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Analysis, Design and Control of Two-Level Voltage Source Converters for HVDC Systems

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ABSTRACT

The Voltage Source Converter (VSC) is replacing the conventional line commutated current source converters in High Voltage DC (HVDC) transmission systems. The control of a two-level voltage source converter and its design dealt with HVDC systems and various factors such as reactive power, power factor, and harmonics distortion are discussed in detail. Simulation results are given for the two-level converter and designed control is used for bidirectional power flow. The harmonics minimization is taken by extending the 6-pulse VSC to multipulse voltage source converters. The control is also tested and simulated for a 12-pulse voltage source converter to minimize the harmonic distortion in AC currents.

Keywords: Two-level Voltage Source Converter, HVDC, Multipulse, Fundamental frequency

1. Introduction

High Voltage DC (HVDC) transmission systems are often economic means for delivering electric power over long distances and/or in connecting two synchronized AC networks, which may be at different frequencies[1]-[8]. Most of the commercial HVDC systems have employed the line commutated current source converters with the thyristors as a switching device until recently. The VSCs (Voltage Source Converters) are replacing the thyristor converters in HVDC systems because of various advantages. Self commutated device based voltage sourced converters with ratings suitable for power transmission are now possible because of the emergence of new devices such as Insulated Gate Bipolar Transistors (IGBTs), Gate Turn-Off Thyristors (GTOs) with high voltage and current ratings [9]-[10]. A two-level voltage source converter is now a widely used converter topology for HVDC systems. The prototype model of a 300 MW VSC based HVDC system is developed at reasonable high power level [11]-[12]. The IGBT (Insulated Gate Bipolar Transistor) is used in VSC based HVDC system for medium power level with Pulse Width Modulation (PWM) technique for harmonics elimination.

The GTO is used for high power level with fundamental frequency switching and PWM control is not preferred as it increases the switching losses [13]. Various other voltage source converter topologies are proposed for HVDC applications, such as multilevel and ripple reinjection techniques [14]-[15]. These converters are proposed to avoid the PWM techniques in case of high power converters to reduce the switching losses. But the number of devices in the circuit and control complexity increases with the increasing number of levels in case of multilevel

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converters. A self commutated Back-to-Back (HVDC) link of 100 MW with 16 units of basic two-level converter is proposed in the literature [16] and a 96-pulse converter operation is achieved with substantial reduction in harmonics and with a DC voltage control. Many voltage source converter configurations are proposed for reducing harmonics, improving the system operation and control. Here, a basic two-level voltage source converter is used for the HVDC systems. The design of VSC is presented with the analogy of a synchronous machine which can operate either as a generator or as a motor with unity power factor. The control of the converter is developed for the control of DC voltage and flow of real power. The switching devices are operated at a fundamental frequency switching (FFS). The analysis and design of this two-level converter is carried out mainly to demonstrate that there is no need of wide variation in DC link voltage for unity power factor operation. A reasonable high power factor and high performance of the converter can be achieved without much variation in the DC link voltage. The application of two-level VSC is justified for improving the power factor, harmonics and reducing the switching losses for HVDC systems.

2. Principle of Operation

The operating principle of a designed two level voltage source converter is explained here. The operation of a voltage source converter can be realized similar to the operation of a synchronous machine. It can operate at leading, as well as lagging, power factors. The AC voltage at the supply side is sinusoidal and at the converter side is stepped voltage waveform. These two voltages are interfaced through a reactance. The magnitude of DC voltage is having a fixed relation with the AC voltage at the converter input. The supply voltage (V_s) and excitation voltage (E) of the synchronous machine have analogy with the supply (V_s) and the fundamental voltage (V_c) of the voltage source converter. The basic schematic diagram of the voltage source converters used in HVDC system is shown in Fig.1. Both the amplitude and the phase angle of the output fundamental voltage V_c of VSC are controlled with respect to the source voltage V_s. Two voltages are interfaced through a reactor X. The voltage drop across the reactor X can be controlled to determine the active and reactive power flows.

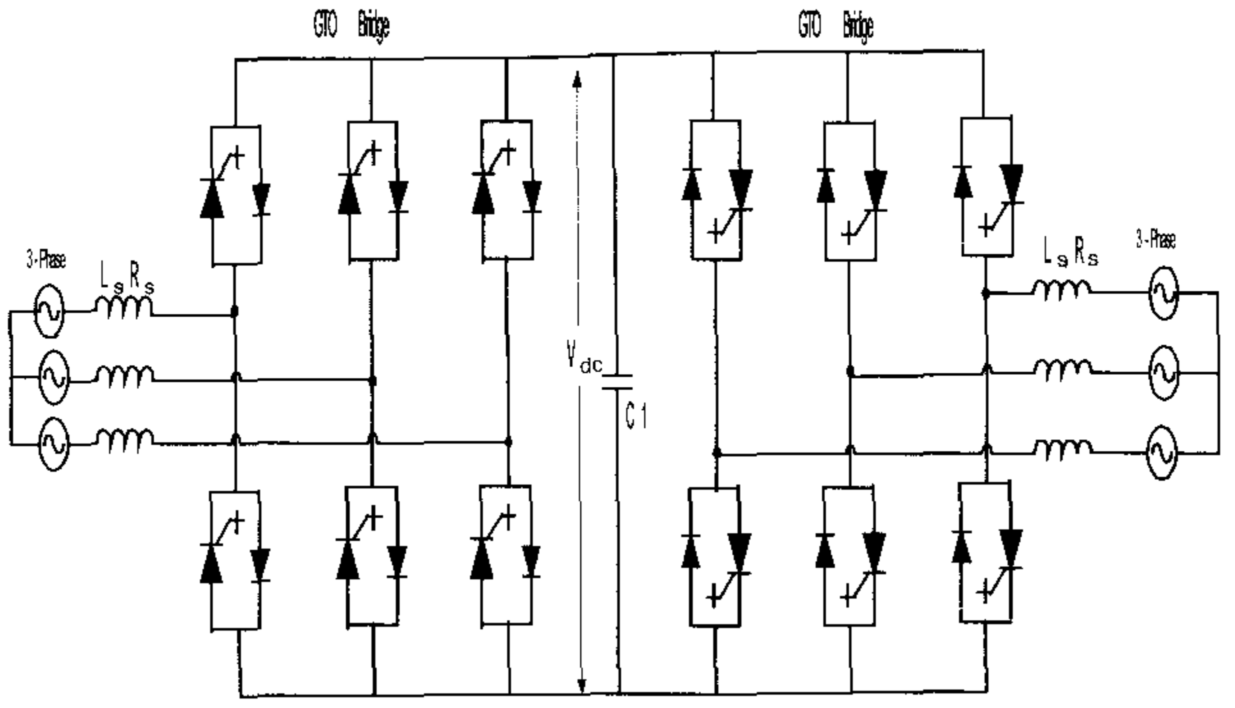


Fig. 1 Basic diagram of a voltage source converter based HVDC system.

The magnitude of the two voltages controls the reactive power flow in the circuit and the phase angle between two voltages controls the active power flow in the system. The basic equations governing the active and reactive powers are

$$P = \frac{V_s V_{c1}}{X} \sin \delta \tag{1}$$

$$Q = \frac{V_{c1} \cos \delta - V_s}{X} V_s \tag{2}$$

where V_s = supply voltage at the angle of 0°, V_{c1} = fundamental of converter voltage at the angle of δ°, δ is the angle difference between the two voltages V_s and V_{c1} and X = reactance between the supply voltage and converter voltage waveform.

From these above equations it can be seen that the active and reactive powers are controlled independently through (V_{c1} sin δ) and (V_{c1} cos δ), respectively. Therefore, by adjusting (V_{c1} sin δ) and (V_{c1} cos δ) properly, a voltage source converter is able to operate at any desired power factor. The design of two-level voltage source converter is carried out mainly focusing on power transfer, supply and converter voltage magnitude and angle difference between these voltages. The supply voltage is taken as fixed magnitude of 1 pu and angle of 0°. Three devices remain ON at all time. There are six mode of operation in a cycle and each mode of 60° for a 6-pulse VSC.

3. Control Algorithm

The control algorithm is to regulate the DC voltage at the given reference value and to control the active power flow from AC grid to DC side, along with supplying required reactive power to the AC mains. A capacitor is used at the DC bus to support the DC bus voltage at the required value for real power balance between the two sides of the converter, which is most important for the successful operation of the HVDC system. The energy stored in the capacitance reduces or increases if the active power is not balanced between the two sides of the converter stations. It consists of two controllers; one is the DC voltage controller and other one is the current controller.

3.1 DC Voltage Controller

DC voltage controller is shown in Fig. 2a, in which reference currents (I_d*, I_q*) are achieved by the DC voltage controller from the reference real power and reference DC voltage as given below,

$$I^*_d = (P^*/Vs) + K_V\,(V^*_{dc} - V_{dc}) \qquad (3)$$

$$I^*_q = 0 \qquad (4)$$

where P^* is the reference real power to be transmitted from one side to another side, K_V is proportional gain constant, V_s rms supply voltage, and V_{dc}^* reference DC voltage. Reference reactive current (I_q) is taken as zero, to maintain the reactive power zero. The first term in the equation (3) decides the power flow in the system and second term achieves DC voltage regulation by means of controlling the additional amount of active power flowing from AC side to DC side.

