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Modeling, Controller Design and Simulation of Power System Friendly Power Supply

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Abstract. The paper is based on the performance comparison of single-phase diode-bridge rectifier and the proposed front-end converter in terms of the Total Harmonic Distortion (%THD) of the line current, power factor of the system and ability of energy saving of the converter by capability of reverse power flow action. The parameters of the voltage control-loop for proposed converter are derived by two methods named Unity Modulus (Magnitude Optimum) method and Ziegler-Nichols method. The parameters obtained from both the methods are compared by the mathematical model for forward and reverse power flow mode of operation. The model is generated in Simulink toolbox of MATLAB and results are obtained for steady state, transient and dynamic conditions. It is observed that the unity power factor is maintained during all the conditions for various loads. Drastic reduction in %THD of input current waveform is obtained in proposed power supply with an added advantage of regenerative capability. For comparison of results of control-loops, a programming file (M-file) is also generated in MATLAB and from the same file the step-response and Nyquist plots are obtained for system control-loops. The experiment results are also obtained for the prototype converter in inverter mode. The power system friendliness of the proposed front-end converter is quite evident from the results presented in the paper.

Key words

Front-End Converter, Unity Modulus Method, Ziegler-Nichols Method, Unity Power Factor, Low % THD, Regenerative Capability, and Power System Friendliness.

1. Introduction

There are various conventional methods by which the output dc voltage can be controlled, e.g. a diode-bridge with a tap changing transformer or an auto-transformer, line-commutated controlled rectifier-bridge, etc. The methods are simple but suffer from disadvantages like size, weight, cost of transformer, poor dynamic response [1], and very high %THD in supply current. Sometimes, in case of an ac-to-dc phase-controlled switching (line-commutated rectifier-bridge), no transformer is required. Thus, the size, weight and cost gets reduced and efficiency becomes high. The normalized harmonic spectrum for the line current of single-phase diode-bridge rectifier is shown in fig. 1, which causes power quality problems like; poor power factor, large amount of harmonics injected in supply lines because of very high %THD in line current. Also concept of energy saving (by regeneration) is not applicable as diodes (and also SCRs in case of line-commutated or naturally commutated phase-controlled rectifiers) are unidirectional devices and do not permit bidirectional flow of power. For the solution of such problem a power system friendly front-end converter scheme is proposed in this paper.

In the paper, a unity power factor front-end converter is proposed, which maintains the unity power factor under various load conditions. The proposed converter has the significant low %THD as compared to single-phase diode-bridge rectifier. The P and PI controller parameters are obtained with the help of Magnitude Optimum method and Ziegler-Nichols method and accordingly the simulation results are obtained for steady state and transient conditions for forward and reverse power flow.

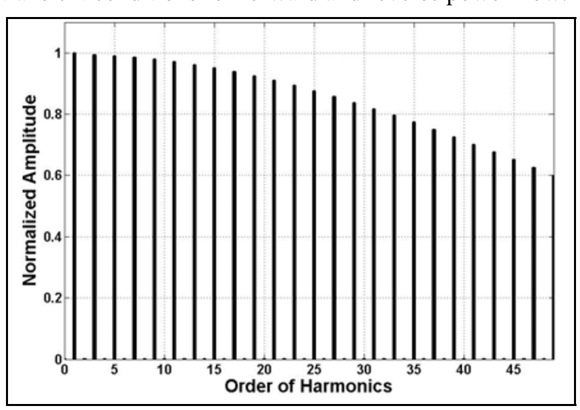

Fig. 1. Normalized harmonic spectrum of line current for single-phase diode-bridge rectifier

