Power Factor Improvement of AC Motor Drive by Implementing Current Injection Technique

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Abstract- **This model presents the bidirectional controlled switch-based current injection circuit with simple gate control scheme. Improved power factor and reduced total harmonic distortion (THD) of AC input line current of front-end rectifier for AC motor drive is achieved using this scheme. In the present system, the three-phase voltage source inverter (VSI) controls the induction motor (IM), while the high-frequency (HF) current injection into the front-end rectifier is from the VSI output. Hence the motor can operate at rated speed. The gating pulses for feedback bidirectional controlled switches are generated at every zero-crossing instances of the respective phase voltages for the duration of $\pi/6$ rad. The sinusoidal pulse width modulation switching signals are generated by using DSP (TMS320F2812). The computer simulation results and experimental results are also presented.**

Index Terms - **Bidirectional, Power factor, Total Harmonic Distortion, Voltage Source Inverter, High Frequency, Digital Signal Processor, Sinosoidal Pulse Width.**

1. INTRODUCTION

Progress in power electronics technology has led to wide spread applications of non-linear loads. Three-phase ac to dc rectifiers are playing an important role in these applications. The non-ideal characteristics of input line current drawn by these rectifiers create equipment malfunction and cause problems with other sensitive loads connected to point of common coupling (PCC). Remedies from poor-quality line current waveforms of three-phase diode bridge rectifier are discussed with various methodologies in [1–13].

The active current shaping has been extensively used as a good choice in single-phase as well as three-phase systems. A 12-pulse three-phase rectifier is proposed in [1]. This scheme is based on current injection system consisting of current injection network and resistance emulator. Current injection device is realised as zigzag transformer. An improvement in input current total harmonic distortion (THDi) is achieved for 12-pulse three- phase rectifier in [2], using two additional transformers. The current injection is performed at the output ports of the 12-pulse rectifier. The non-linearity in the phase-shifting autotransformer and the interphase reactors limits the improvement in THDi. In general, all 12-pulse three-phase diode rectifiers those use only phase-shifting technique have the input currents THD of 15.22%. Comprehensive review of multi-pulse rectifiers is given in [3]. In [4], a modified harmonic reduction technique for three-phase controlled rectifier is proposed. Current injection is realised through a zigzag transformer in the input network.

In [5, 6], the induction machine shares the motor control voltage and the voltage controlling the injection current. Consequently, the machine may not operate at rated speed while simultaneously injecting harmonic current into the input. In the present system, the three-phase voltage source converter (VSI) controls the induction motor (IM), while the high- frequency (HF) current injection into the front-end rectifier is from the VSI output. Hence the motor can operate at rated speed. The overall cost of the drive system is reduced considerably by replacing the traditional large dc reactors in the harmonic injection circuit [7] by smaller ac reactors. However, it still has a lot of passive elements in the current injection circuit as well as the dc side current smoothing purpose inductor. In [8], ac–dc full-bridge converter current injection series resonant converter is presented. This scheme overcomes the drawback of the converter employing current injection technique reported in [9], which is based on half- bridge topology. Hence to regulate the output voltage, widerange of frequency operation is required. Load-commutated silicon controlled rectifier (SCR) current-source-inverter-fedIM drive with sinusoidal motor voltage and current is presented in [10].

In this paper, bidirectional switch-based HF current injection circuit with simple gate control scheme in order to achieve improved power factor and THDi of ac input line current is presented. The gate pulses for feedback bidirectional controlled switches are generated near every zero-crossing instances of the respective phase voltages for the duration of p/6 rad. Thus HF current is injected for one-third time periodof phase voltage waveform instead of 2p period as in [12, 13]. Hence, the feedback switches process current for one-third period instead of 2p period. It is observed that gate pulse width duration of one-third of phase voltage period to feedback switches results in a remarkable improvement in THDi and power factor. In addition to less time period of conduction, the magnitude of current processed by thefeedback switches is also less. This results in less rms value of current in three-phase VSI and front-end rectifier. Hence, power losses in the converter are reduced and efficiency is improved. Therefore this topology will be more useful in medium power level converters.