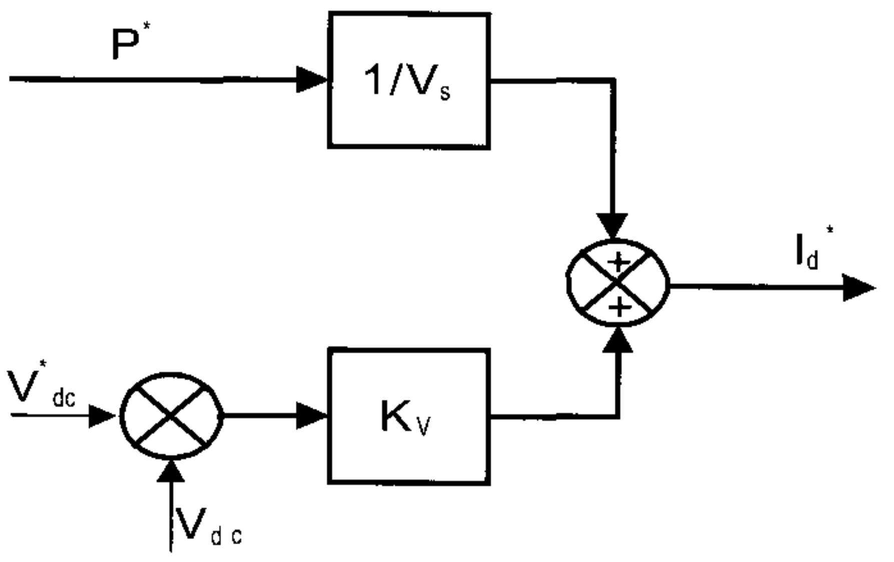


Fig. 2a DC voltage controller

When V_{dc} is lower than V_{dc}^*, the i_d^*, is increased as shown in equation (3), so that a small amount of active power flows into the DC link capacitor through rectifier, thus V_{dc} rises up to V_{dc}^*. When V_{dc} is higher than the V_{dc}^*, then i_d^* is decreased so that amount of active power flow into the DC link capacitor is reduced; thus V_{dc} is lowered to V_{dc}^*.

3.2 Current controller

The reference currents (I_d*, I_q*) from DC voltage controller are given as inputs to the current controller, and it provides reference voltages (V_d*, V_q*). The operation of the current controller can be explained by using the following equations

$$V_d^* = V_d - (R.I_d + \omega L.I_q) - K_I\,(I_d^* - I_d) \qquad (5)$$

$$V_q^* = V_q - (R.I_q + \omega L.I_d) - K_I\,(I_q^* - I_q) \qquad (6)$$

where K_I is proportional gain, V_d, V_q are dq values of supply voltage V_s, and I_d, I_q are dq values of supply current (I_s). The block diagram of the current controller is shown in Fig. 2b. A complete control scheme for back-to-back HVDC system is shown in Fig. 3.

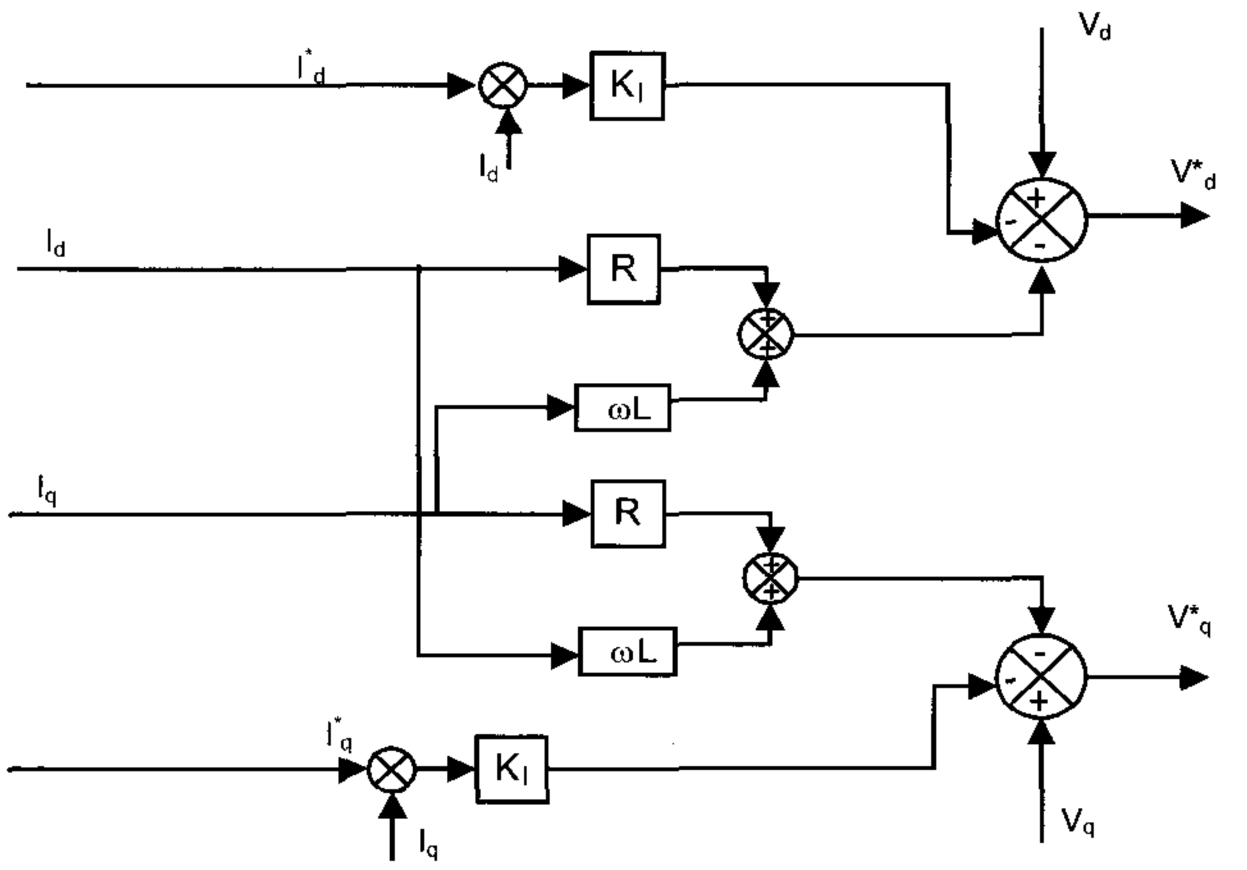


Fig. 2b Current controller

4. MATLAB Based Simulation of Two-Level Voltage Source Converter

The two level converter is simulated in the MATLAB environment with Simulink and Power System Block set (PSB) toolboxes. Fig. 4a shows the MATLAB model of