2. Proposed Front-End Converter and PWM Switching Scheme

The proposed front-end converter with 8 IGBT structure is shown in fig. 2. In this scheme, two single-phase converters are connected in parallel to supply the load and hence to reduce the harmonic currents in the mains as well as to improve the ripple contents at the dc link. Sine-triangular PWM is used for the control of the converters. For each converter, leg-B triangular waveform is 180° phase-shifted compared to that of leg-A for the same converter. For leg-A of converter-2 triangular wave is phase shifted by 90° compared to that of converter-1 so that harmonic frequencies around the second multiple of carrier wave get cancelled. The PWM switching scheme waveforms of the proposed converter is shown in figs. 3, 4, and 5. This is because harmonics at two times the carrier frequencies will be 180° phase shifted and hence flux produced by these cancel each other at the input transformer secondary side. For the proposed converter the frequency of carrier is taken 11 times the frequency of sinusoidal reference, which is 60 Hz. So harmonic currents of two times the carrier frequency will not flow at the secondary side and hence the dominating harmonic present at the primary side will be at the side bands of four times the carrier frequency (i.e., 4 x 11 x 60 Hz = 2640 Hz), with much reduced amplitudes as compared to the fundamental component [2]-[3].

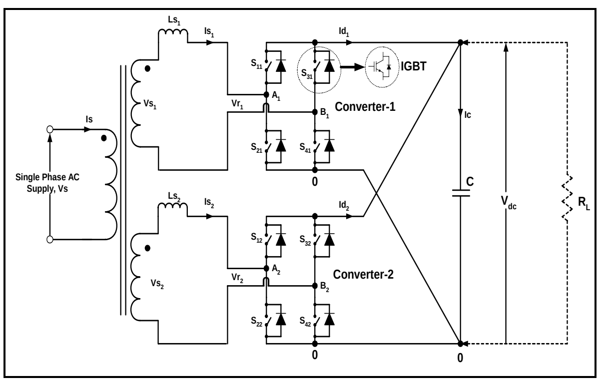

Fig. 2. Power Schematic of proposed front-end converter

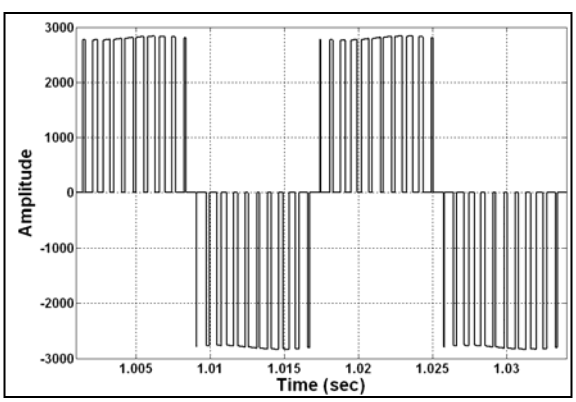

Fig. 3. Voltage waveform V_{A1B1}= V_{A10}-V_{B10} (i.e. V_{r1})

3. Design of Control Loops

There are two control-loops in proposed converter i.e. current control-loop and voltage control-loop [4]. There

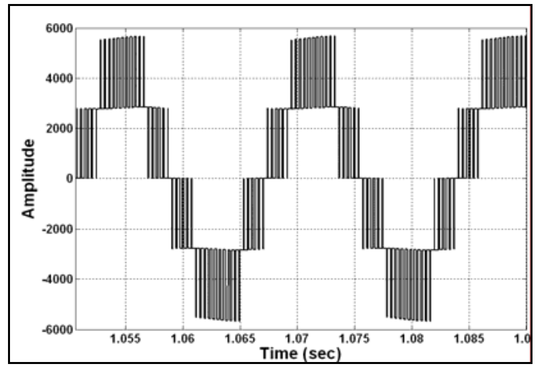

Fig. 4. Voltage waveform V_{AB}= V_{A1B1}+V_{A2B2} (i.e. V_r)

