Design considerations of Traction converter for three phase AC locomotive

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Abstract- This paper presents some of the important design issues of traction converter for three phase AC locomotive. The analytical approach is required to select appropriate components which will make the system more reliable, stable with minimum power loss. The mathematical approach required in the design of each component is presented. The main components of TC such as IGBTs, Driver circuit, heat sink, precharging resistor, DC link capacitor, resonant filter, bleeder resistors, earth fault resistors, braking chopper are discussed in this paper. The behavior of each component under variation in power supply and supply frequency are discussed. The analysis presented in this paper is very much useful for a designer while designing a converter inverter system for a vehicular system. The control strategy adopted for front end converter is discussed and simulated results using PSIM is also presented.

Keywords: Traction converter, Inverter, DC link, Resonant, PSIM.

I. Introduction

The traction drives consists of power electronic have become more complex over the past decades due to the advancement of high power and high speed semiconductors such as IGBT, IGCT, microprocessor control and three phase inverter drives . Now a day it is common to operate 3 phase induction motor drives with traction electric multiple unit and locomotive. The three phase induction motor drive provides an improved in the overall performance of electric traction equipment. With the ability to increase the level of the available power, the train operator has been able to improve train operating times, the speed of the traction unit and the demand on the power supply system. With the introduction of inverter drives it has become necessary to complete systems approach to ensure the safe operation of electrification infrastructure, critical areas of train telecommunications and the safety signaling.

Single-Phase AC-DC boost converters with bi -directional power flow capability is widely used in variable speed drives for traction application [1]. With proper control technique, IGBT based AC-DC boost converters provide high power quality in terms of high power factor, well-regulated dc output voltage, low total harmonic distortion (THD) and fast response when compared with conventional converters [2]. These converters are also used in other applications such as battery energy storage system for load levelling, UPS, battery charger, power conditioning. IGBTs with PWM technology are normally used in these converters for medium power and low frequency applications [3]. The advancement in control technology of the boost AC-DC converters makes it cost effective, reliable, compact due to revolution in microelectronics [4]. High speed digital signal processors (DSP) are available at reasonably low cost to provide direct PWM signals with fast software algorithms which considerably reduces the hardware [5].

A further challenge for the system was to achieve good dynamic response under continuous conduction mode regardless of the converters high boost ratio and low switching frequency. With the development of digital technology, power electronics converters have recurrently digital control system, executed by the microprocessors or digital signal processors (DSPs) based systems [6].

For real time control of the converters which can be implemented by improved algorithms with dedicated processors should provide fast dynamic response. Both the conventional PI controller and PR (Proportional-Resonant)controller have been employed in the control of these converters. It is important to observe that the controller provides high quality sinusoidal output with minimum distortion to avoid generating harmonics [5]-[8]. The current controllers play a significant role to maintain the quality of current supplied. Two controllers which have been used in current controller are conventional PI controller and PR controller. The proposed PR control scheme is capable of tracking a sinusoidal line current reference without an additional prediction or complex control algorithm at a low switching frequency of 750Hz.The voltage controller was also implemented to maintain the DC link voltage at desired voltage level.

This paper presents the design and control for 3.7 kW AC-DC boost traction converter system that boost a nominal 230V AC to regulated 560V DC link voltage. The response of these controllers are compared and presented. The controller performance is tested with fluctuations in AC supply as typical operating condition for this type of systems at different load levels.

II. Traction Converter

The general circuit diagram of a traction converter is shown in Fig.1. It consists of a front end converter which is connected to the supply line side and a voltage source inverter (VSI) which drives the motor directly. To increase the power capacity, stability, to reduce harmonics at the input line side and to achieve unit power factor more number of converters can be connected in parallel. Generally for this application converters are controlled by PWM technique. In PWM converters which consists of high speed switching device like IGBT can obtain unit power factor by controlling converter input voltage. Different ratings of IGBTs are available upto 1500A, 4500V. Therefore based on the application IGBTs can be selected with current and voltage ratings. Similarly these IGBTs require Gate driver circuit which should provide a voltage of +/- 20V at gate terminal. Proper heat sink should be selected for cooling purpose so as to maintain the allowable temperature rise. Water cooled heat sinks are generally preferred for high power application.

The front end converter is powered from secondary winding of a main transformer and the inverter drives a traction motor. The FEC converts ac power from a secondary winding of main transformer to regulated dc power. The output dc power of the converter unit is fed to inverter units to drive a traction motor. The inverter unit (VVVF inverter) converts dc power from converter unit to three-phase ac power of adequate voltage and frequency, to control a traction motor. The converter and inverter are designed for the maximum voltage to load during starting as well as the maximum power output of the traction motor running in power mode and in regenerative braking mode. Suitable over- current/over-voltage protections for IGBT elements and power circuits are provided.