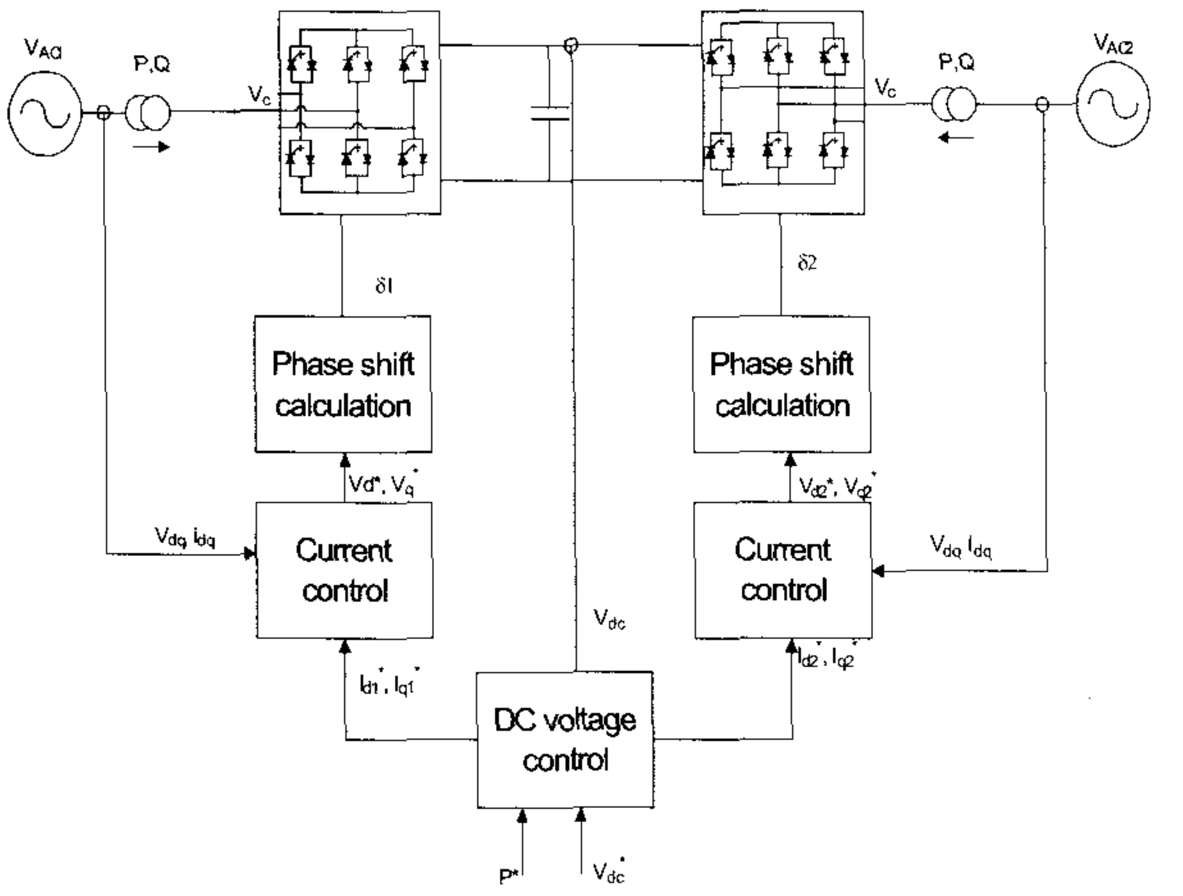


Fig. 3 VSC based HVDC transmission system with Control

two level 6-pulse converters, and Fig. 4b shows the model of a 12-pulse voltage source converter. In this model, two 2-level GTO bridges are used in parallel on the DC side. Two VSC bridges are fed from a Y/Y and Y/Δ transformer with a phase shift of 30° between two bridges. The 2-level GTO universal bridge is used to model the converter. The control algorithm is implemented using Simulink blocks. Three-phase grid supply of 33 kV, 50 Hz, is connected to the converter through interface with reactance of 0.2 pu. Three -phase AC input is fed to the bridge through interface reactance. The voltages at the two sides of the transformer are measured as supply and converter voltage. A dc capacitance is connected at the dc side to store the energy at the dc bus. The system parameters used for the simulation is given in Appendix.

5. Results and Discussions

The performance of a two-level voltage source converter in HVDC system is demonstrated for active power flow control. Equation (1) is considered for power calculation and the reactance is taken as 20% and supply voltage is taken at constant value. The converter voltage (V_{c1}) is controlled from ±20% so that it exhibits the performance of a synchronous machine. The power factor is varied by varying the excitation voltage (V_{c1}), which is analogy to the converter side voltage here in VSC. The converter voltage is varied ± 20% for the power flow of 10% to 120%. Table 1 gives the angle between ac voltage and converter voltage, current, power factor for various power levels with both supply and converter voltages are considered equal and at a value of 100%. Table 2 shows the variation required in the converter voltage to achieve the unity power factor. The converter voltage can be maintained at 1 pu for low power levels. But for active power above 50% of rated power, the converter voltage has to be increased from 1.01% to 1.03% to achieve the unity power factor.