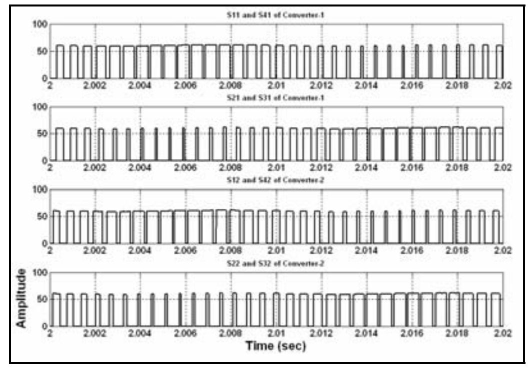

Fig. 5. Switching Waveforms for Converter-1 & 2

is a faster inner current control-loop and outer is 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 the loads. Another technique named harmonic resistance emulator [5] can be used for the single-phase power factor correction. The loading condition includes reverse power flow (regenerative) mode of operation also. In the proposed work, a stationary reference frame model is used for the simulation studies, as it involves with only fixed frequency operation. The outer voltage loop is working with dc quantities and the inner current loop is working with sinusoidal quantities. The reference sine wave for the inner current control-loop is derived from the input mains. The block schematic of current and voltage control-loops are shown in figs. 6 and 7, respectively. In designing the control-loops the two different methods are used for finding the parameters of current control-loop and voltage control-loop. The cases are taken for the under damped, critically damped and over damped system for each of the methods. The considered methods are Unity Modulus method [6] and Ziegler-Nichols method [7]-[9]. The parameters of PI [10] controllers obtained (based on mathematical models of the system) from both the methods are listed in table-I.

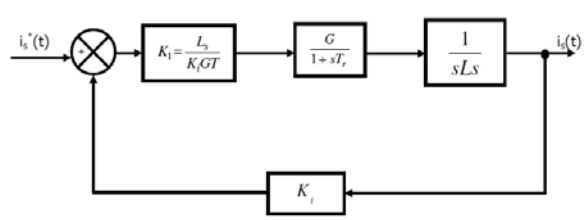

Fig. 6. Block schematic of the current control-loop

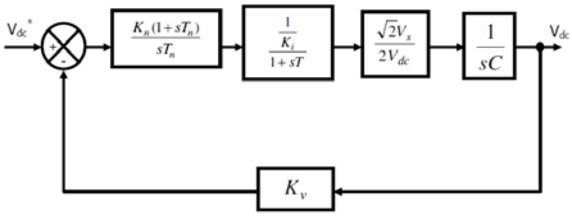

Fig. 7. Block schematic of the voltage control-loop

Table I - Comparison of PI Controller Parameters for Voltage Control-Loop

Type of the System	Values of PI Controller Parameters			
	Unity Modulus Method		Ziegler-Nichols Method	
	K_n	T_n	K_n	T_n
Under Damped System ($\zeta = 0.707$)	9.06	0.01214	4.08	0.0914
Critically Damped System (ζ = 1)	4.5307	0.02428	1.1989	0.0647
Over Damped System (ζ = 1.2)	3.1463	0.03496	0.4917	0.0539

4. Simulation and MATLAB Programming

The simulation for the proposed front-end converter is performed by generating mathematical model in Matlab-Simulink. The results are obtained from both the methods i.e. Unity Modulus method and Ziegler-Nichols method under transient, dynamic and fault conditions. During fault condition, only one converter is capable of taking full load current when another converter fails. The simulation results obtained considering that converter-2 is working and converter-1 is faulty. The simulation results are obtained for forward power flow mode of operation as well as reverse power flow (regenerative) mode of operation. The simulation results are shown in fig. 8 to fig. 18. Power system friendliness features of the proposed power supply like; good dynamic response, unity power factor for various loading conditions, reduced % THD in supply current, and regenerating capabilities are clearly demonstrated by these results. The general MATLAB program (M-File) is prepared for the calculation of the various parameters of current and voltage control-loops of the proposed converter. The various plots taken with the help of program for under damped system are shown in figs. 19 to 21.