The electric brake is regenerative brake. In the electric brake mode, the generated power by traction motors in generator mode is fed back to the catenary by the VVVF inverters and the PWM converters.

The front end AC-DC boost converter can be designed with different topologies depending upon the number of switches, dc link capacitors, locations of inductors, hard or soft switching capability, presence of isolation and operating mode. For traction application as power rating increases, converters are connected in parallel to reduce harmonics at input and output side of the converter. These converters offer the advantages of low voltage stress on the switches, reduced losses at reduced switching frequency for same level of performance in terms of reduced harmonics and high power-factor at input AC mains and regulated ripple free DC output voltage at varying loads. IGBTs are most suitable device for front end converter as well as voltage source inverter. The 3-phase inverter consists of six IGBTs with anti parallel diodes. The other components which requires more careful attention are design of DC link capacitor, resonant filter circuit, braking chopper, precharging circuit, over voltage protection, earth fault detector, cooling system. Each of these components design approach is discussed in this paper.

The design of the traction converter is very important for reliable operation of the drive especially when the supply AC source is fluctuating. Some of the important component designs are presented in this section.
Here the motor is of 3.7kW, 415V, 8A, 1300 RPM
So the DC link voltage must be 415*√2 = 586V
DC LINK CAPACITOR
Output power of one motor = 3.7 kW
By considering inverter and motor efficiency = 0.92
Input power to inverter = 4.02 kW
DC link current = 6.86A
If the supply frequency is 50 Hz, then a ripple voltage of twice the supply frequency will appear at the DC link side. Therefore,
Ripple Frequency = 100Hz
For peak-peak ripple voltage (ΔV) = 5V
Dc link capacitance, $C = I/\omega\Delta V$ (1)
$= 6.86/2*3.14*100*5$
$= 2.2$ mF

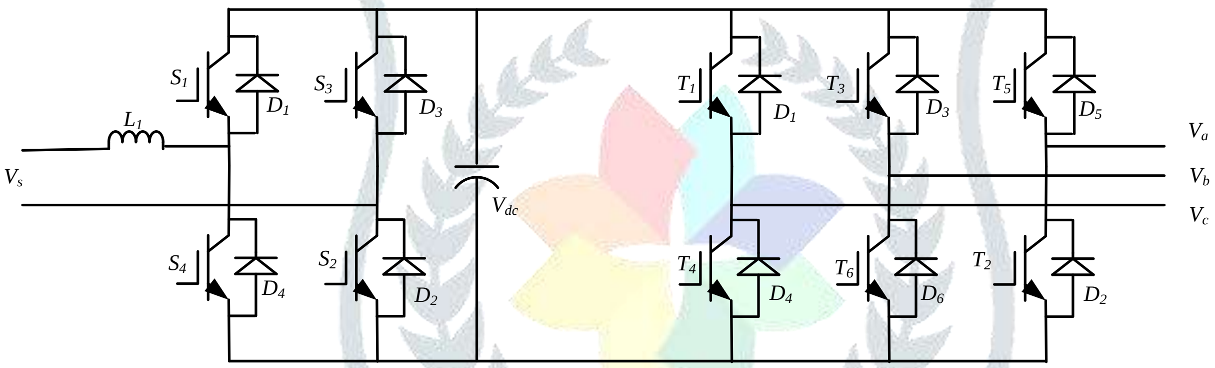

Fig.1. IGBT based Traction converter.

LC resonating circuit

AC-DC converter injects current harmonics to DC side. The second harmonic is the most important because its wide amplitude is almost independent of the modulation technique. to reduce its effect on output voltage, resonant filter LC is used. The higher order harmonics are filtered by capacitor C. therefore amplitude of each voltage harmonics is proportional to the current harmonics. The resonant circuit buffers out the periodic pulsations of the line current at double the line frequency. The periodic pulsation occurs because the fundamental power in a symmetrically loaded three phase induction motor. By connecting LC circuit with DC link capacitor C it is suitable to reduce the voltage harmonics on converter output voltage. LC resonate to a frequency equal to double of the supply frequency. The resonant filter values can be obtained from the following equation.

$$C_r = \frac{1}{\omega^2 L} \quad (2)$$

Braking resistor with braking chopper

It helps in conversion of braking energy into heat for drives with quick speed variations without the use of additional electronics. It should be compact in construction, high load rating, very high short-time rating, and increased power by forced cooling and good corrosion resistance. The following equation used to find the value of braking resistor

$$R_b = \frac{V_{dc}}{I_b} \tag{3}$$

Figure 1shows the circuit diagram of two parallel operated single-phase AC-DC PWM boost converters. Each converter consists of four IGBT switches with anti-parallel diodes to produce a controlled DC voltage across DC link.These converters are normally controlled in unipolar PWM mode for reduced size of AC inductor with double frequency ripples. The input ac side has an inductance for boost operation and the output dc side has a single common capacitor of large value for smoothing the dc bus voltage. An inductive load has been connected in dc side. For appropriate operation of this converter, the output voltage must be greater than the input voltage, at any time.

