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Reverse Harmonic Injected High Power Square Wave Inverter Fed Induction Motor

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Abstract - In past decades, a simple L-C filter can reduce harmonics for low power inverters, for medium and high power applications the size of L-C filter is bigger, Latter Pulse Width Modulation (PWM) techniques are implemented for medium power, but these are limited by the switching losses with high operating frequency. The limitation of PWM can be overcome by Multi Level Inverter (MLI). Again these MLI are fed by separate DC sources, which are operated at fundamental frequency, the design and control are complex with the increase in number of levels. In this paper, a power frequency square wave VSI with series compensators is fed for high power Induction Motor Drive. The series compensators produce voltages at harmonic frequencies and are injected in reverse direction; the net effect causes pure sinusoidal waveform. The DC bus voltages required for series compensators are less in magnitude and operated at harmonic frequency. This strategy improves the conversion efficiency of square wave VSI. The compensators used are of single phase H-Bridge inverters with high frequency switches (IGBT).

Index Terms - Induction Motor, Series Compensators, Harmonic Voltages, High Power Square Wave.

I. INTRODUCTION

The Voltage Source Inverter (VSI) fed induction machine drive systems have many advantages such as a rugged and low cost rotor structure, capability of high waveform fidelity with Pulse Width Modulation (PWM) operation, reasonably high performance, etc. However, their applications are still limited to the lower end of the high-power range due to the limitations on the ratings of the gate-turn-off type semiconductor power devices. To achieve high power applications [1] in such systems, multi-level inverters [2] have been developed in the past decade as a promising approach. Another strong contender in achieving high power is by improving the conversion efficiency. In the case of multi Level Inverters Economic factor will be low and high complexity and input voltage for each individual H-bridge [3] requires a separate DC source at fundamental frequency.

An important factor in industrial progress during the past five decades has been the increasing sophistication of factory automation which has improved productivity many-fold. Manufacturing lines typically involve a variety of variable speed motor drives which serve to power conveyor belts, robot arms, overhead cranes, steel process lines, paper mills, and plastic and fiber processing lines to name only a few.

Prior to the 1950's all such applications required the use of a DC motor drive since AC motors were not capable of smoothly varying speed since they inherently operated synchronously or nearly synchronously with the frequency of electrical input. To a large extent, these applications are now serviced by what can be called general-purpose AC drives [4-5] In general, such AC drives often feature a cost advantage over their DC counterparts and, in addition, offer lower maintenance, smaller motor size, and improved reliability High performance applications typically require a high-speed holding accuracy better than 0.25%, a wide speed range of at least 20:1 and fast transient response, typically better than 50 rad / s, for the speed loop.

In this paper, the series compensators [6] are connected in each phase, to produce harmonic voltages'. These voltages are injected in reverse direction at each phase to generate pure sinusoidal voltage. These compensators require the magnitude of voltage with a dividing factor of harmonic number of nominal DC voltage. So as compared to the Multi Level Inverters the propose converters are less complex and economical. The newly presented Elimination of Harmonics in a Square-wave inverter [7] by using series compensators for high power applications has some unique features and it can overcome some of these limitations. The purpose of this work is to elimination of harmonics in square wave inverter for high power application.

II. FUNDAMENTAL OF PROPOSED INVERTER TOPOLOGY

The proposed topology has evolved from the typical series compensating devices like the Unified Power Quality Conditioner (UPQC), Digital Video Recorder (DVR), etc. Fig.1 shows the basic converter topology of voltage source inverter fed induction machine drive. The main square-wave inverter is solely responsible for the fundamental voltage .In each phase a single-phase series-connected PWM inverter [8] that produces only the required harmonic voltages as shown in Fig.1.

The single-phase harmonic cells in each phase normally have common DC bus voltage. Usually, the value of this common DC bus voltage is less than that of the main 3-phase square-wave voltage source inverter. This justifies the PWM mode of operation of the series compensators. The common bus DC voltage is generated separately for each harmonic cell operated at harmonic frequency.