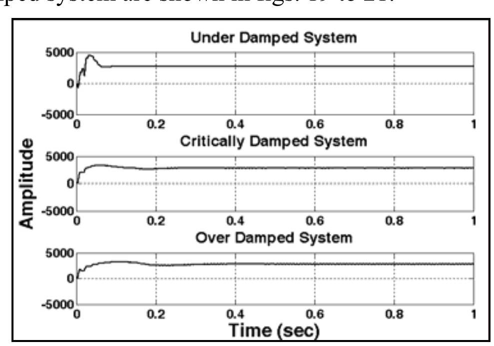

Fig. 8. V_{dc} waveform under forward power flow mode of operation (Unity Modulus method)

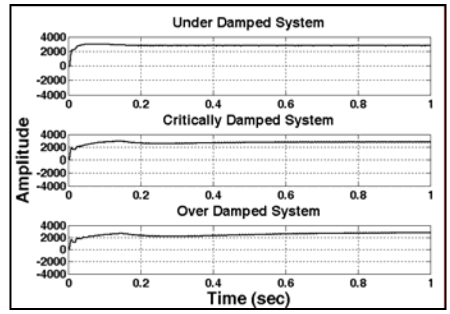

Fig. 9. V_{dc} waveform under forward power flow mode of operation (Ziegler-Nichols method)

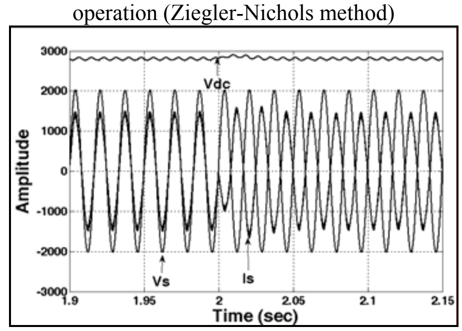

Fig. 10. V_{dc}, V_s and I_s waveforms for forward power flow to reverse power flow mode of operation

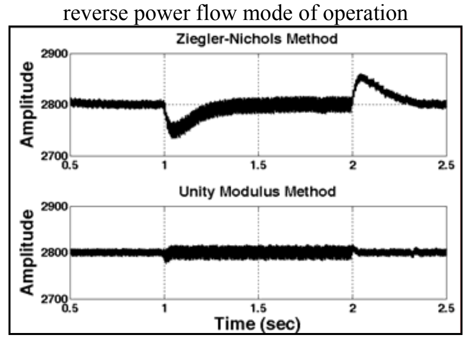

Fig. 11. Waveforms of dc-link voltage for under damped system during load change conditions

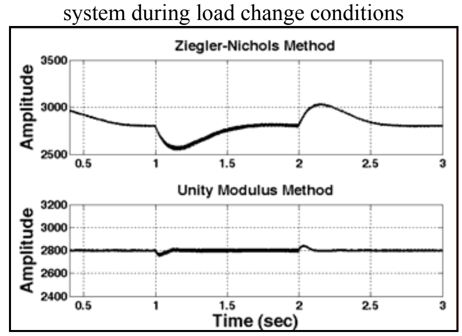

Fig. 12. Waveforms of dc-link voltage for critically damped system during load change conditions

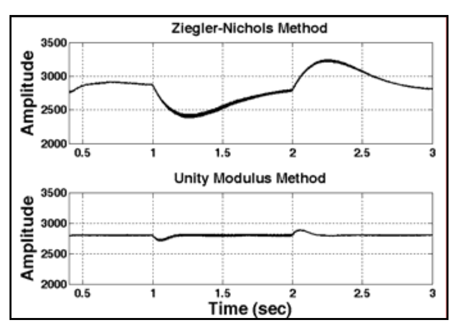

Fig. 13. Waveforms of dc-link voltage for over damped system during load change conditions

