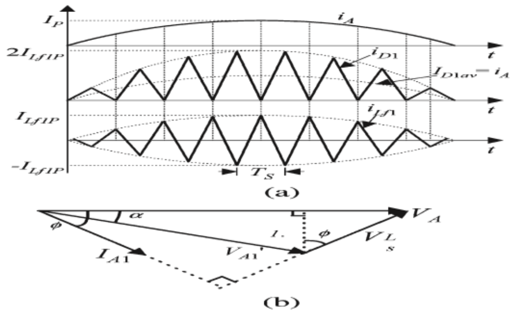

Fig. 4: (a) Waveforms of the input line current i_A, the input current of the rectifier i_{D1}, and the current through the switched inductor i_{Lf1} in the positive cycle of phase A. (b) Phasor diagram at the fundamental frequency.

4. Analysis:

In order to simplify the analysis following assumptions are made

(1) Input three-phase supply is balanced and purely sinusoidal.

(2) The switching frequency is far greater than the power line frequency (fs>>f).

(3) Output filter capacitance is adequately large, so that the output voltage can be considered as constant over a half power cycle period.

(4) All the switches and components are considered to be ideal.

The three-phase voltages are given by

$V_A = V_m \operatorname{Sin}\omega t$

$V_B = V_m \operatorname{Sin}(\omega t-2\pi/3)$

$V_C = V_m \operatorname{Sin}(\omega t + 2\pi/3)$ (1)

In the absence of a neutral connection to the bridge rectifier, the sum of AC currents must be equal to zero at all times, i.e.,

$i_A + i_B + i_C = 0$ (2)

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A. Input supply current, i_a:

Since the switching period is very small and due to the presence of C_o and L_{Sa}, in effect, the AC line current in a switching period is the sum of average values of i_{La} and i_{Ca}.

Therefore,

$$i_a = \frac{DT_S V_P}{2L_a}\sin\omega t = KV_P\sin\omega t \quad (3)$$

Where

$$K = \frac{DT_S}{2L_a}$$

V_p is the peak value of input phase voltage, and D is the duty cycle of switching period.

B. ***Output DC voltage, V_0:***

To have almost constant DC voltage V_0, at the output of the rectifier, generally large capacitor, C filter is connected. This acts as the input voltage to HF inverter. The current in the interval, T_d (discharge time), when the S_4 is on, is given by

$$iLa(t) = I_{Lap} - (\frac{V_0 - V_a}{L_a})T_d \quad (4)$$

But at the end of the interval, iLa = 0. Therefore, from (4)

$$I_{Lap} = (\frac{V_0 - V_a}{La})T_d \quad (5)$$

Duty cycle D is given by (6)

$$D = \frac{V_0 - V_a}{V_0} \quad (6)$$

At the peak of supply voltage,

V_a =Vp and ton and t_d periods are equal.

$$V_0 = 2Vp \quad (7)$$

C. ***Power factor and THD:***

The power factor can be defined as the ratio of real input power, P to the product of input rms voltage, Va rms and input rms current, Ia rms

$$P = \frac{1}{\pi}\int_0^{\pi} v_a i_a d\omega t = \frac{1}{\pi}\int_0^{\pi} V_P\sin\omega t\gamma\beta\frac{\sin\omega t}{1-\beta\sin\omega t}d\omega t \quad (8)$$

Where $\beta = Vp/V0$

Therefore, power factor (PF) is given as

$$PF = \frac{P}{V_a I_a} = \frac{\sqrt{2}}{\sqrt{\pi}}\frac{u}{\sqrt{x}} \quad (9)$$

Total harmonic distortion (THD) is given as

$$THD = \frac{1}{PF}\sqrt{1-PF^2} = \sqrt{\frac{\pi x - 2u^2}{2u^2}} \quad (10)$$

D. ***Design of inductor, La:***

During on period, the voltage across L_a is V_a and $V_0 - V_a$ during discharge period. As one moves towards the peak of supply voltage from valley points, the function V_0-V_a decreases. At the peak of the supply voltage, it has the least value, and in effect, discharge time may be too long. Three-phase input power is given by

$$P = 3\,V_a I_a \quad (11)$$

At the peak of input phase voltage,

$$L_a = \frac{3}{4}\frac{(1-D)TsVp^2}{P} = \frac{3}{4}\frac{(1-D)Vp^2}{fsP} \quad (12)$$

E. ***Design of capacitor, C_a:***

In a switching cycle current through the capacitor is given by the average value of this current is zero. The rms value, I_{Ca} is given by

$$i_{ca} = (-\frac{4I_{Cap}}{Ts}t + I_{Cap}) \quad (13)$$

The average value of this current is zero. At the peak of supply, peak value of the capacitor current and supply current is equals. Therefore,

$$I_{Ca} = \frac{I_P}{\sqrt{3}} \quad (14)$$

$$Ca = \frac{4\sqrt{2}}{3\sqrt{3}}\frac{TsP}{Vp^2} = \sqrt{\frac{32}{27}\frac{P_0}{V_P{}^2\, fs\eta}} \tag{15}$$

Where f_S is switching frequency, P_0 is output power and η is the efficiency of the converter.