II. OPERATING PRINCIPLE

In the proposed converter, current injection technique is implemented using three bidirectional switches with relatively simple gate control circuit. The input three phase supply is assumed to be balanced. The switching point closing the switch for π/6 rad before the phase voltage zero crossing is determined by the crossing point of the other two phases. The rated power of each feedback switch is very low in contrast to the high output power of the converter. Hence, power losses are minimal. The current injection results in high frequency modulation of input voltage of front-end converter and leads to conduction of three diodes at any instant of input phase voltage. The ac input current is the instantaneous sum of injected current and the front-end rectifier input current. During the injection period, the average value of the front-end rectifier current and the HF-injected current over the switching cycle varies over the supply frequency cycle.

Since the switching frequency is much higher than the supply frequency, the average value of these currents over the switching cycle can be treated as the instantaneous value of these currents over the supply frequency cycle. The peak-to peak value of current through L_f and peak value of current through the diode D_1 is same. As the capacitor C_f blocks the dc component of the injected current i_{inj}, the injected current is alternating. Further the operating waveforms show that diodes D_1, D_3 and D_5 remain in conduction for positive half-cycle of respective phases R, Y and B. While diodes D_4, D_6 and D_2 remain in conduction for negative half-cycle of respective phases R, Y and B. The conduction period of diode is 180 degrees. In positive half cycle of input phase voltage diode has two modes of conduction. For 120 degrees (from 30 to 90 degrees) input phase current and upper diode current are same. For remaining 60 degrees current is injected. Hence, diode carries high frequency current. Operating waveforms for other two phases can be studied on the similar basis. The three-phase full-bridge VSI is operated with sinusoidal pulse width modulation (SPWM) technique with reference waveform of 50 Hz and carrier frequency of 33 kHz.

Two operating modes are elaborated here. Other modes of operation can be understood on the same ground

A. Mode I – (0 to π/6)

During this period, diodes D_5, D_6 and D_1 are in conduction as mentioned in Fig..1. Out of these three diodes the diode D_1 carries HF current. This frequency is equal to switching frequency of VSI. When switch S_1 of VSI turns-on, the current through diode D_1 increases from 0 to its peak value I_{D1p}. Similarly, when switch S_4 of VSI turns-on, the current through D_1 decreases from its peak value I_{D1p} to 0. The peak value I_{D1p} of diode current varies in the envelope of input supply current. The peak current through the diode D_1 is same.

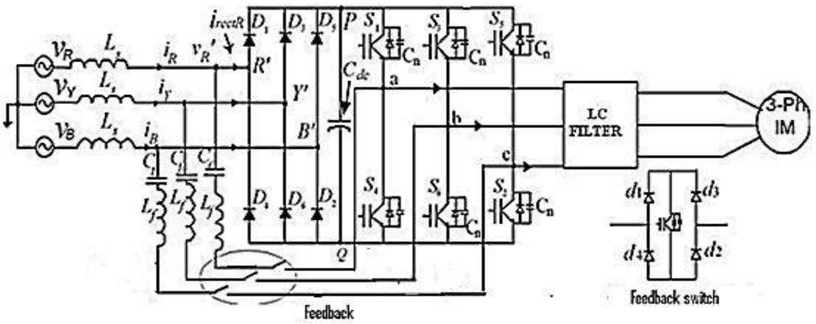

Fig 1. High-power factor front-end rectifier for VSI-fed AC drive

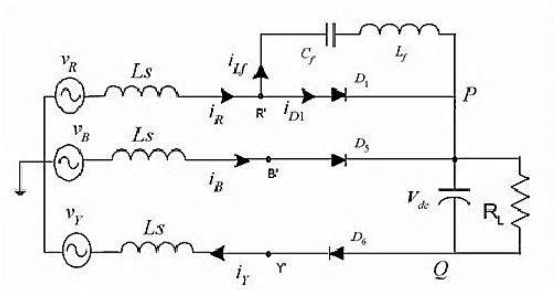

Fig 2 Equivalent Circuit of Front End Rectifier for Mode 1 When Switch S_1 of VSI is in Conduction

The negative half-cycle of current through L_f is carried by diodes d_3, d_4 and IGBT in the bidirectional feedback switch while current in positive half-cycle of L_f is carried by diodes d_1, d_2 and IGBT in the bidirectional feedback switch. For 'R' phase the input line current is instantaneous sum of the rectifier input current and injected current. While for other two phases ('B' and 'Y'), phase current and front-end rectifier current is same because during this period, there is no HF current injection.