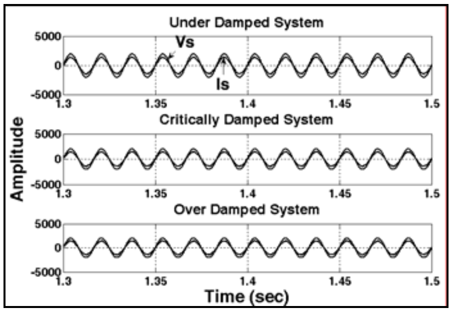

Fig. 14. V_s and I_s waveforms under forward power flow mode of operation

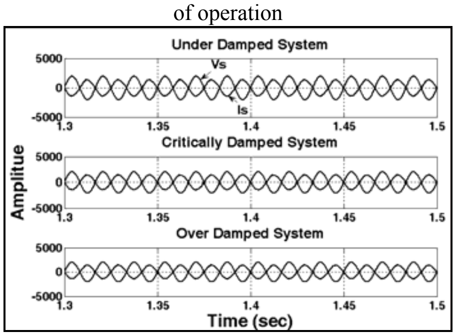

Fig. 15. V_s and I_s waveforms under reverse power flow mode of operation

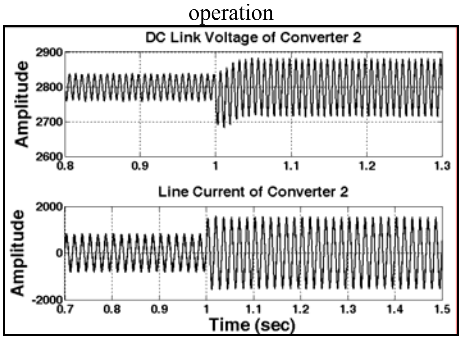

Fig. 16. Waveforms of dc-link voltage and line current during fault condition (i.e. only one converter is working)

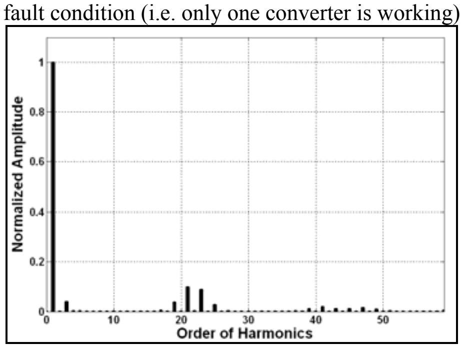

Fig. 17. Normalized harmonic spectrum of line current for one converter (i.e. I_{s1})

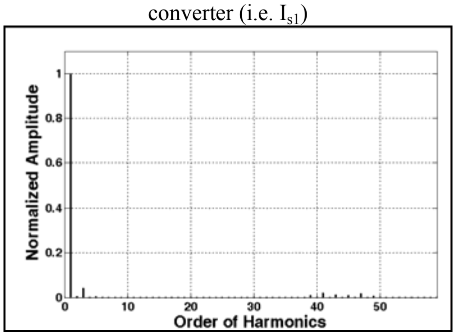

Fig. 18. Normalized harmonic spectrum of combined current reflected to primary (i.e. I_s)

