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Design and Control of Active Front End Converters for Traction Application

Dr. Premananda Pany

Synergy Institute of Engineering & Technology, Dhenkanal, Odisha, India
Email ID: pnpany[at]gmail.com

Abstract: ***Supply Line disturbances, harmonics in line current, low power factor to electric power system are some of the common problems in traction power supply system. In order to overcome these problems a control structure is proposed which consists of dc link voltage controller and proportional resonant (PR) current controller using phase angle estimator. Current controllers are designed using PR controller to overcome the limitations of PI controller such as steady state errors, limited disturbance rejection capability and unsatisfactorily performance under parameters variations, nonlinearities etc. The simulations are carried out with both PR and DQ model-based controllers and comparative results have been presented. The simulation is carried out in PSIM environment and the results demonstrate fast response and improved power quality in terms of reduced harmonics in AC mains current, high power factor and well-regulated DC output voltage. This model can easily be adopted in the actual system while reducing the overall complexity in design and control of the existing system***.

Keywords: Single phase AC-DC boost converter, proportional resonant (PR), DQ model-based controller, PSIM

1. Introduction

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 boosts 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 main drawback associated with PI controller is that it is unable to maintain the unit power factor during load change and the steady state error which occurs due to the dynamics involved in integral term. The simplified circuit configuration of the traction converter system is presented is Section II. The analysis of control strategies using PI and PR controller is presented in Section III. Section IV presents the simulation results and discussion. The controller performance is tested with fluctuations in AC supply as typical operating condition for this type of systems at different load levels.

2. AC-DC Parallel Traction Converter

AC-DC boost converters can be designed with different topologies depending upon the number of switches, dc link capacitors, locations of inductors, hard or soft switching capability, and 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.

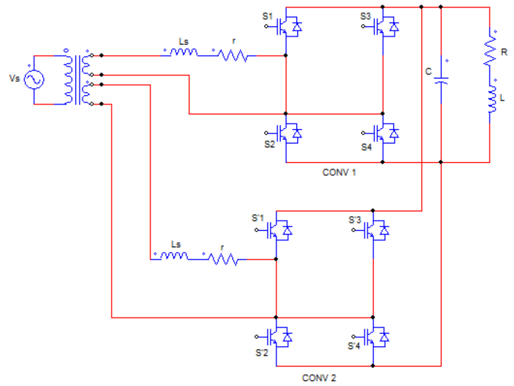

Figure 1: Block diagram of AC to DC parallel traction converters

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

$$v_L = L\frac{di_s}{dt} = v_s(t) - KV_o \quad (1)$$

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.

3. Analysis of PI and PR Controller

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.

PI Controller

The control algorithm of AC to DC parallel traction converters is shown in Figure 2. The control includes a PLL (Phase Locked Loop), DC link voltage controller and two current controllers. The PLL generates the input supply voltage angleθ_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]

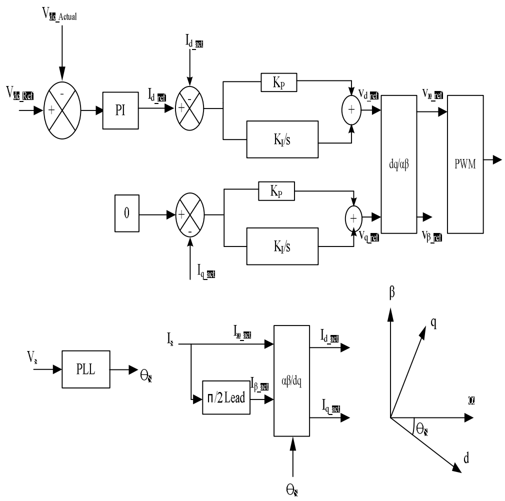

Figure 2: dq-model based Controller implementation for PWM converter

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 αβ frame, then after αβ-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 generate the reference dq-voltages. The dq-voltages are again transformed into αβ 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.

PR controller

The control structure with proportional resonant (PR) controller for AC-DC parallel traction converters is shown in Figure 3. The control includes a PLL (Phase Locked Loop), DC link voltage controller and two PR current controllers. The PLL generates the input supply voltage angles for each converter [11]. This voltage angle is required to make supply current in-phase with the supply voltage.

The DC voltage controller is typically a proportional–integrative (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. To share the active power equally in between two converters, the half of amplitude of active component of reference input current is multiplied with the input voltage angle and given to each current controller.

The current controller keeps the actual current at its reference value. Here, proportional resonant (PR) controller is used in each current controller. The inputs for the PR controllers are the errors between reference currents and actual currents. Each PR controller generates the reference voltage signal required for the PWM of each converter. Unipolar PWM control scheme is used to generate switching pulses for each converter.

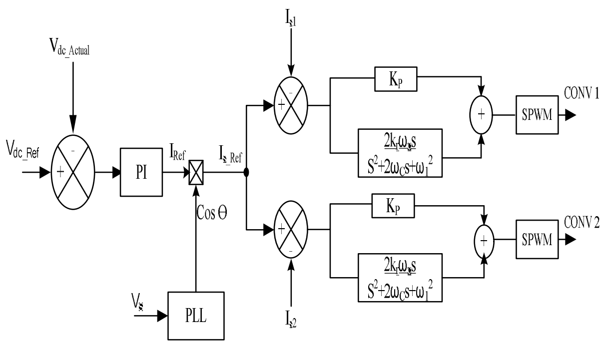

Figure 3: PR Controller implementation for PWM converter

The current controller is constructed based on the proportional-resonant (PR) controller whose transfer function is given by Equation (2).

$$G_{PR}(s) = K_P + \frac{2K_r s}{s^2+\omega_0^2} \qquad (2)$$

Where K_P is the proportional gain, ω_0 is the resonant frequency and K_r is the gain. The PI controller provides an infinite gain with a constant variable and gives good response without steady state error to a step reference but is unable to track a sinusoidal reference. The PR controller provides an infinite gain at the resonant frequency and zero phase shift.