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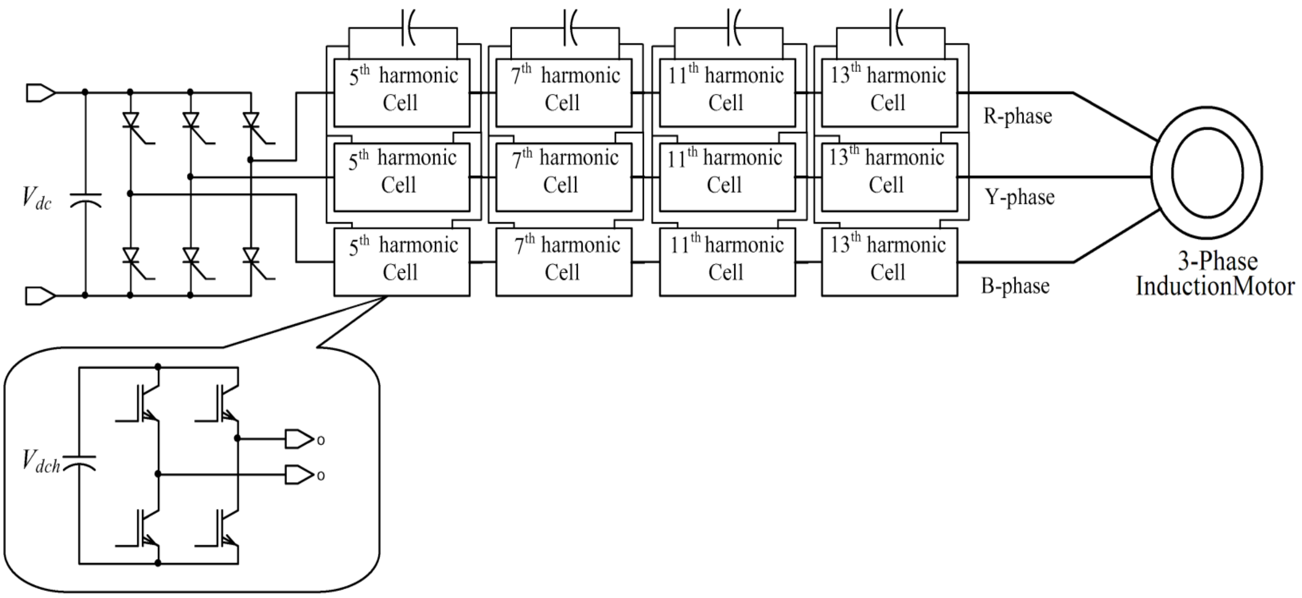

Fig.1 Basic Converter Topology of Voltage Source Inverter fed Induction Machine Drive

Alternatively, a small amount of controlled active power has to be drawn by the series compensator to control this DC bus voltage .The desired harmonic voltages are injected reverse direction to the line, as shown in Fig.1.

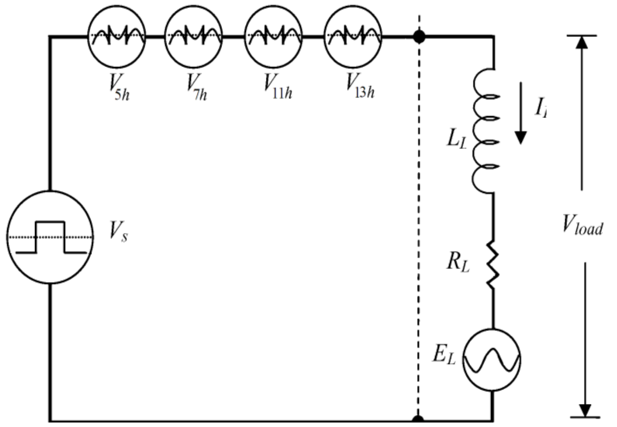

Fig.2 Equivalent Single-Phase Circuit of Proposed Converter with Load.