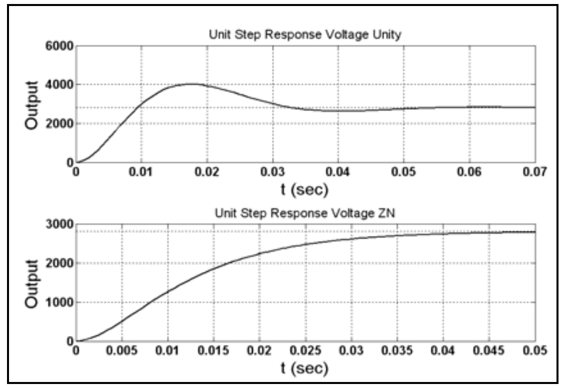

Fig. 19. Step response of voltage control-loop for under damped system

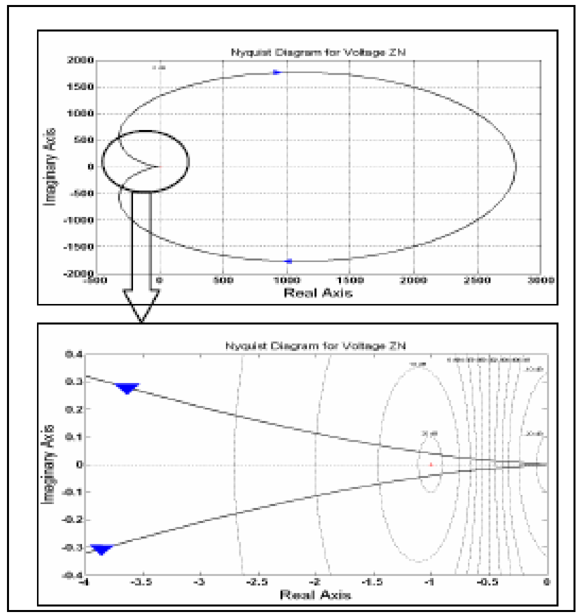

Fig. 20. Nyquist plot of voltage control-loop for under damped system (Ziegler-Nichols method)

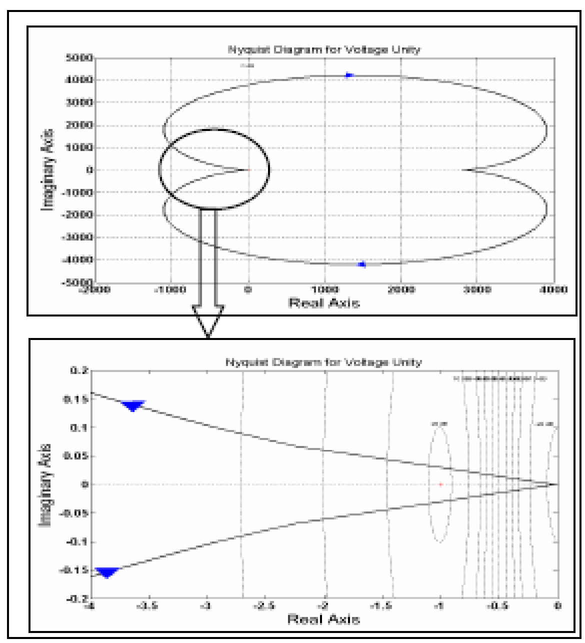

Fig. 21. Nyquist plot of voltage control-loop for under damped system (Unity Modulus method)

5. Experiment Results

For the analysis of the simulation model, the prototype of the front-end converter of 750 W is developed in the laboratory. At present the experiment results for the converter are obtained in the inverter mode for the open-loop system. The experiment test setup for the driver card and prototype in the inverter mode operation are shown in figs. 22 to 23, while the obtained experimental results are shown in figs. 24 to 31. The obtained results show the dead-band of 4 µs between the IGBTs of the same leg of the converter.

Fig. 22. Experiment test setup for prototype converter

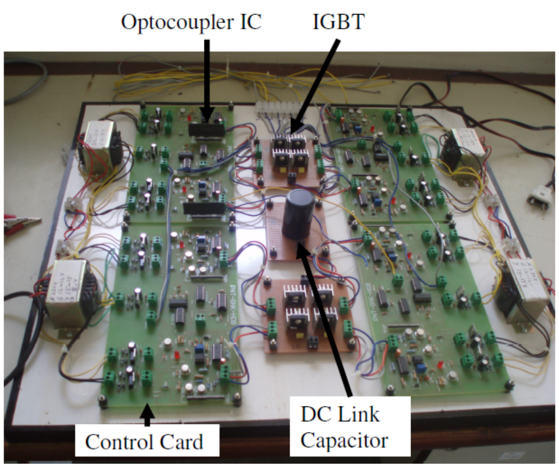

Fig. 23. Top view of the hardware prototype control cards

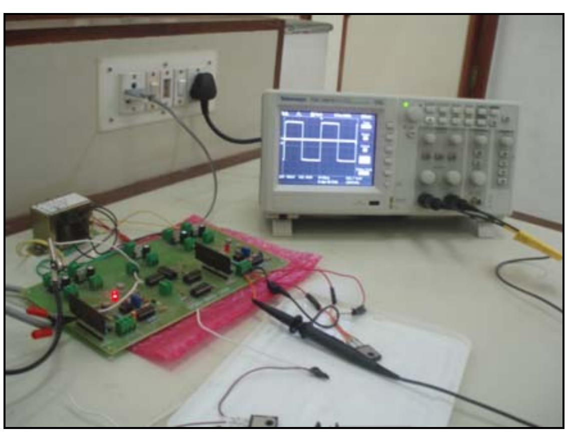

Fig. 24. Experimental test setup for driver card when one of the IGBTs of the inverter leg has fault condition