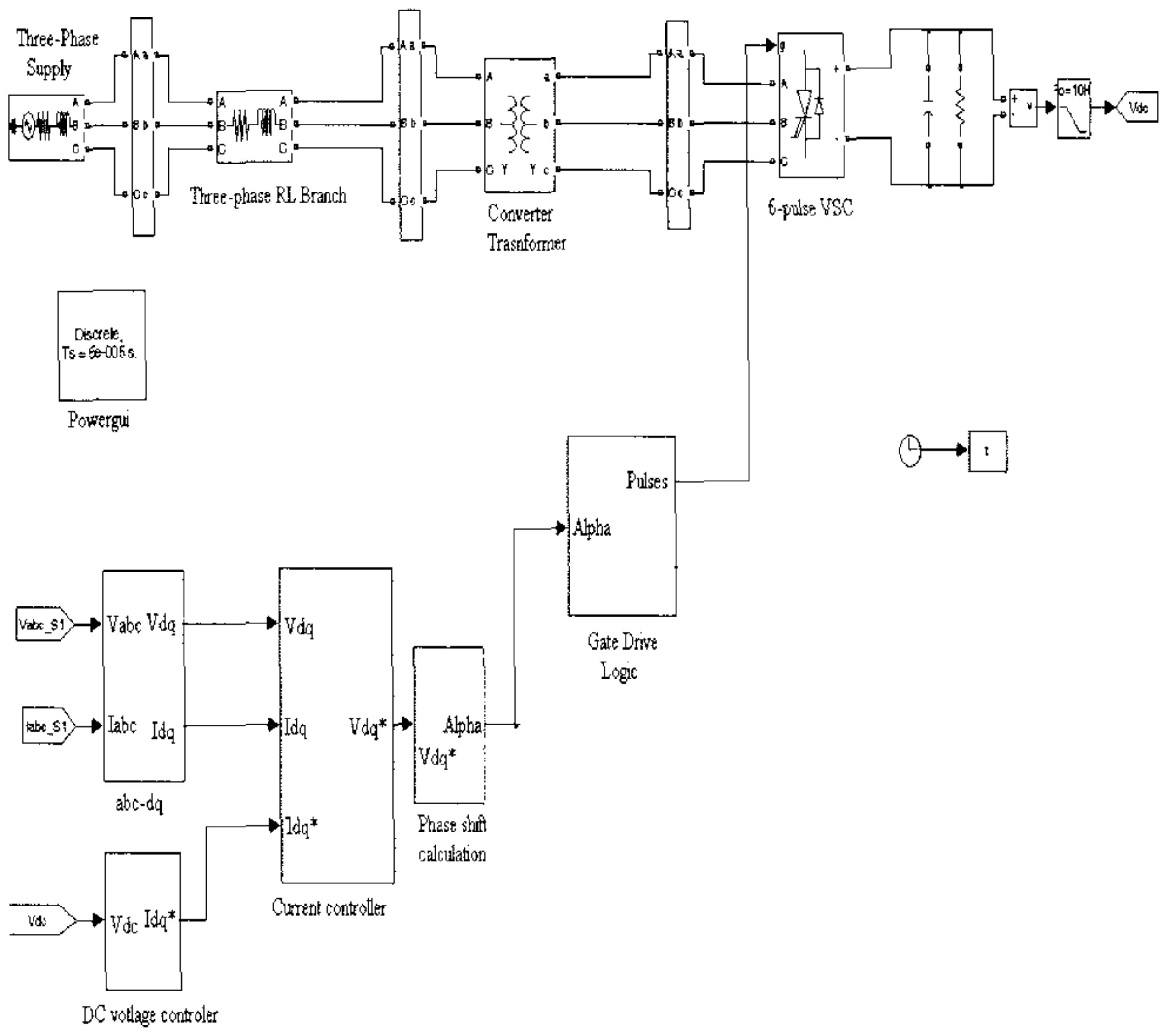


Fig. 4a MATLAB model of two-level, 6-pulse voltage source Converter

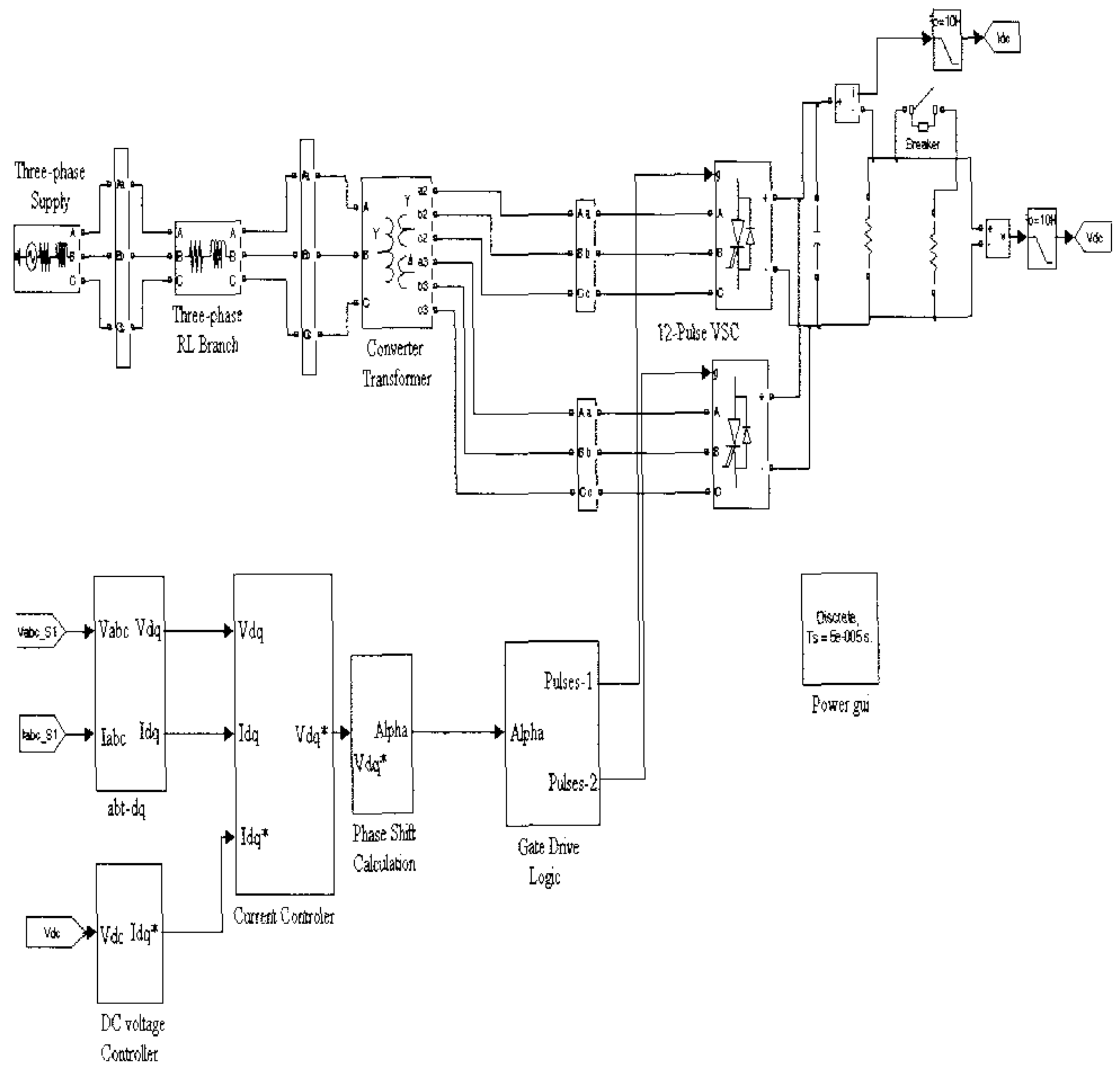


Fig. 4b MATLAB model of two-level, 12-pulse voltage source converter

Table 1 Performance with constant converter voltage

Power	V_s (pu)	V_{c1} (pu)	I (pu)	δ (deg)	Pf
10 %	1	1	0.1	1.146	0.9999
20 %	1	1	0.2	2.2924	0.9998
30 %	1	1	0.3001	3.4398	0.9995
40 %	1	1	0.4003	4.5886	0.9992
50 %	1	1	0.5006	5.7392	0.9987
60 %	1	1	0.6011	6.8921	0.9982
70 %	1	1	0.7017	8.0478	0.9975
80 %	1	1	0.8026	9.2069	0.9968
90 %	1	1	0.9037	10.3698	0.9959
100 %	1	1	1.0051	11.537	0.9949
110 %	1	1	1.1068	12.709	0.9939
120 %	1	1	1.2089	13.8865	0.9927

Table 2 Converter voltage variation for unity power factor

Power	V_s (pu)	V_{c1} (pu)	I (pu)	δ (deg)	Pf
10 %	1	1	0.1	1.146	0.9999
20 %	1	1	0.2	2.2924	0.9998
30 %	1	1	0.3001	3.4398	0.9995
40 %	1	1	0.4003	4.5886	0.9992
50 %	1	1.01	0.5006	5.6822	0.9987
60 %	1	1.01	0.6002	6.8235	0.9997
70 %	1	1.01	0.7	7.9676	1
80 %	1	1.01	0.8001	9.115	0.9999
90 %	1	1.02	0.9002	10.1642	0.9998
100 %	1	1.02	1	11.3077	1
110 %	1	1.02	1.1002	12.4558	0.9998
120 %	1	1.03	1.2	13.4743	1

Fig. 5a shows the variation of ac current with the fundamental converter voltage (V_{c1}). Fig. 5b shows the variation of power factor with the fundamental converter voltage (V_{c1}). It shows that the characteristic between ac current with the converter voltage is similar to the V curve of a synchronous machine. The unity power factor can be achieved with constant converter voltage at low powers. Fig. 5b shows the variation of the power factor with converter voltage, which is similar to the inverted V curve of the synchronous machine. When the converter voltage is increased, the power factor also improves and it attains unity at 1 pu power level. At these varying power levels, the power factor reaches unity for the converter voltage in the range of 1 pu to 1.03 pu. For the high power flow of the converter its voltage needs a little variation for maintaining the unity power factor. Fig. 6 shows the variation of power factor with the active power for the fixed fundamental converter voltage (V_{c1}) of 1.01 pu and 1.014 pu. The power factor is around 0.82 for the 10% of active power for the converter voltage of 1.014 pu, but it is unity for same power with the converter voltage of 1.01 pu.