A per-phase equivalent circuit of this proposed system (Fig.1) is shown in Fig. 2. The load is a motor with equivalent leakage impedance R_L, L_L, and the sinusoidal back EMF E_L at fundamental frequency. The square wave voltage alternatively varies with $+V_{dc}/2$ to $-V_{dc}/2$ with a time period of $2\pi/\acute{\omega}_f$. Here V_{dc} is the DC bus voltage and $\acute{\omega}_f$ is the fundamental frequency of square wave VSI.

Let us assume that the modulation depth (m) of the n^{th} harmonic component of the series compensator is as follows:

$$m = \frac{4}{n\pi} \qquad (1)$$

n^{th} harmonic output component of series compensator can be defined as:

$$V_{nh}(t) = mV_{dch}(t)\sin(n\omega_f t) = \frac{4V_{dch}(t)}{n\pi}\sin(n\omega_f t) \qquad (2)$$

Here $V_{dch}(t)$ Dc bus voltage of series compensator at any time '*t*'. Modulation depth "m" is taken as 1 for all series compensators. After perfect compensation the load voltage containing only higher order harmonics and small switching harmonics in the series compensators itself, Assuming that the dynamics of $V_{dch}(t)$ is very slow, the average active power (P_{nh}) absorbed [9] by the series compensator due to the n^{th} harmonic voltage is as follows:

$$P_{nh} = \frac{1}{2}\left(\frac{4}{n\pi}\right)^2 \frac{\left(V_{dc}/2 - V_{dch}(t)\right)V_{dch}(t)R_L}{R_L^2 + \left(n\omega_f L_L\right)^2} \qquad (3)$$

It is to be noted that all the triplen harmonics (3,6,9…) will not contribute any power since there is no natural connection in square wave VSI. Neglecting losses of DC bus capacitor, the dynamical equation of $V_{dch}(t)$ can now be written as follows:

$$3\sum_{n=5}^{\infty} P_{nh} = V_{dch}(t)C_h \frac{dV_{dch}(t)}{dt} \qquad (4)$$

Here C_h is the total DC bus capacitance of series compensator and Fundamental load current does not affect the DC bus voltage balance as there is no fundamental component of voltage at the output of the series compensator [4].

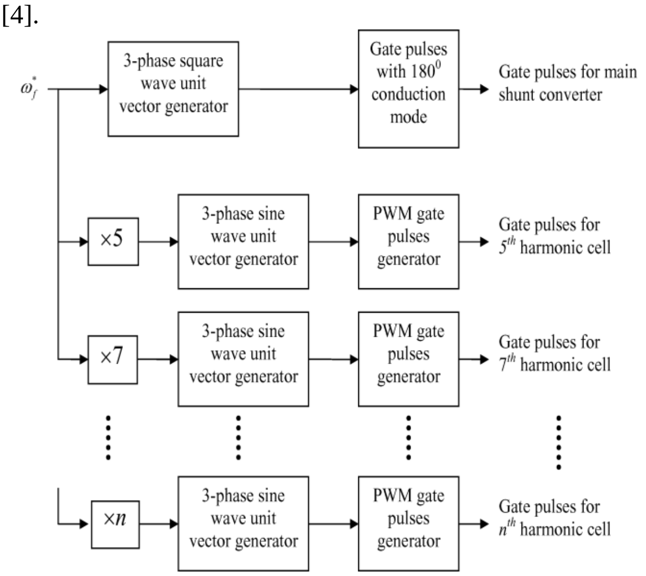

Fig.3 Gate pulses generation for the basic converter topology (Fig.1)

The block diagram of basic switching control strategy for the topology is shown in Fig. 3.

III. PRACTICAL ISSUES OF SERIES COMPENSATOR

In the earlier section, it is assumed to have zero losses in series compensator, however the practical series compensator has switching and conduction losses [10]. In steady state, the series compensator current is mostly dominated by the fundamental component of current, I_S sin (ω_f t) which is shown in Fig. 4. In this equivalent circuit, V_{CE}(sat) (or V_F) drop of the IGBT switches can be approximately represented by a square-wave voltage signal whose fundamental frequency is same as that of the series compensator current. Fig. 4 represents approximate equivalent circuit of each harmonic cell.