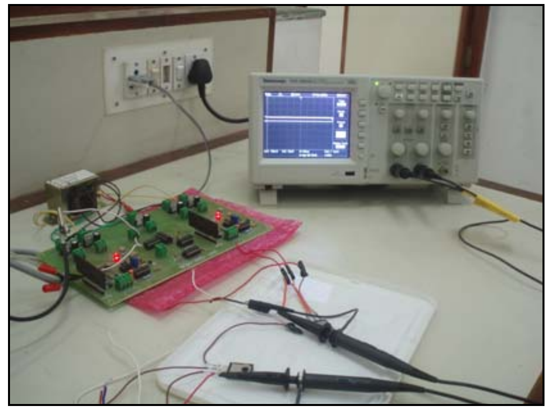

Fig. 25. Experimental test setup for driver card when both the IGBTs of the inverter leg have fault condition

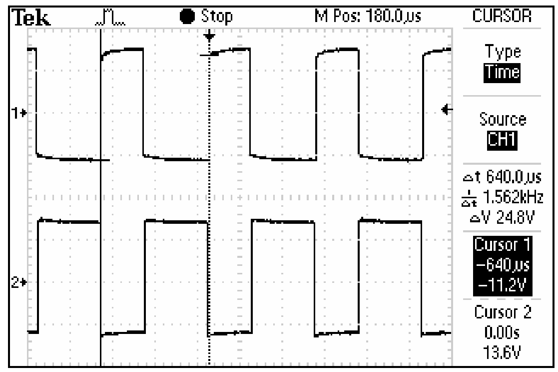

Fig. 26. Gate pulses for the same IGBTs of the same leg (Scale: X-axis: 1 division = 2 ms, Y-axis: 1 division = 10 V)

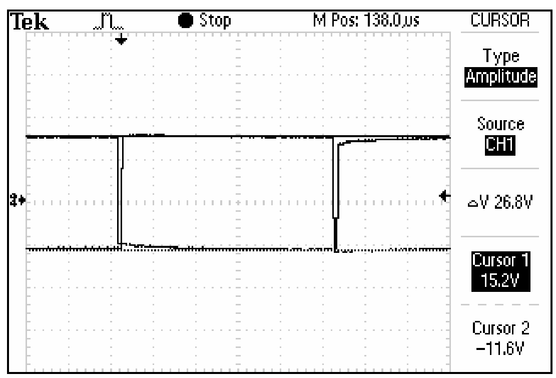

Fig. 27. Enlarged view of gate pulses for the IGBTs of the same leg (Scale: X-axis: 1 division = 2 ms, Y-axis: 1 division = 10 V)

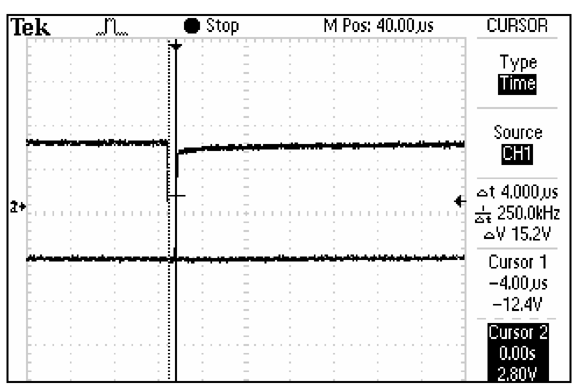

Fig. 28. Enlarged view of gate pulses for the IGBTs of the same leg showing dead-band (Scale: X-axis: 1 division = 2 ms, Y-axis: 1 division = 10 V)