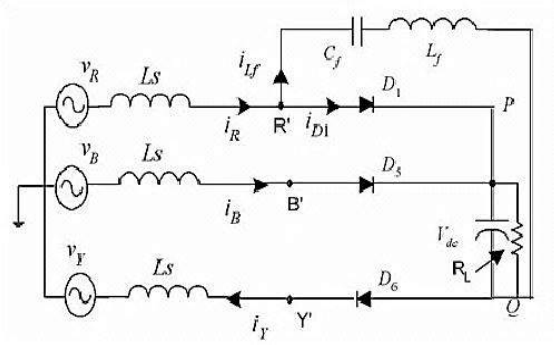

Fig 3 Equivalent Circuit of Front End Rectifier for Mode 1 When Switch S_4 of VSI is in Conduction

B. Mode II (π/6 to 2π/6)

During this mode, diodes D_1, D_6 and D_5 of the front-end rectifier are in conduction. In this mode, the diode D_5 has HF modulation of input voltage. Hence, when switch S_5 of VSI turns-on, the current through diode D_5 increases.

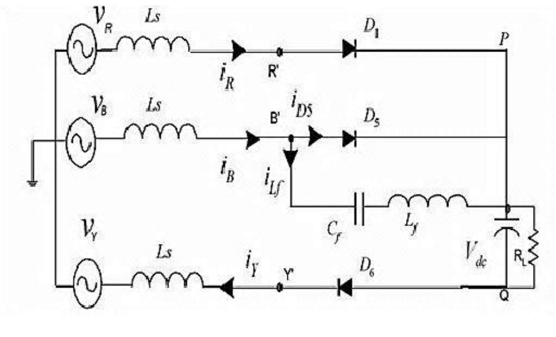

Fig 4 Equivalent Circuit of Front End Rectifier for Mode 2 When Switch S_5 of VSI is in Conduction

This diode current decreases when the switch S_2 of VSI turns-on. During this mode current injected in phase-R is zero. Hence, Input R phase current is same as input current of front-end rectifier. Whereas, for phase-B the input current is the instantaneous sum of the rectifier input current and injected current. The equivalent circuit of front end rectifier for this mode when switch $s_2$is in conduction is given below.

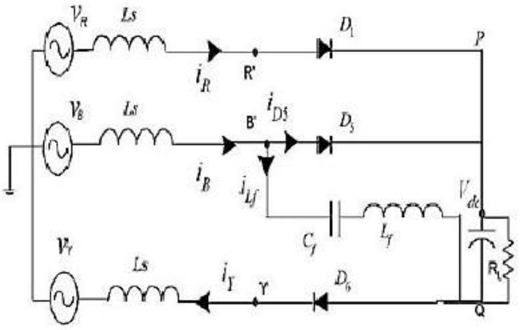

Fig 5 Equivalent Circuit of Front End Rectifier for Mode 2 When Switch S_2 of VSI is in Conduction

III. OPERATING WAVEFORM

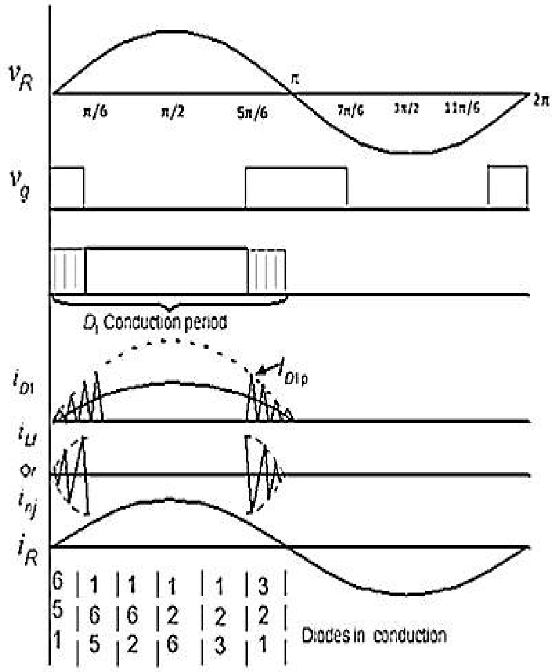

Fig. 6 Operating Waveform of the Proposed Rectifier

IV. ANALYSIS OF CONVERTER

The analysis of the converter and its design are explained below. The balanced three-phase ac input supply phase voltages are given by V_R, V_Y and V_B.

