고속전철용 4상한 입력 컨버터 병렬 운전에 관한 연구

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A Study on the Parallel Operation of a Front-end-converter for a High Speed Electric Traction Drive

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Abstract - Front end AC to DC converters of the boost type are used in traction applications for generating the DC link for the inverters. A GTO based converter is usually switched with a switching frequency of 300 to 500Hz, resulting in low frequency harmonic problems.. In order to avoid this, multiple converters with phase shifted carrier waveforms are used to suppress the low frequency harmonics. A detailed study of an AC to DC converter, with two converters parallely operated with phase shifted carrier wave forms is presented in this paper.

1. Introduction

AC/DC converters are widely used in all types of electric traction applications. On an ac traction system one of the control of the traction unit is the conversion of the overhead line voltage, including voltage variations and harmonic distortion to a controlled dc supply.

With the advances in power device technology, it is possible to use PWM 4-quadrant front-end AC-DC converters with induction motor as the main traction drive.

In this paper, We studied the parallel operations of two AC-DC converters as a front end converters of the high speed traction drives. Control schemes are explained. Simulations and proto type experimental results show the good performance of parallel operating AC-DC converters.

2. Converter Control Strategy

The block schematic of the converter is shown in Fig.1.

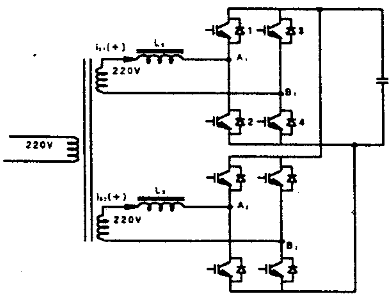

Fig. 1. front end converter schematic

Two single-phase converters are connected in parallel to suppress the harmonic currents in the mains. Same sine reference wave with phase shifted (180°) triangle waveforms (60×9) are used for the two legs of the same converter. For the leg-A, when the sine is greater than the triangle the top switch is turned on. For the leg-B, when the sine is greater than the triangle, bottom switch is turned on. So the pole voltages V_{AO} and the V_{BO} have fundamentals 180° phase shifted and the carrier frequency and its sidebands (fc±2, fc±4 etc.) with zero phase shift. At the transformer end the fundamental gets added and the carrier frequency and its sidebands get cancelled. This is also true with odd multiple of carrier frequency and its side bands (3fc±2, 5fc±2 etc.,)[4]. Now the resultant converter PWM waveform will have harmonics at the side bands of even multiple of the carrier frequency. For the second converter same sine reference is used with 90° phase shifted triangle waveforms, as compared to converter-1. The 90° phase shift for the triangle waveforms of the two converter cancels the evenmultiple sidebands at the transformer primary. Thus the resultant current drawn from the mains will have low frequency harmonics at the side bands of four times the carrier frequency [4]. Thus phase shifting the carrier wave appropriately, and with suitable PWM control nearly, a sinusoidal input current with unity power factor can be drawn from the mains, even with low switching frequency.

The block schematic of the output DC voltage regulation is shown in Fig.2. There is an inner current loop and an outer voltage control loop. The output DC voltage is controlled by matching the input power from the converter to the output power demand from the load, while maintaining unity power factor at all loads.

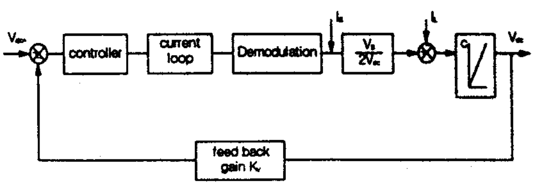

Fig. 2. Block Schematic of the voltage controller

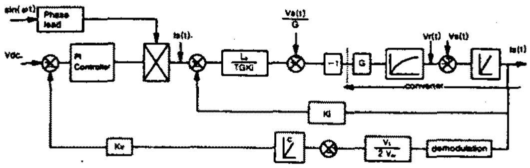

Fig. 3. Block Schematic of the control loop

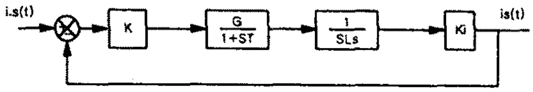

Fig. 4. Block schematic of the current control loop

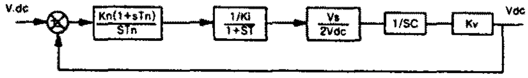

Fig. 5. Block schematic of the voltage control loop

The power balance equation at unity power factor is

$$V_S \cdot I_S = V_{DC} \cdot I_L \tag{1}$$

Where,

V_S, I_S : the rms value of the input fundamental component

V_{DC}, I_L : the output DC voltage and load current

The total load current(from both the inverters) is

$$I_L = I_{L1} + I_{L2} = V_S \cdot I_S / V_{DC} \tag{2}$$

From eqn.2, it can be seen that the input current amplitude should be controlled for output voltage control. A stationary reference frame model is used for the simulation study, as it involves with only fixed frequency of operation. The block schematic of the stationary reference frame control loop is shown in Fig.5. The scheme consists of a fast inner current loop and outer voltage loop. In stationary reference frame model the outer voltage loop is working with DC quantities and the inner current loop is working with sinusoidal quantities. The reference sinewave for the inner the inner current loop is derived from the mains. The converter current and voltage equation can be written as