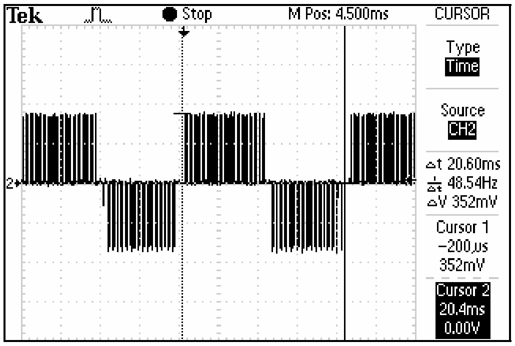

Fig. 29. Experimental waveform $V_{A2B2}= V_{A20}-V_{B20}$ (i.e. V_{r2}) (Scale: X-axis: 1 division = 2 ms, Y-axis: 1 division = 10 V)

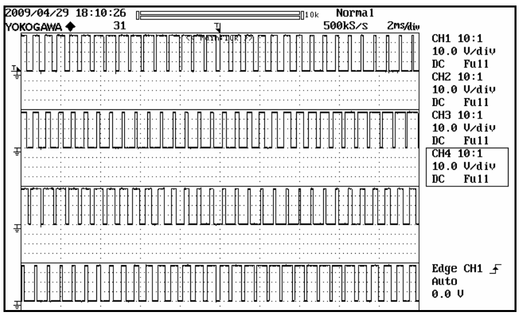

Fig. 30. Experimental switching waveforms for Converter-1 & 2 (Scale: X-axis: 1 division = 2 ms, Y-axis: 1 division = 10 V)

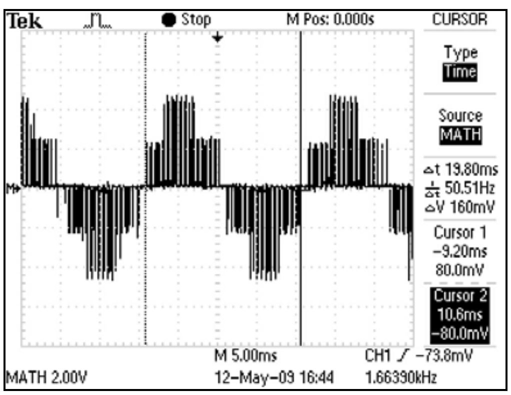

Fig. 31. Experimental waveform $V_{AB}= V_{A1B1}+V_{A2B2}$ (i.e. V_r) (Scale: X-axis: 1 division = 2 ms, Y-axis: 1 division = 10 V)

6. Conclusion

The parameters of the current and voltage control-loop for the proposed topology is found with the help of Unity Modulus and Ziegler-Nichols method. According to the various values of the current and voltage control loops parameters simulation is done in Simulink (MATLAB). For all the cases i.e. transient and dynamic condition the results form the unity modulus method found more suitable than Ziegler-Nichols method except the transient condition for underdmaped case where the Ziegler-Nichols method found more suitable than unity modulus method. The % THD of line current in the case of the single-phase diode bridge rectifier is found 328.50 % and it is 4.078 % in the case of the proposed front-end converter. The simulation results are also obtained for the fault condition and transition mode of operation. It is also observed that unity power factor is maintained in all the cases for proposed converter during the various load conditions. The results obtained show the desired power system friendly performance of the proposed converter. The experiment results for the switching pattern and the working of the dead-band circuit for the switches of the same leg also shows desired performance of the developed prototype converter.

7. Appendix

Specifications of font-end converter are:

Specifications	For proposed converter	For prototype converter
Input Voltage (ac)	1432	30
Output Voltage (dc)	2800	60
Supply Frequency	60	50
Switching Frequency	660 Hz	1.65 KHz
Rated power	1400 kW	750 w
Assumed % η of converter	98	80
Max. modulation index	0.8	0.8
DC Link Capacitor	10000 µF	9.37 mF
Boost inductor	1.81 mH	1.6171 mH

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