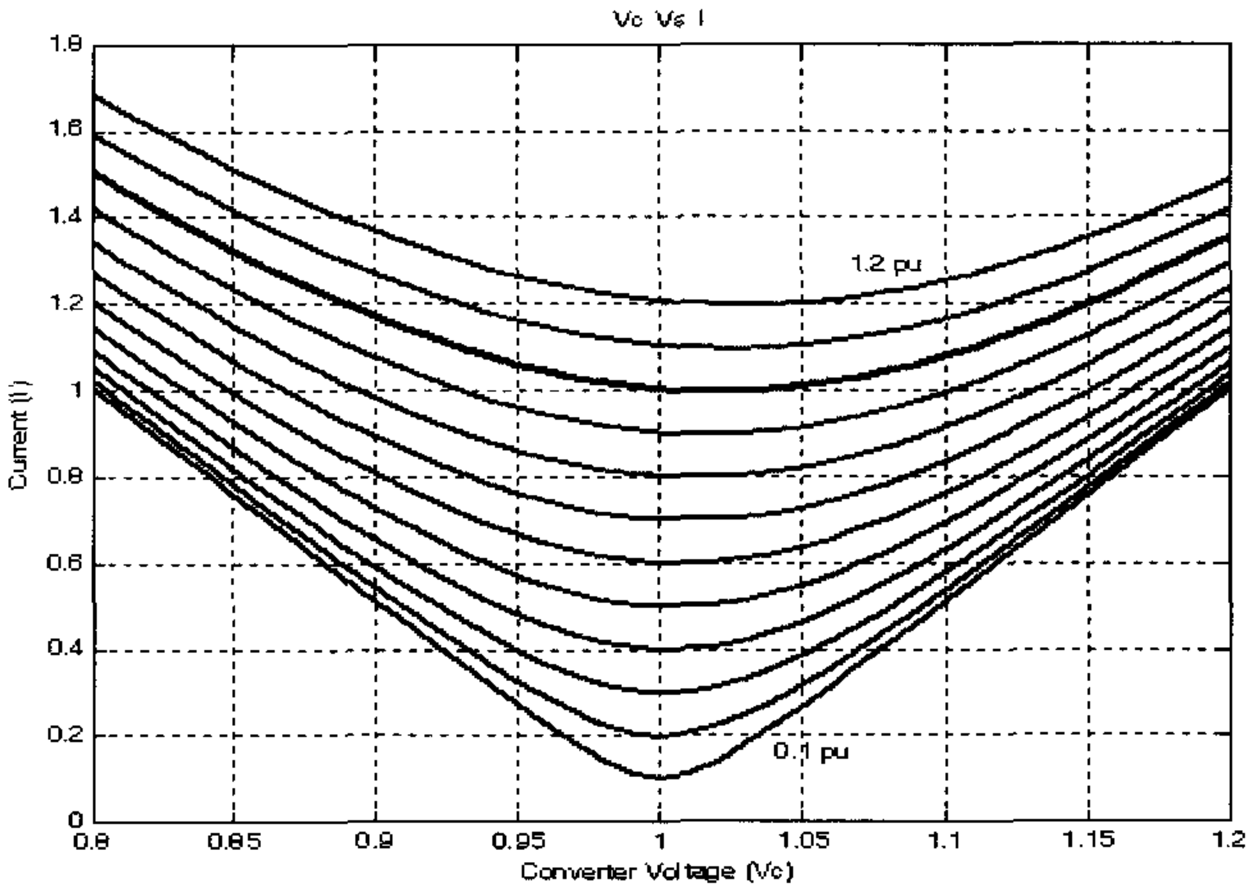


Fig. 5a Variation of Supply Current with Converter Voltage

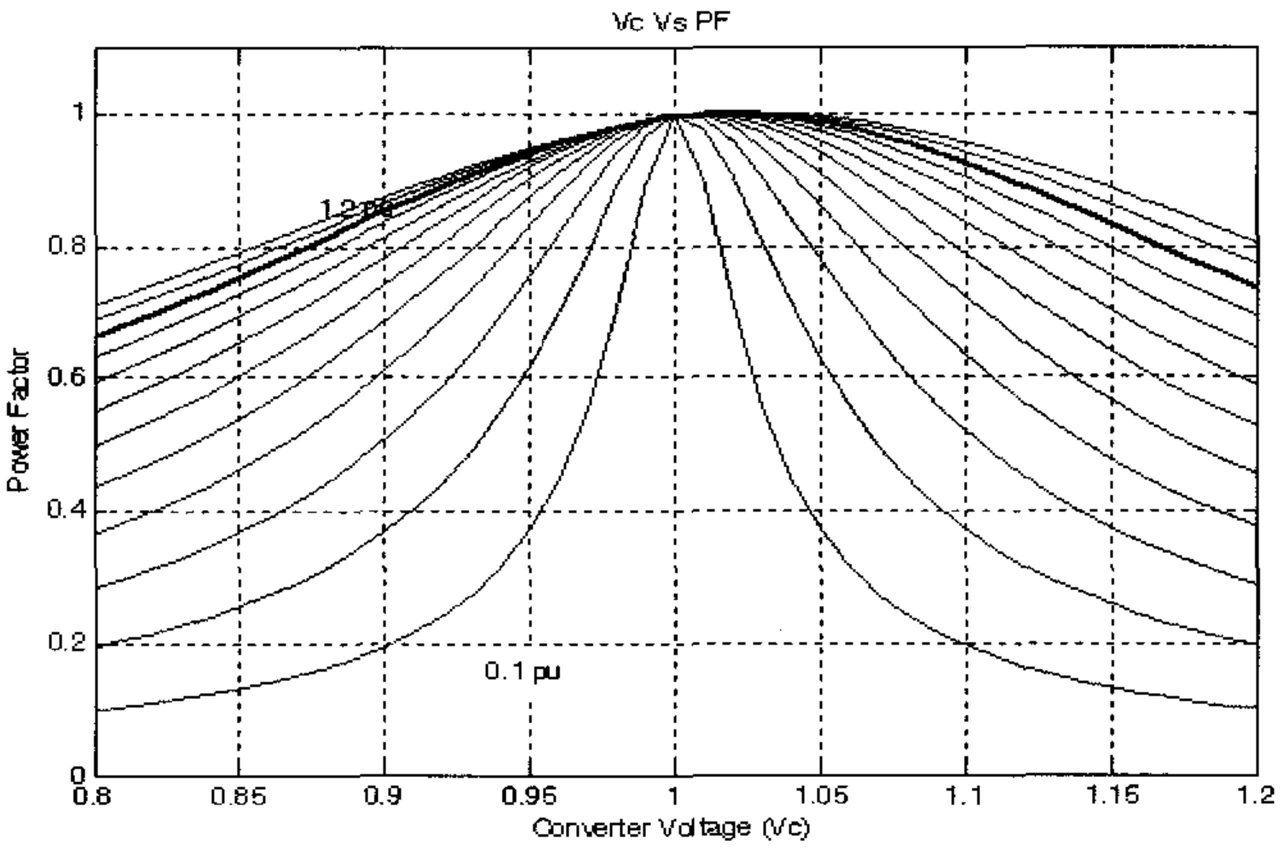


Fig. 5b Variation of Power factor with Converter Voltage

The interface reactance is considered as 20% in this system, which is one of the main parameters influencing the active power flow. The effect of varying the reactance is also studied on the performance of the system from 5% to 50%. Effect of this variation of reactance on the power factor and ac current is shown in Fig. 7a and Fig. 7b respectively. From these results it is observed that for a two-level converter, the power factor is improved with fixed dc voltage. This converter can be operated either in reactive power control mode or dc voltage control mode. For the reactive power control mode a small variation in the dc voltage is required to maintain reactive power to zero value.

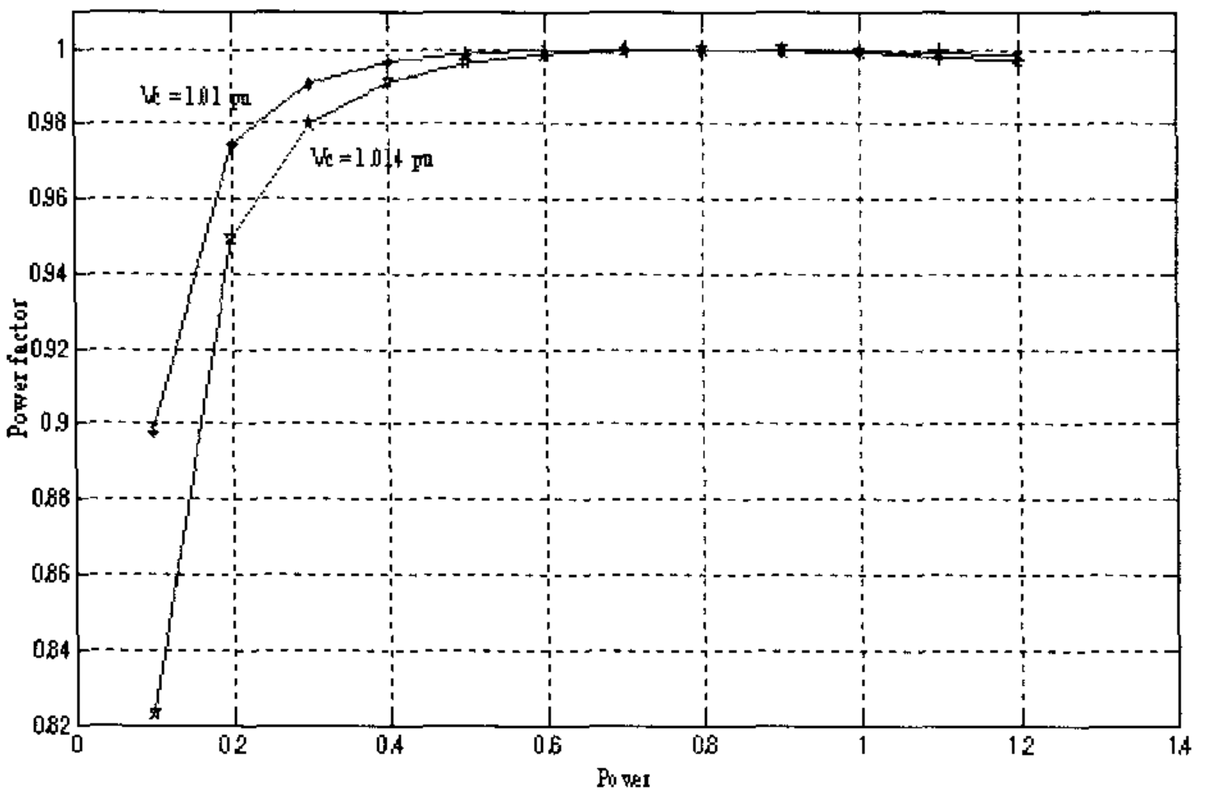


Fig. 6 Power factor variation with Power at V_c = 1.01 pu and 1.014 pu

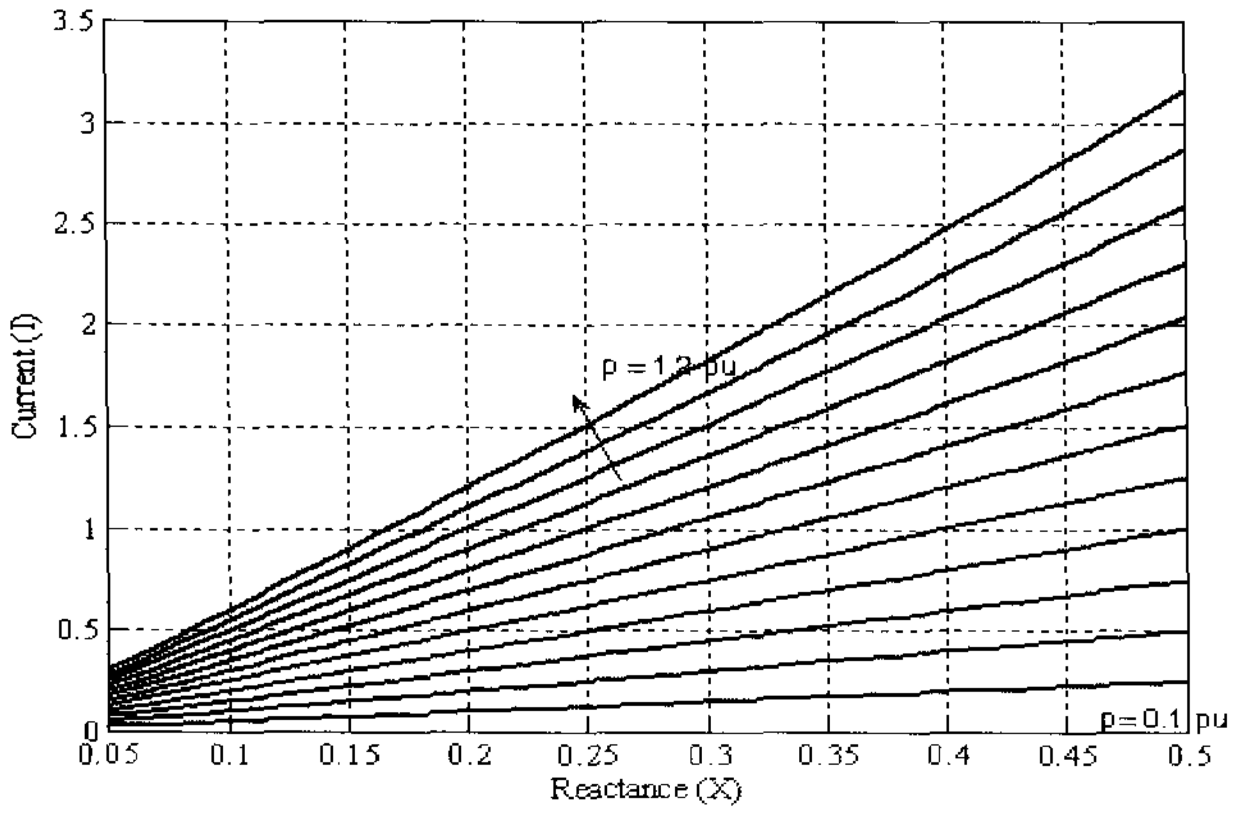


Fig. 7a Variation of Supply current with Reactance

Simulated performance of a two-level converter is shown in Fig. 8 and Fig. 9. The steady state and dynamic behavior of the converter are shown separately for both 6-pulse and 12-pulse voltage source converters. A 6-pulse GTO VSC bridge is used to realize a two level converter.