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	560V DC
Boost Inductor, Ls	25mH
Inductor Parasitic Resistance	10mΩ
DC link Capacitor	2.2mF
Load - RL	53Ω, 35mH
Switching Frequency	750Hz

4. 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 PI and PR controllers whereas the outer DC link voltage loop is designed with PI controller. The performance of the PI current controllers is significantly affected with load variation, supply voltage fluctuation, DC link voltage variation. The simulation results show that PR controller tracks the sinusoidal reference better than PI controllers with all waveforms are in phase. PR controller also mitigates the harmonics better than PI controller. Figure 4(a) and Figure 4(b) 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 and there is considerable amount of phase difference with PI controller. This is due to the poor performance of the integral action in PI controller. Figure 5(a) and Figure 5(b) show the converter input current and voltage waveform when DC link voltage change from 500V to 600V. with PI controller during any change in DC link voltage, the input current and voltage waveform are distorted with phase difference as shown in Figure 5(a), but 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 Figure 5(b).

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 Figure 6(a) and Figure 6(b). There exists a phase difference between voltage and current at the input side of the converter during any change in supply voltage with PI controller as shown in Figure 6(a). Whereas this supply voltage fluctuation does not affect in case of PR controller as shown in Figure 6(b).

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 Figure 7(a) and Figure 7(b) respectively. Performance in disturbance rejection is better with PR controller than PI controller.

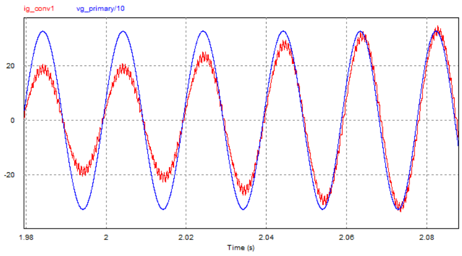

Figure 4(a): During load change at t=2 sec.(PI)

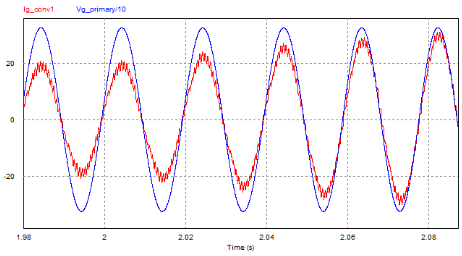

Figure 4(b): During load change at t=2 sec.(PR)

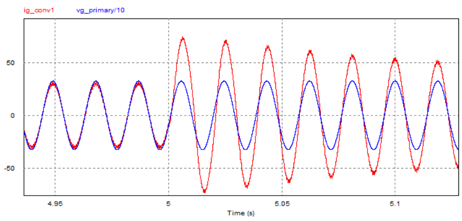

Figure 5(a): During change in DC link voltage from 500v to 600v. (PI)

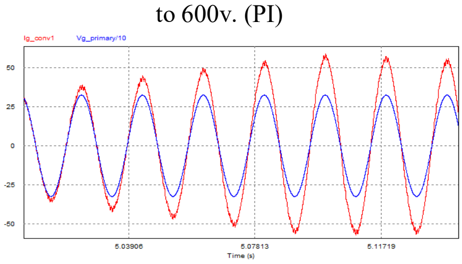

Figure 5(b): During change in DC link voltage from 500v to 600v. (PR)

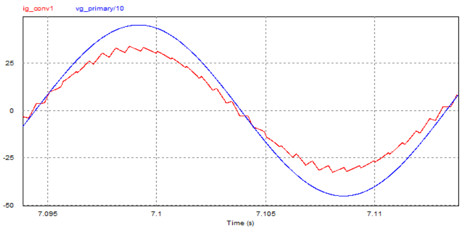

Figure 6 (a): Vs changed from 230 to 325 (PI)

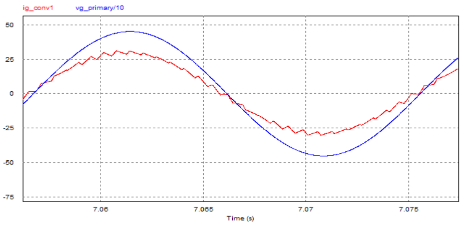

Figure 6 (b): Vs changed from 230 to 325 (PR)

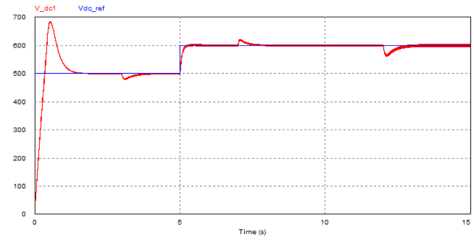

Figure 7(a): DC link voltage control loop response with PI current control loop

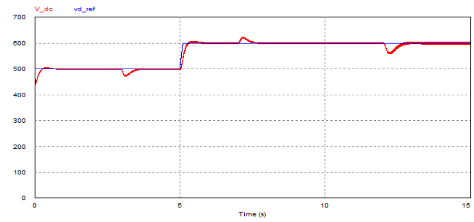

Figure 7(a): DC link voltage control loop response with PR current control loop

5. Conclusion

A single-phase, AC-DC dual converter system with constant switching frequency is presented for maintaining sinusoidal input current at unity power factor under wide range of load variation, supply voltage fluctuation and DC link variation. 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 than PI controller.

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