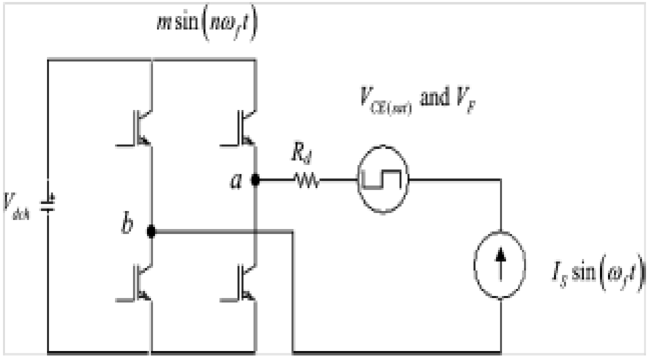

Fig.4 Equivalent circuit of each harmonic cell for estimation of loss.

The square-wave voltage represented is also in phase with the series compensator current I_S sin (ω_f t). In case of a MOSFET-based compensator, the drain resistances (R_d) can be represented as shown in Fig. 4. Due to this, small active power shares the switching losses of the compensator. Depending upon the device switching characteristics, the compensator DC bus V_{dch} also shares the switching losses. Moreover, half of the total switching per fundamental cycle ($1/\omega_f$) is soft switching which is represented as Zero Voltage Switching (ZVS) [11].

IV. RESULTS

A fixed DC bus voltage of 4400V is applied to the proposed converter topology as shown in Fig.1 and is operated in 180^0 conduction mode. The PWM Switching frequency for the series compensator is 5KHZ. In order to investigate the performance of the proposed converter, the converter is connected to a 60KVA, 5.6KV, 50HZ, 3-phase Squirrel Cage Induction Motor which is modeled in SIMULINK. The fundamental frequency of the proposed converter is varied up to 1KHZ for speed control. The DC bus voltages of series compensator are tabulated in Table 1.

TABLE 1. SERIES COMPENSATOR FREQUENCIES AND DC BUS VOLTAGES.

parameter	fundamental	5^{th} harmonic cell	7^{th} harmonic cell	11^{th} harmonic cell	13^{th} harmonic cell
Frequency (Hz)	50	250	350	550	650
DC Bus Voltage (V)	5600	1100	790	500	420

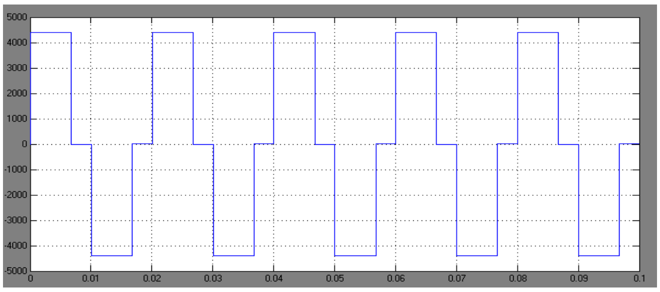

Fig.5 Output of basic 3-phase square wave Voltage Source Inverter.

3-phase square wave VSI voltage waveform in r-phase is shown in Fig. 5.

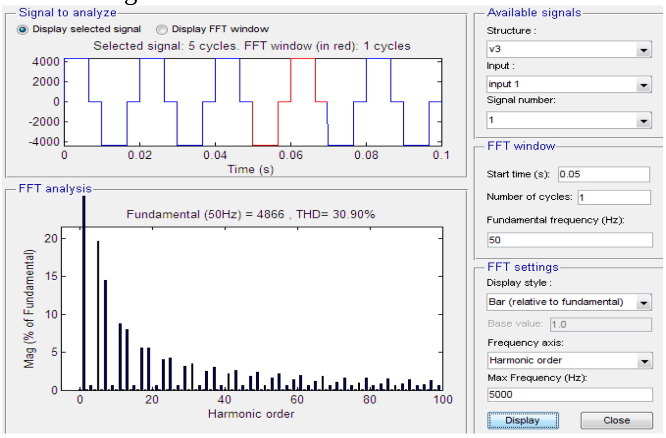

Fig. 6 Harmonic Spectra of quasi square wave output of 3-phase square wave VSI

Fig.6. shows the FFT analysis of quasi-square wave output of 3-phase VSI. The Total Harmonic Distortion (THD) is 30.9%