The main features of PWM rectifiers are [9]:
• Nearly sinusoidal input current,
• Regulation of input power factor to unity,
• Low harmonic distortion of line current
• Adjustment and stabilization of DC link voltage (or current),
• Reduced capacitor (or inductor) size due to the continuous current,
• Properly operated under line voltage distortion andline frequency variations.
• Bi-directional power flow.

The inductor voltage can be expressed as

$$v_L = L\frac{di_s}{dt} = v_s(t) - KV_o \tag{4}$$

From Equation (1), when K=1, the inductor voltage will be negative and thus the input current will decrease. When K= -1, the inductor voltage will become positive and input current will increase. Finally, if K = 0 the input current increase or decrease its value depending of V_s. This allows for a complete control of the input current.

If condition $V_o > V_s$ is not satisfied, for example during start up, the input current cannot be controlled and the capacitor will be charged through the diodes to the peak value of the source voltage (V_s) as a typical non controlled rectifier. After that, the converter will start working in controlled mode increasing the output voltage $V_o$to the reference value.

The value of AC side boost inductor Ls and DC link capacitor are designed based on the input supply voltage, DC link voltage level and switching frequency.

The value of L_s and C are obtained as

Ls = 25mH
C = 2.2mF

The inductor parasitic resistance is taken as 10mΩ.

III. Simulation and analysis of FEC.

The objective of overall control scheme is to improve power quality in terms of high power factor at the input side of the converter, well-regulated DC output voltage as well as reduced harmonics in AC mains currents. The controllers are tested at varying load condition, fluctuating AC source voltage and step DC link voltage.

The control algorithm of AC to DC parallel traction converters is shown in Fig. 2. The control includes a PLL (Phase Locked Loop), DC link voltage controller and two current controllers. The PLL generates the input supply voltage angle θ_s. This voltage angle is required for transforming αβ quantities into dq quantities and vice versa. This voltage angle is also required to make supply current in-phase with the supply voltage. Moreover, a PLL algorithm synchronises the supply current with the supply voltage.

The DC voltage controller is typically a proportional–integral (PI) controller, which controls the amount of power required to maintain the actual DC-link voltage at its reference value. The DC voltage controller delivers the amplitude of active component of the input current i.e the reference d-axis current. The reference q-axis current is taken as zero to make power factor as unity at converter input side. [10]

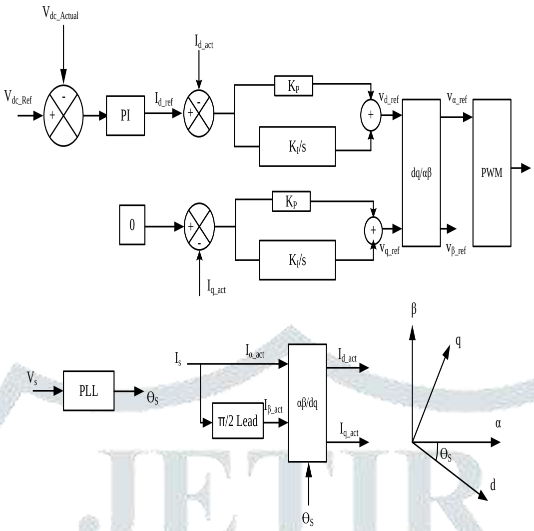

Fig.2. *dq*-model based Controller implementation for PWM converter.

The current controllers keep the actual currents at their reference value. These current controllers generate the reference voltage signals required for the PWM of each converter. Here, dq-theory based current controller is used. In this, first actual currents are converted into $\alpha\beta$ frame, then after $\alpha\beta$-currents are transformed into *dq*-currents. These actual *dq*-currents are compared with the reference *dq* currents and the errors are given to PI controllers. These PI controllers generates the reference dq-voltages. The *dq*-voltages are again transformed into $\alpha\beta$ frame. α-axis voltages are the reference voltage signals. These signals are given as input to the PWM generator to generate switching signals for both converters.