$$v_R = V_m \sin \omega t \tag{1}$$

$$v_Y = V_m \sin\left(\omega t - \frac{2\pi}{3}\right) \qquad (2)$$

$$v_B = V_m \sin\left(\omega t + \frac{2\pi}{3}\right) \qquad (3)$$

In the absence of a neutral connection to the front-end rectifier, the sum of ac input line currents must be equal to zero at any instant, that is

$$i_R + i_Y + i_B = 0 \qquad (4)$$

It also applies to the derivative of sum of the ac currents. The input line current is instantaneous sum of the rectifier input current and HF-injected current. Hence ac input line currents are given by

$$i_R = i_{LfR} + i_{\text{rect}R},\ i_Y = i_{LfY} + i_{\text{rect}Y},\ i_B = i_{LfB} + i_{\text{rect}B} \qquad (5)$$

Where i_{LfR}, i_{LfY} and i_{LfB} are the HF-injected currents (i_{inj}) and i_{rectR}, i_{rectY} and i_{rectB} are the input currents of the front-end diode bridge rectifier. Applying Kirchhoff's voltage law (KVL) to equivalent circuit shown in Fig.. 2.

$$v_R - v_Y = L_s\frac{\mathrm{d}i_R}{\mathrm{d}t} + L_s\frac{\mathrm{d}i_Y}{\mathrm{d}t} + V_{\text{dc}} \qquad (6)$$

$$v_R - v_B = L_s\frac{\mathrm{d}i_R}{\mathrm{d}t} - L_s\frac{\mathrm{d}i_B}{\mathrm{d}t} \qquad (7)$$

$$v_R' = v_R - L_s\frac{\mathrm{d}i_R}{\mathrm{d}t} \qquad (8)$$

The input line current through the source inductor, L_s is given by

$$i_R = \frac{1}{L_s}\int (v_R - v_R')\,\mathrm{d}t \qquad (9)$$

Where V_R is the actual voltage applied to front-end rectifier. HF-injected current produces HF modulation of input voltage. Solving equations (6) to (9), we obtain

$$\begin{aligned} v_R' &= V_{\text{dc}}/3 \\ v_Y' &= -2V_{\text{dc}}/3 \\ v_B' &= V_{\text{dc}}/3 \end{aligned} \qquad (10)$$

Since at any instant three diodes of the front-end rectifier are in conduction, this front-end rectifier now can be viewed as three-phase inverter operating in 180 degree conduction mode with input dc voltage as V_{dc} and output ac voltages as V'_R, V'_Y and V'_B. From (9), the input supply current i_R during $0<\theta< 2\pi/6$,

$$i_R = \int_{t_0}^{t} \frac{1}{L_s}\left(V_m \sin \omega t - \frac{V_{\text{dc}}}{3}\right)\mathrm{d}t \qquad (11)$$

$$i_R = -\frac{V_m}{\omega L_s}\cos \omega t - \frac{1}{3L_s}V_{\text{dc}} \cdot t + I_{R0} \qquad (12)$$

Where, I_{R0} is the initial value of current for this interval. Thus, instantaneous input phase current has two superimposed components first is sinusoidal component and second is ramp component because of dc excitation resulted from current injection in the front-end rectifier. The ac input line current through Ls contains HF current ripples. Small value of Ls is sufficient to suppress current ripples. This type of equations for the 'R'-phase current for remaining interval, that is, from 2π/6 to π are also obtained.