$$L_s \frac{dI_S(t)}{dt} = V_S(t) - V_R(t) \tag{3}$$

Where $V_S(t)$, $V_R(t)$ are the instantaneous fundamental value of the input and converter PWM voltages.

Fig.3 shows the converter model for the control. The converter is represented as a first order delay block with a gain G. The delay time constant is due to the PWM switching and is equal to the triangle period. So the current response according to Fig.3 is

$$T\frac{dI_s(t)}{dt} + i_S(t) = \frac{i_S^*(t)}{K_i} \tag{4}$$

Where, $i^*_s(t)$, K_i is the current feed back gain. From eqn.3 and eqn.4 The reference voltage for PWM control can be written as

$$V^{*}(t) = \frac{V_S(t)}{G} - \frac{L_S}{TGK_i}\left(i^*_S(t) - K_i i_S(t)\right) \tag{5}$$

The current control loop for the present study can be written as shown in Fig.4. From Fig.4 the current loop transfer function equation is

$$\frac{i_S(t)}{i^*_S(t)} = \frac{1}{\frac{S^2LT}{KGK_i} + \frac{SL}{KGK_i} + 1} \tag{6}$$

Now for a damping factor of 0.5 the gain

$$K = \frac{L}{TGK_i} \tag{7}$$

Substituting eqn.7 in eqn.5 the current control block can be approximated as

$$i_S(t) = \frac{1/K_I}{1+ST}\, i^*_S(t) \tag{8}$$

The voltage control loop block schematic is shown in Fig.5. The PI control parameters can be calculated using symmetric optimization[3]. The PI parameters as a first approximation are (harmonic filter components are not included)

$$T_n = 4T \text{ and } K_n = CK_I / 2mTK_V \tag{9}$$

Where,

m : the modulation index (m=0.8).

For a unity power factor, the relation ship between the input voltage, input current and the fundamental component (VR(t)) of the input converter PWM voltage is

$$V_R = \sqrt{V_S^2 + \omega^2 L_S^2 I_S^2} \tag{10}$$

From eqn.10 the converter input inductance can be found out for a maximum load current. The DC link inductance can be determined from the ripple caused by the second harmonic current. For a voltage ripple ΔV(5% of the DC link voltage), the capacitance value is

$$C = \frac{mI_S}{2\Delta V \times 4f_S} \tag{11}$$

3. Simulation and Experimental Results

The whole scheme is simulated using SIMULINK software. The two converter currents and the transformer primary current are shown in Fig.6. The current ripple of the transformer primary is highly reduced when compared to the individual converter currents. Fig.9 shows the converter DC link voltage ,input mains reference and the transformer primary current. The scheme is tested for forward and reverse power flow. The control scheme maintains unity power factor Fig.7 shows the transition from reverse power flow to forward power flow. The transition is instantaneous with minimum transients. The converter is also tested for sudden load changes(Fig.7). In all these conditions the controller. maintains always unity power factor with less transients in the controlled signals. The whole scheme is experimentally verified using a laboratory prototype of 20KW power level. The parallely operated two converter scheme is switched on with a load of 10Ω. The

DC link voltage controlled to maintain 400V.

The two converter currents along with the reference input voltage mains is shown in Fig.8. Sharing of the total load current equally between the converters is clearly visible in Fig.8. Both converters have the same fundamental current, but with switching ripple current opposing each other, due to the phase shifted PWM strategy.

Fig. 9 shows resultant transformer primary winding current along the primary voltage. The current waveform shows the ripple reduction. The converter works with unity power factor, always at the transformer input side.

Fig.10 shows the converter switch on waveforms with no load. The initial current rises very fast to charge the DC link. The two converters share the current equally.

Fig. 11 shows the DC link voltage and the converter currents(with 20Ω load) when the reference voltage is suddenly increase(350V to 450V). The DC link voltage rises exponentially without any undesirable transient.