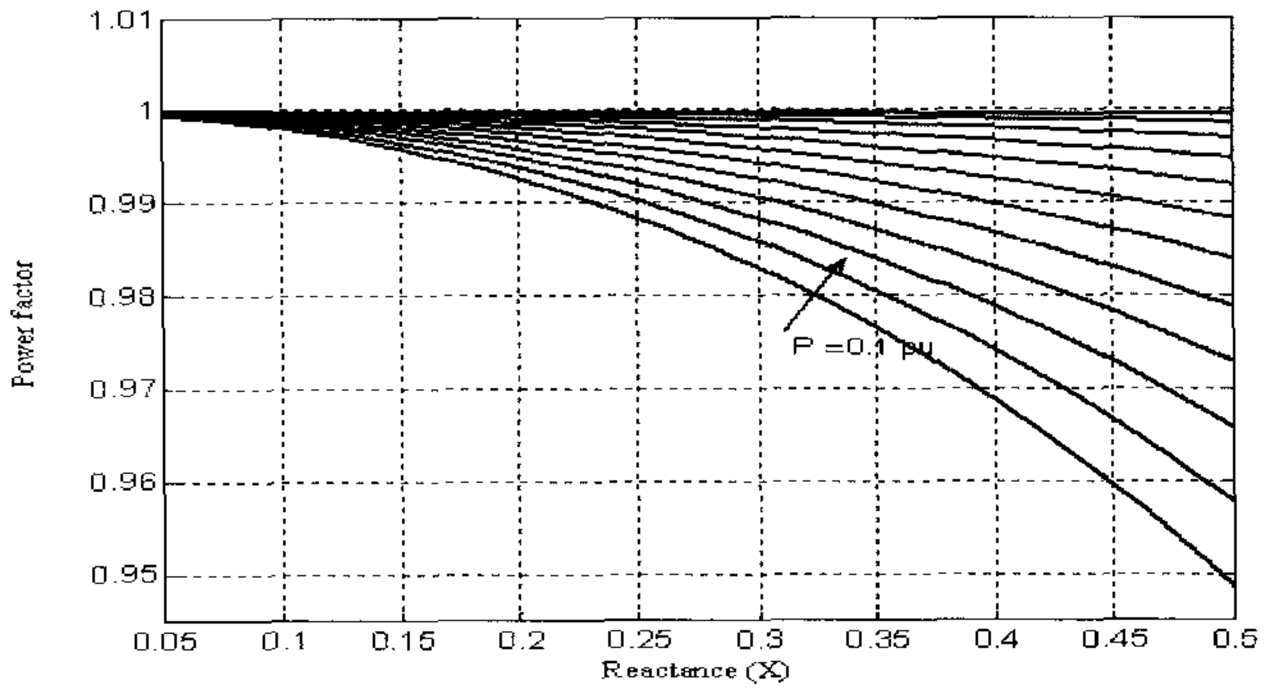


Fig. 7b Variation of power factor with Reactance

The switching of the bridge is carried out at fundamental frequency switching. In the steady state condition, the power demand at the dc side is maintained constant throughout the simulation as 100 MW, i.e 1 pu. The control is designed in such a way that the dc voltage is maintained constant to balance the power in ac and dc side. The power demand is also taken as power reference to the control system to keep the system in stable condition. The steady state performance is shown in Fig. 8a. During the dynamic performance the power demand at the dc side is increased from 50 MW to 100 MW at 0.5 sec. The behavior of the system during power change is shown in Fig. 8b. The designed control system acts immediately to bring back the dc voltage to its reference value to maintain the power balance. The voltage regulator compares the dc voltage with reference voltage and produces the reference current. In current control loop, the reactive current is compared with its reference value. The output of the PI controller is considered as a reference input to the current controller and it is taken as an angle (δ) between supply voltage and fundamental converter voltage required for the desired power flow. The pulse produced from the reference of the supply voltage using phase locked loop (PLL) is shifted by an angle (δ). The converter voltage is shifted by an angle δ from the supply voltage. This angle δ may be positive or negative depending on the direction of power flow. The reactive power drawn from the supply is maintained to zero value. The power factor at the supply side is maintained unity.