5. Performance Evaluation:

The computer simulation of front end rectifier with current injection and without current injection are shown in fig 5- 8

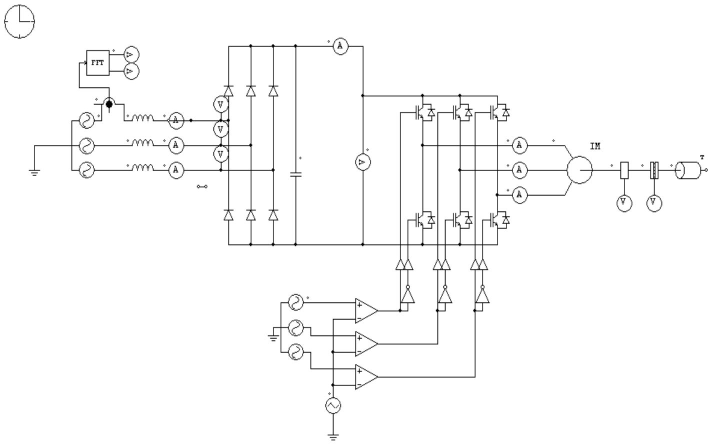

Fig. 5: Front end rectifier without current injection.

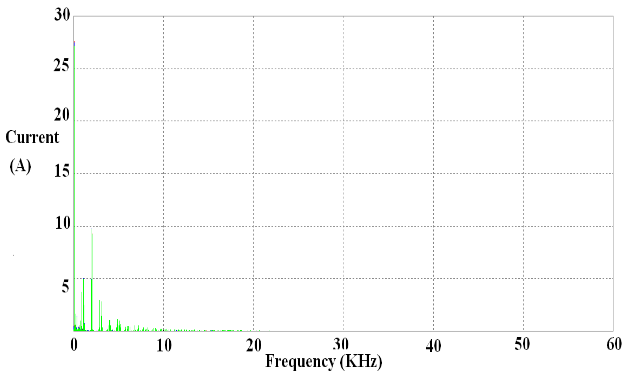

Fig. 6: Harmonic spectrum of before current injection.

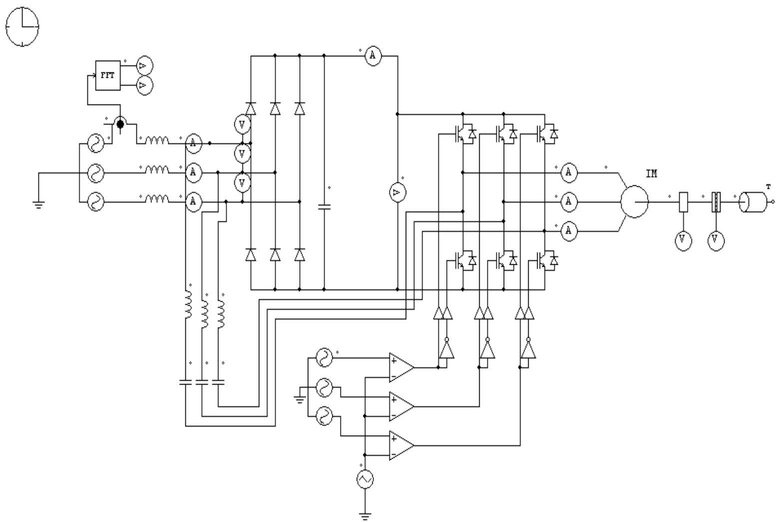

Fig. 7: Front end rectifier with current injection.

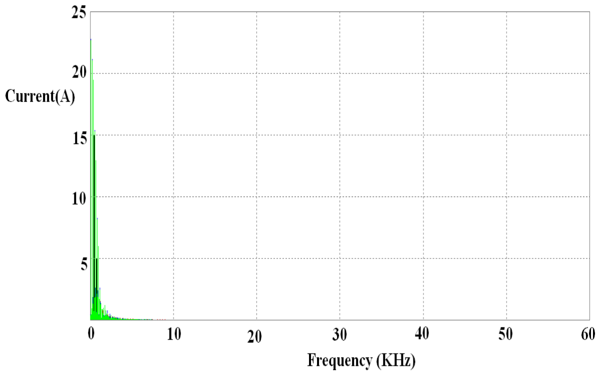

Fig. 8: Harmonic spectrum of after current injection.

Conclusion:

An ASD with high input PF and improved harmonic performance has been proposed. The PF of the three phases AC input line current is improved by using HF current injection .The main advantage of this approach is that it does not require any additional active component for HF current injection. The source current THD which was 27.5% using the conventional scheme is reduced to 22.5% .These results were verified through simulation experiments using PSIM.

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