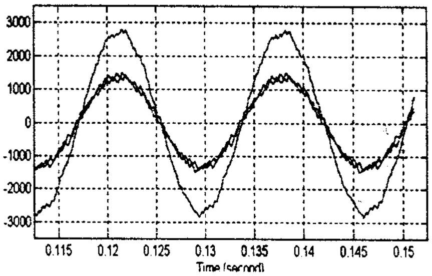

Fig. 6. Input AC to DC converter currents with a carrier frequency of 540 Hz

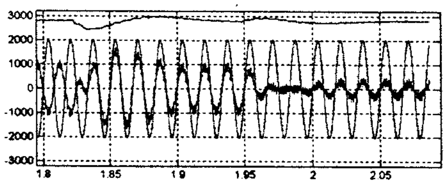

Fig. 7. DC Link voltage and converter currents durring forward and reverse power flow

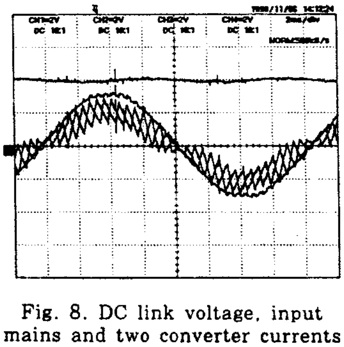

Fig. 8. DC link voltage, input mains and two converter currents (50A/div., 200V/div.,10Ω)

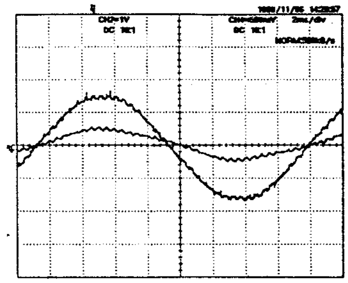

Fig. 9. Transformer primary current and primary voltage (200A/div.,200V/div.,10Ω)

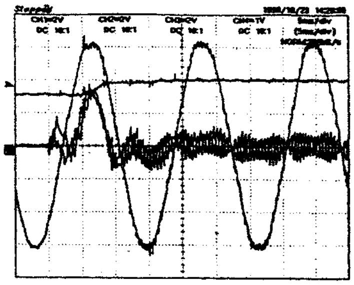

Fig. 10. DC link voltage and converter currents during switch on without load.(DC:200V/div., AC:100V/div.,50A/div.)

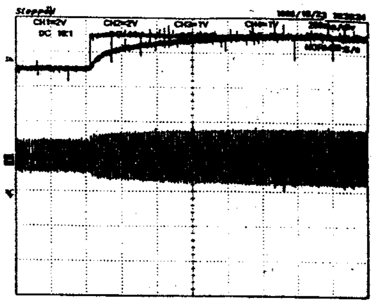

Fig. 11. DC link voltage and converter current during voltage reference increase.(350V→450V) (100V/div.,50A/div.,20Ω)

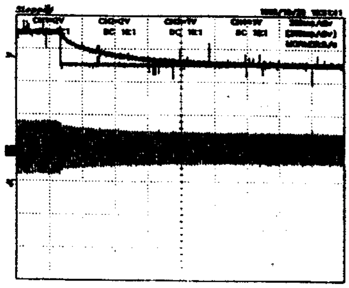

Fig. 12. DC link voltage and converter current during sudden reference reduction(450V→350V) (100V/div.,50A/div.,20Ω)

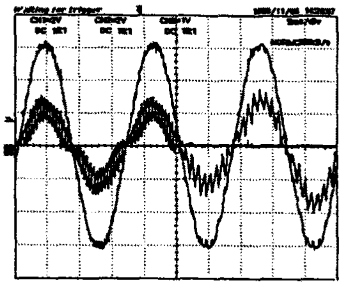

Fig. 13. Converter currents when one converter is switched off. (100V/div.,50A/div.)

Similarly the reference voltage is suddenly reduced(450V to 350V). Here also the DC link voltage reduces exponentially without any transients.(Fig.12)

The two converter control is also operated for sudden tripping of one converter. This is shown in Fig.13. When one of the converter is switched of suddenly, the total load current will be transferred to the other converter without any undesirable system transients.

4. Conclusion

A detailed study of a front end AC to DC converter with two single phase converters connected in parallel is presented in this paper. The appropriate current and voltage control loop design using simple modeling of the converters is presented with simulation studies, during forward and reverse power flow with sudden application of load. There is a phase shift between the input transformer primary mains voltage and the secondary induced voltage (which is taken as the source voltage for PWM control). This phase shift will depend on the transformer parameters and the load. So sinusoidal current reference with appropriate phase shift has to be provided, depending on the load, to the current loop for unity power factor .

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Appendix

Simulation parameters:

- Input Voltage - 1432Vrms
- Output Voltage - 2800V
- Switching Frequency - 540Hz
- Rated Power - 1400KW
- DC Link Capacitor - 9600μf
- Input inductance - 2mH

Experimental parameters

- Input voltage - 220Vrms
- Output voltage - 400V
- Switching frequency - 540Hz
- DC link capacitor - 5500μf
- Input inductance - 2mH