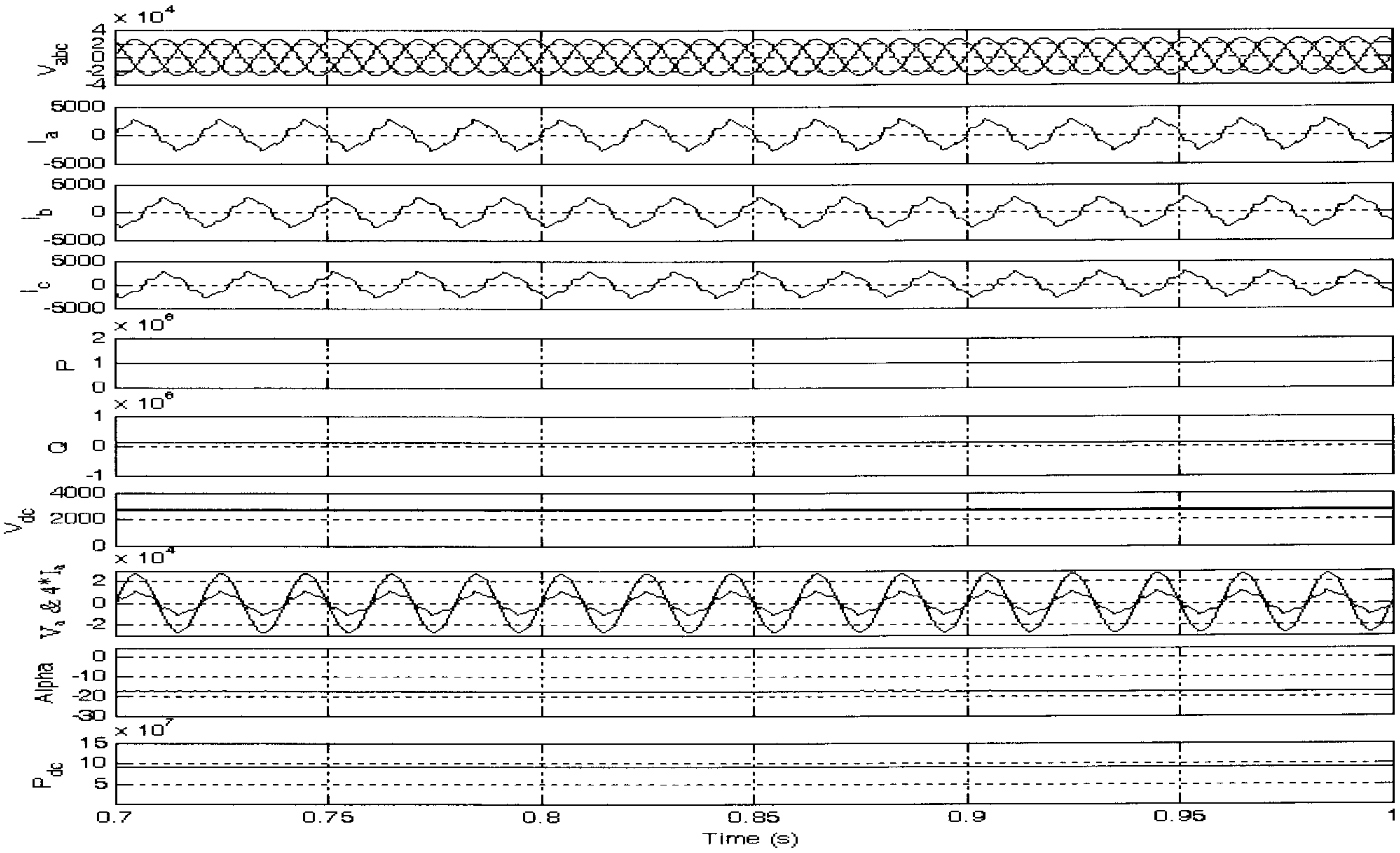


Fig. 8a Steady state performance of Two-Level, 6-pulse Voltage Source Converter

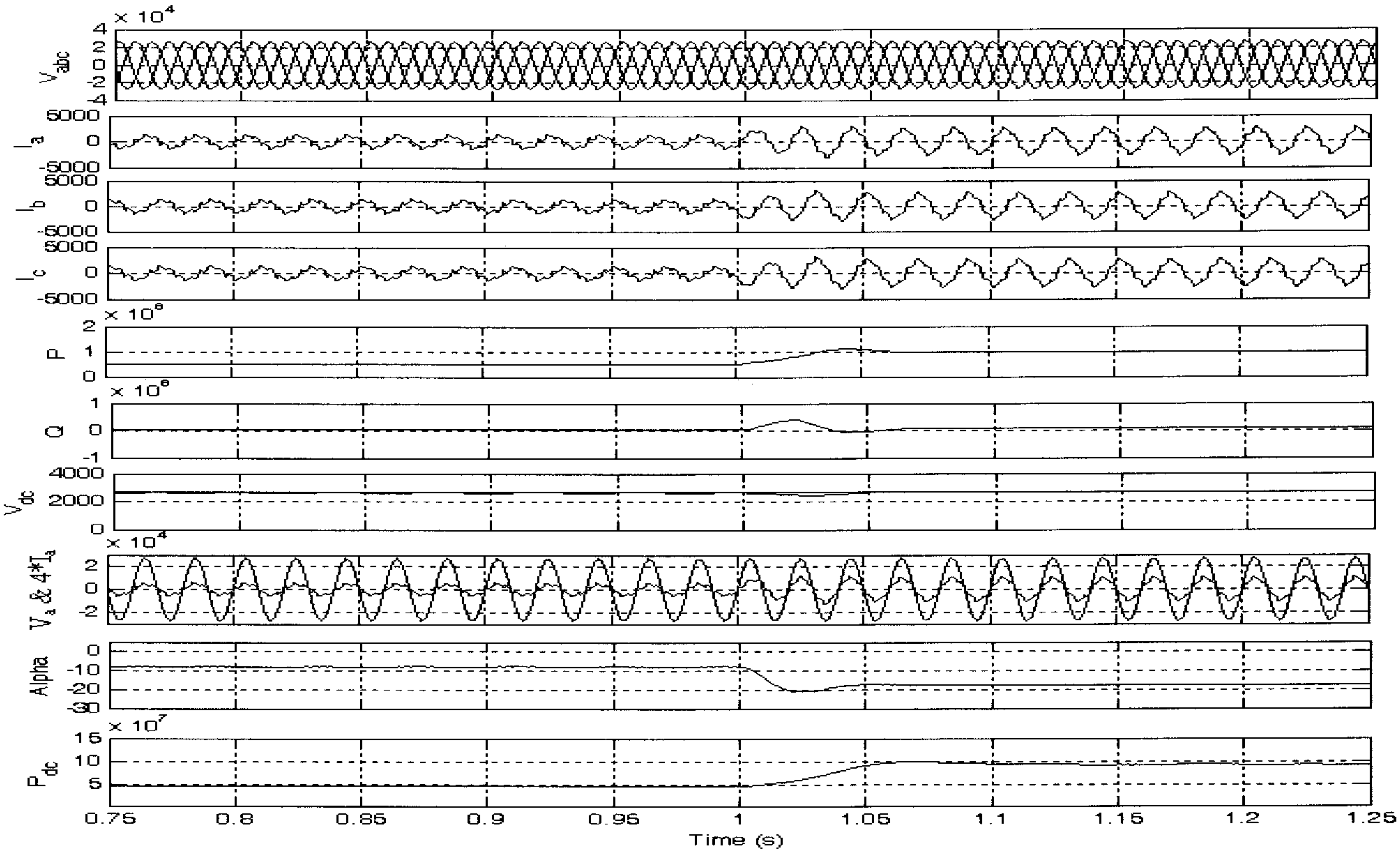
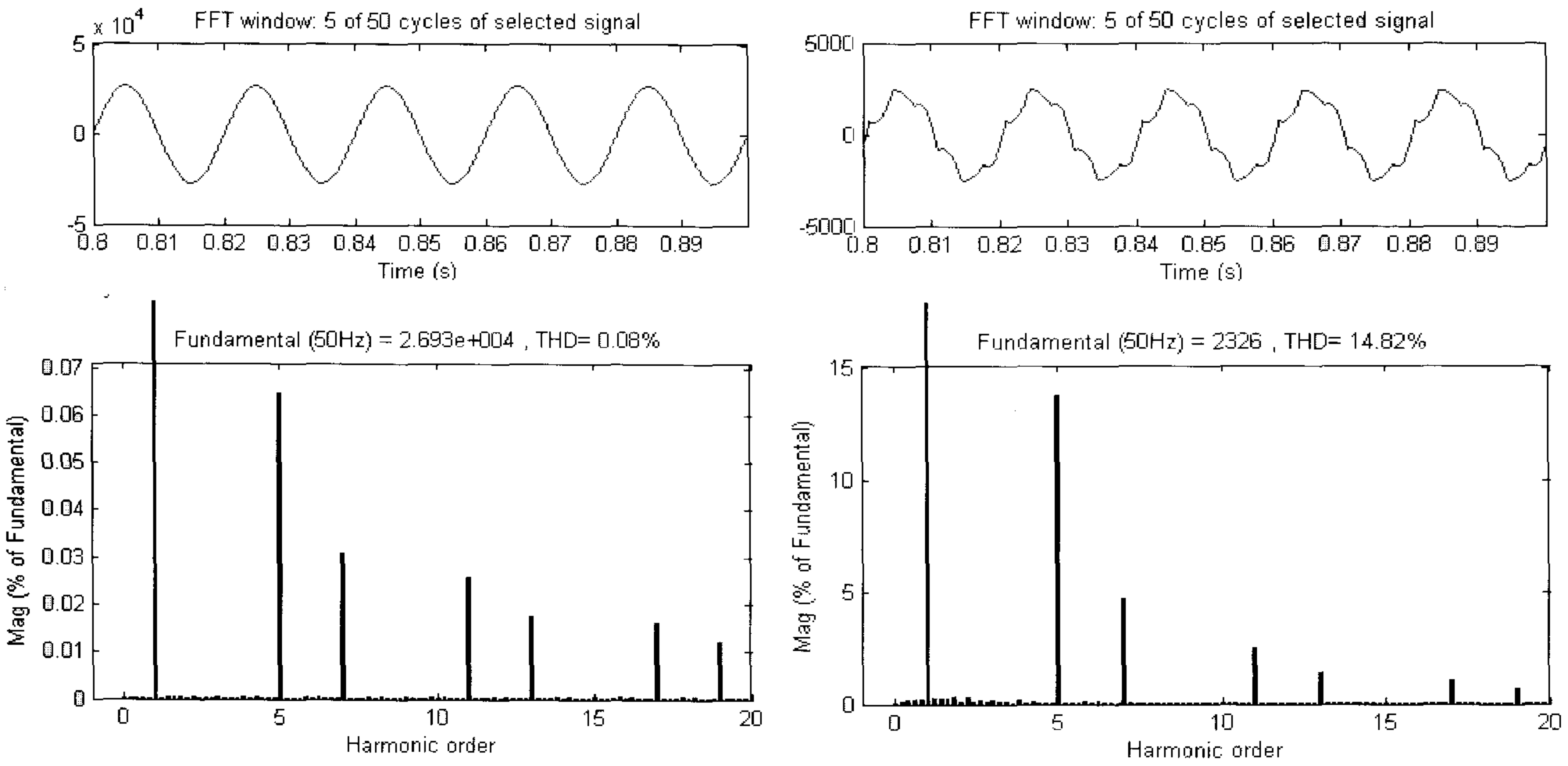