In a single phase system, the reference current is a 50Hz AC sinusoidal signal. For single phase PWM rectifier high band width current controller is required to accommodate 50Hz reference signal. Due to limited switching frequency, sampling effect, quantizing effect high gain may cause instability. Therefore, the current bandwidth cannot be easily extended. Even though the bandwidth is larger than 50Hz, a significant amount of phase delay results in tracking the sinusoidal reference signal. This problem can be easily overcome by using resonant control method. [12]

TABLE-1

Supply voltage	230V AC (nominal)
DC Link Voltage	586V DC
Boost Inductor, Ls	25mH
Inductor Parasitic Resistance	10mΩ
DC link Capacitor	2.2mF
Load - RL	53Ω, 35mH
Switching Frequency	750Hz

IV. Simulation Results

This section demonstrates the superiority of PR controller over PI controller used in this model through simulation results using PSIM software. The parameters used in this model are shown in Table-1. Two converters are controlled in parallel to achieve nearly unity power factor at the input side of the converters and desired DC link voltage without any steady state error. The inner current control loops for these converters are designed with PR whereas the outer DC link voltage loop is designed with PI controller. The simulation results show that PR controller tracks the sinusoidal reference with all waveforms are in phase. PR controller also mitigates the harmonics better than PI controller. Fig. 3 show the response of current controllers when load changes from RL (R=52Ω, L=35mH) to half of the load. It is observed from the simulation result that input voltage and current waveforms are in phase with PR controller. Fig.4 show the converter input current and voltage waveform when DC link voltage change from 500V to 600V. with PR controller any change in DC link voltage does not affect the controller performance and it maintains the voltage and current waveforms are in phase as shown in Fig.4.

Next case is considered with fluctuation in supply voltage V_s from rated 230V to 325V occasionally. This change clearly affects the controller performance as shown in Fig 5 and this supply voltage fluctuation does not affect in case of PR controller as shown.

The disturbances in the dc link voltage signal caused by change in load, fluctuation in supply voltage and variation in dc link reference voltage is more with PI controller than PR controller as shown in Fig 6 respectively. Performance for disturbance rejection is better with PR controller than PI controller.

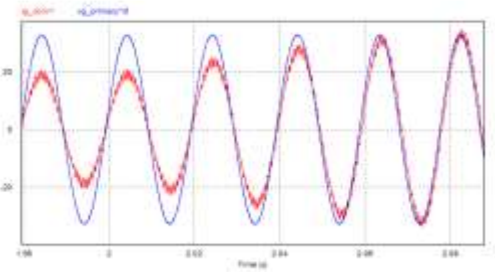

Fig. 3 During load change at t=2 sec.(PI)

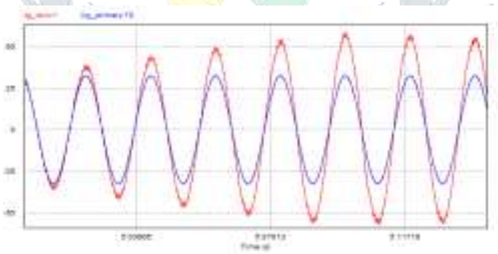

Fig.4. During change in DC link voltage from 500v to 600v.

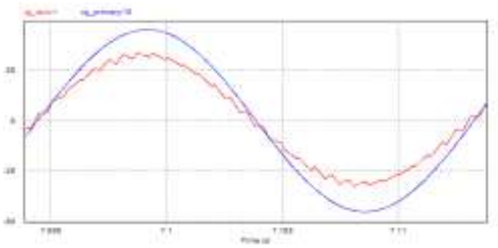

Fig 5. Vs changed from 230 to 325

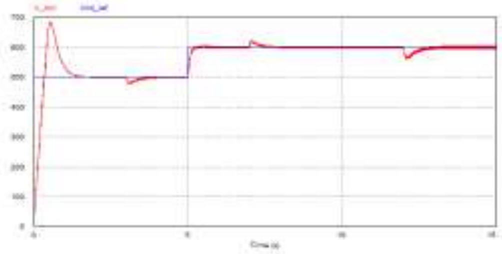

Fig.6 DC link voltage control loop response with PR current control loop.

V. Conclusion

Some of the important hardware design of a traction converter system with constant switching frequency is presented in this paper. Also simulation of front end converter for maintaining sinusoidal input current at unity power factor under wide range of load variation, supply voltage fluctuation and DC link variation are also presented. It is shown that the limitations associated with PI controllers like maintaining unity power factor, disturbance rejection under different operating conditions can be alleviated. The proposed PR controller also provides solutions for the drawbacks associated with conventional PI controllers that have slow dynamics and high distortion in the control feedback signal. Also implementation of control algorithm is much easier with PR controller.

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