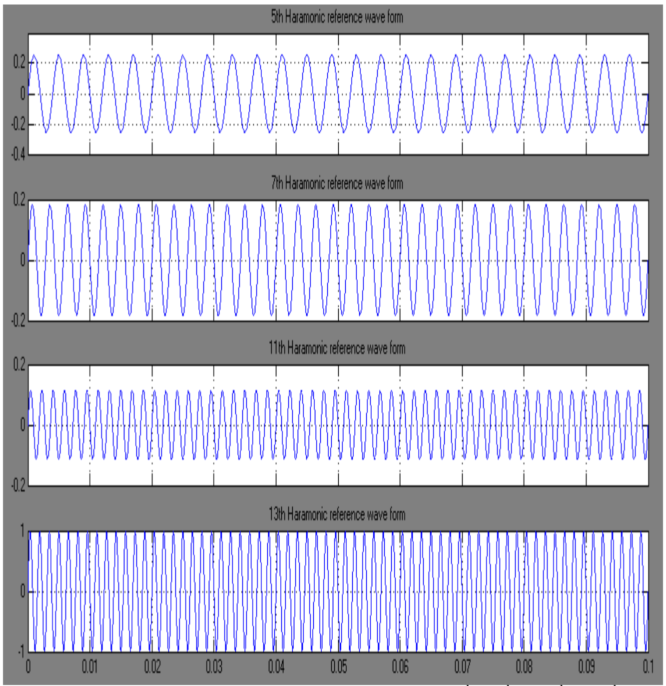

Fig.7 Reference voltage wave form for 5^{th}, 7^{th}, 11^{th}, 13^{th} harmonic cells

Fig.7. shows the reference input voltage wave form for 5^{th}, 7^{th}, 11^{th}, 13^{th} harmonic cells respectively. Fig.8. shows the PWM output wave forms of 5^{th} harmonic cell.

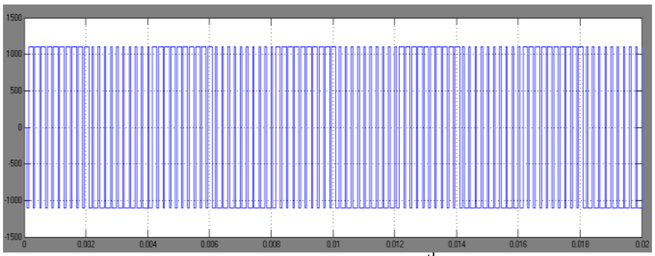

Fig.8 PWM output wave form of 5th harmonic cell

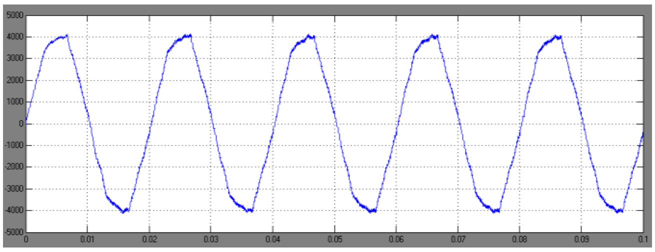

Fig.9 Load voltage in steady state

Fig. 9 shows the load voltage waveform in steady state condition.