Then all these equations are solved to find the value of the input current at the end of each interval as the initial value for the next interval. Using the fact that when repetitive condition prevails, to satisfy the symmetry final value of current in last interval should be equal to negative value of current in the first interval, the expressions for current during various intervals of positive cycle of 'R' phase are derived.

$$pf = \cos\varphi = \frac{V'_{R1}\sin\alpha}{\sqrt{V_R^2 + V'^2_{R1} - 2\cdot V_R \cdot V'_{R1}\cos\alpha}} \qquad (13)$$

MATLAB programs are developed to observe the variation in power factor with respect to different parameters. The variation of power factor with respect to input power for various values of $\beta = V'_{R1}/V_R$ is studied when $\beta = 1$, high power factor can be obtained at a particular value of P_{in} and not for any value of P_{in}. β=1 maintains the high-power factor throughout the loading conditions, that is, at any value of P_{in}, with the selected value of X_{Ls}. Hence, β=1 is selected. The line voltage, rated output power and switching frequency of VSI are selected as base voltage, base power and base frequency, respectively, to calculate value of Ls. Hence power factor correction is done.

V. SIMULATION RESULTS

Digital simulation of the proposed converter is carried out using PSIM software package. With reference to data manual of this software, an interpolation technique is implemented which calculates the exact switching instants. With this technique, the error because of the misalignment of the switching instants and the discrete simulation points is significantly reduced. Input voltage and input current waveforms of the converter without HF current injection for 'R' phase are plotted in Fig.7. Fast Fourier transform (FFT) analysis of this waveform shows that THDi is 72% and power factor is 0.81. The waveforms of input phasevoltage and phase current of R-phase of the converter onfull load with current injection are given in Fig. 8. Fig. 9 shows the input current harmonic spectrum at rated power. The converter input power factor is found to be 0.99 and THDi 8%.

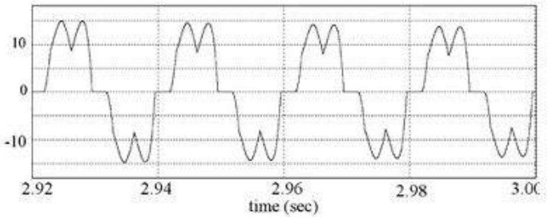

Fig 7. Input phase current of ‘R’ phase of the converter without HF current injection

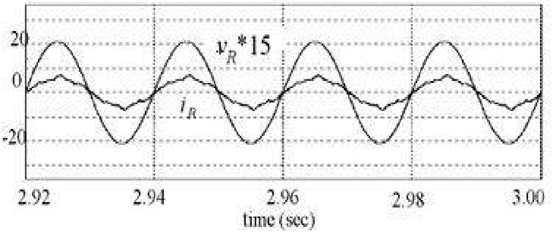

Fig 8. Input phase voltage and phase current of ‘R’ phase of the converter with HF current injection

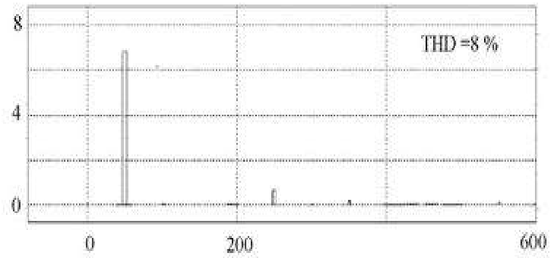

Fig 9. Harmonic spectrum of the input current with HF current injection

VI. EXPERIMENTAL RESULTS

The front-end rectifier input current before and after HF current injection is studied experimentally and shown in Figs. 10 and 11. Fig. 10 shows the input current before HF current injection, Fourier analysis of this current shows that it has high harmonic content hence poor THDi and power factor of 72% and 0.79 respectively. Input current waveforms with HF current injection are presented in Fig. 11. There is noticeable improvement in THDi and power factor when proposed HFcurrent injection scheme is implemented through bidirectional switches.These waveforms show that the injected current is bidirectional. This injected current is carried by bidirectional switch in feedback circuit. As clear from the equivalent circuits drawn in Fig. 3, diode current decreases when injected current increases and vise versa.HF current harmonics present in input line current because of vR′ are filtered out easily by placing small inductor in series with supply and harmonic free inputs are obtained as shown in Fig. 11.