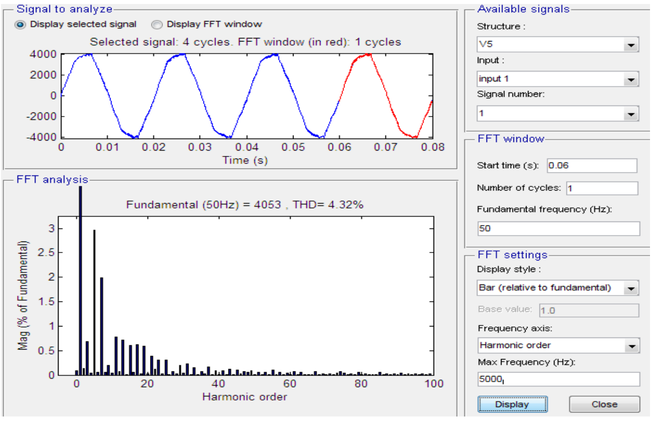

Fig. 10 Output voltage THD

The spectrum analysis of the output voltage with THD of 4.32% is shown in Fig. 10

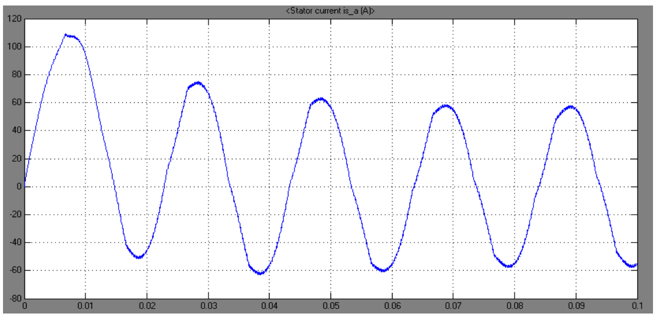

Fig.11 Stator current of Induction Motor

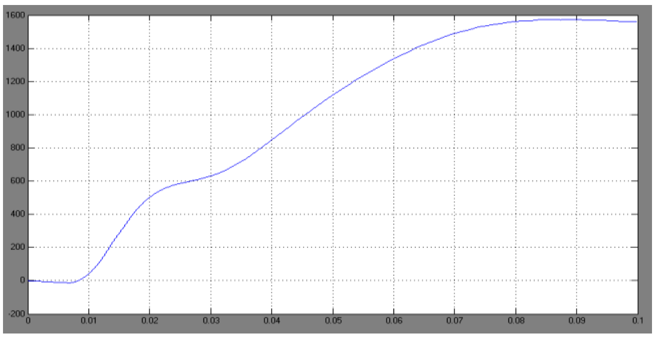

Fig.12 Speed curve of Induction Motor

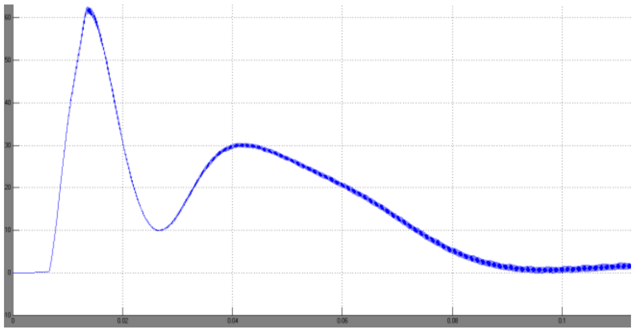

Fig.13 Electromagnetic Torque characteristics of Induction Motor.

The stator current, speed curve and electromagnetic torque characteristics of the Induction motor which is connected to the system are shown in Fig. 11, 12 and 13 respectively.

V. CONCLUSIONS

In this paper, an open-loop natural control of voltage source inverter has been proposed mainly for high-voltage, high power applications. The main square-wave inverter is built with high-voltage low switching- frequency semiconductor devices like Integrated Gate Commutated Thyristors (IGCTs). The series compensators are IGBT (Isolated Gate Bipolar Transistors) based inverters. The series compensators produce only the desired harmonic voltages to make the net output voltage sinusoidal. For high-voltage application, several compensating PWM (Pulse Width Modulation) inverters are connected in series. Each cell compensates one particular harmonic only; as the order of harmonics increases, the required DC bus voltage level drops. This enables to exploit higher switching frequency for higher order harmonic cell. For variable-speed drives applications, the magnitude of the fundamental output voltage should be controlled by regulating the DC bus voltage of the square-wave inverter.

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