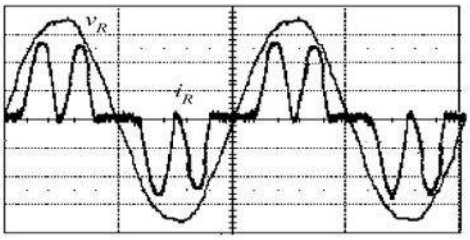

Fig 10. Experimental waveform of the converter without HF current injection Input current, scale: Y-axis : 100 V/div, 5 A/div.; X-axis: 10 ms/div

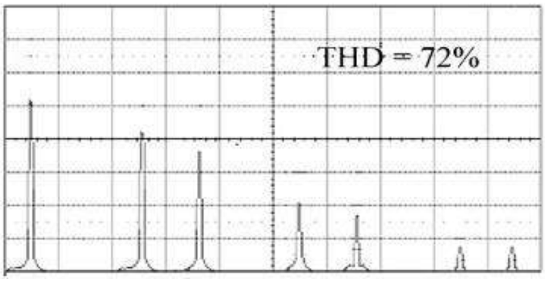

Fig 11. Experimental waveform of the converter without HF current injection Harmonic spectrum of the input current, scale: Y-axis: 2 A/div.; X-axis: 100 Hz/div

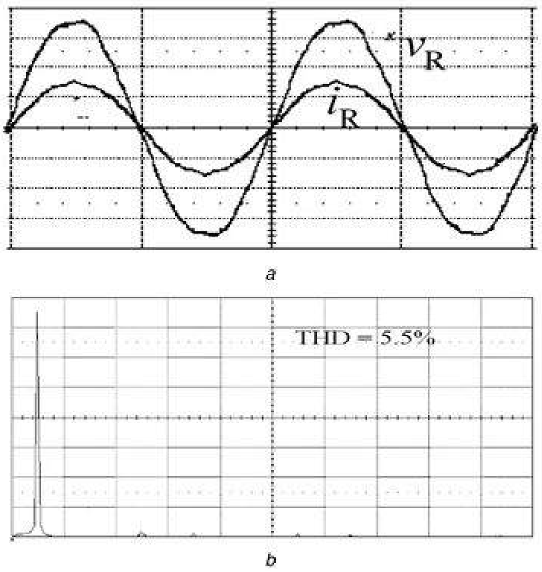

Fig 12 Experimental waveform of the converter with HF current injection

a.Input voltage and input current of ‘R’ phase, scale: Y-axis: 100 V/div.,5A/div.; X-axis: 10 ms/div

b. Harmonic spectrum of the input current, scale: Y-axis: 1 A/div.; X-axis: 100 Hz/div

Here the power losses in the converter are estimated. In PWM application, the IGBT current and duty cycle are constantly changing and makes loss estimation very difficult. Actual losses will depend on temperature, switching frequency, output current magnitude, modulating index and power factor.

VII. CONCLUSION

In this paper, high-power factor operation of front-end rectifier is presented. This is achieved by injecting HF current from output of VSI into the input of front-end rectifier through bidirectional switches. The gate pulses for feedback bidirectional controlled switches are generated at every zero-crossing instances of the respective phase voltages for the duration of p/6 rad. It is observed that gate pulse width duration of one-third of phase voltage period to feedback switches results in a remarkable improvement in THDi and power factor. The feedback switches process current only for one-third period of the input voltage. In addition to less time period of conduction, the magnitude of current processed by the feedback switches is also less. Hence, power losses in feedback circuit are less. All the input line current waveforms are very clean, in phase with respective phase voltages. Substantial reduction in line current harmonics is noticed in FFT analysis of the current waveform. The HF ripples present in input line current of the converter because of HF modulation voltage is filtered out by small inductor in series with the source. In these days, because of advances and availability of power semiconductor devices, to reduce bulky and expensivepassive elements is much more significant than to reduce active elements in terms of size and cost effectiveness. The proposed bidirectional controlled switch along with DSP-based controller is expected to be a good power factor connection retrofit to the front-end rectifiers of existing ac drives without any filter. There is a good agreement between the simulated and experimental results.

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