Fig. 8b Dynamic performance of Two-Level, 6-pulse Voltage Source Converter



(i) voltage (ii) current

Fig. 8c Hamonic spectra of Two-level, 6-pulse converter

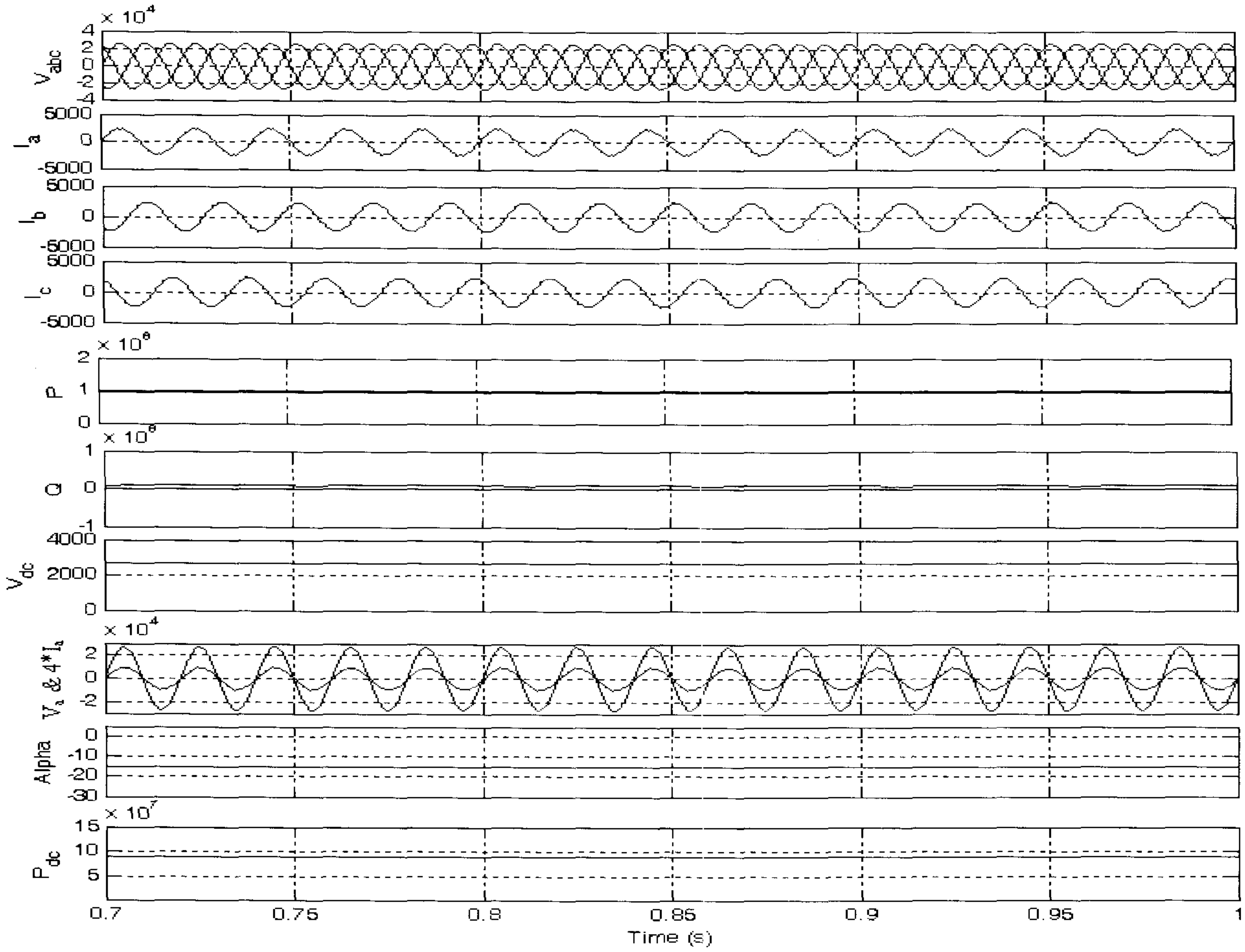


Fig. 9a Steady state performance of Two-Level, 12-pulseVoltage Source Converter

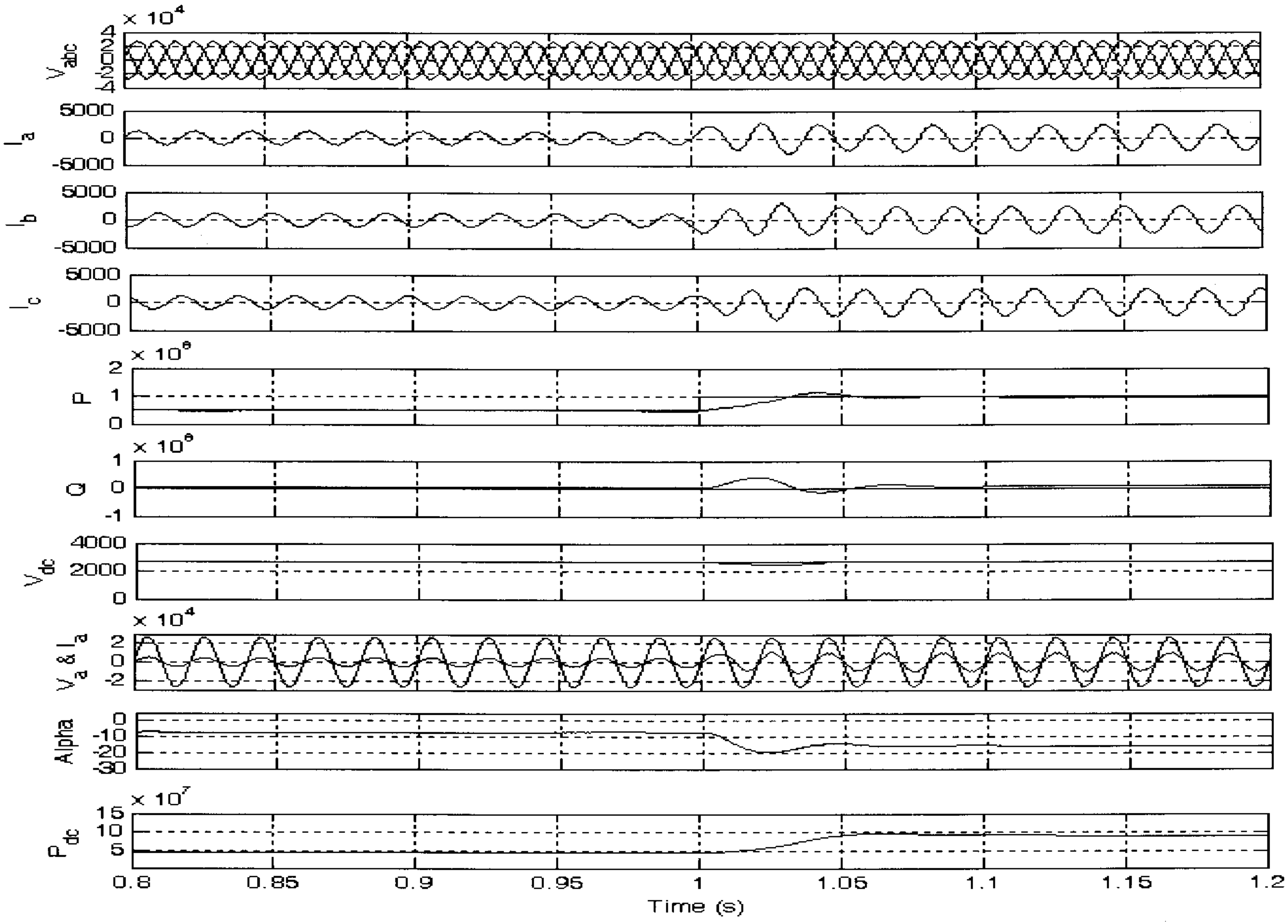
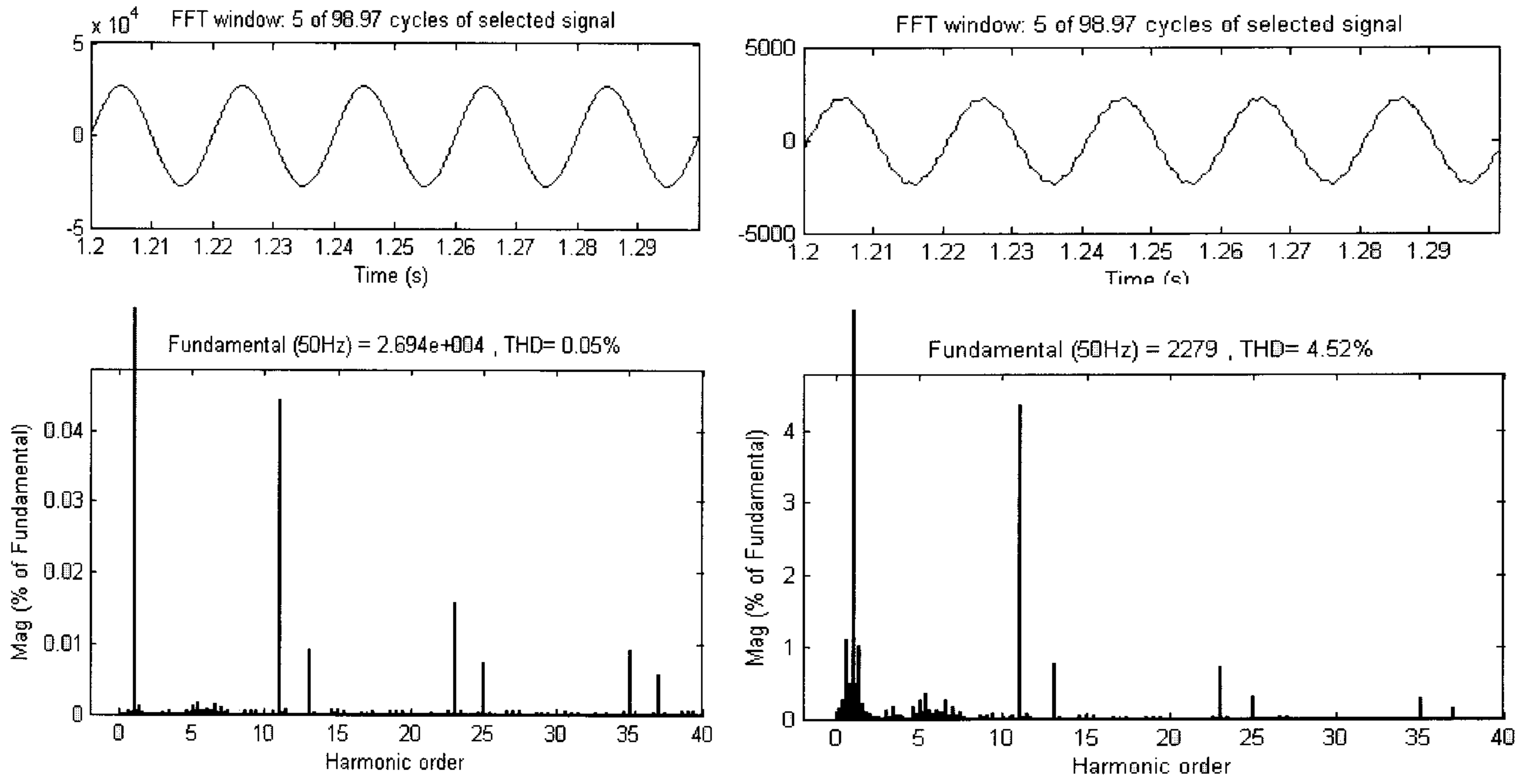


Fig. 9b Dynamic performance of Two-Level, 12-pulse Voltage Source Converter



(i) voltage (ii) current

Fig. 9c Hamonic spectra of Two-level, 12-pulse converter

The harmonic spectra of the supply voltage and current are shown in Fig. 8c. The THD of voltage and current for the 6-pulse converter operation is 0.08% and 14.82% respectively. The harmonics are reduced by using a 12-pulse converter and it is also tested and simulated for the same condition to improve the harmonic characteristics. The steady state and dynamic performance of a 12-pulse converter are shown in Fig. 9a and Fig. 9b respectively. The harmonics spectra of voltage and current are shown in Fig. 9c. The THD of ac current in 12-pulse VSC is reduced to 4.52% from 14.82% of 6-pulse VSC. The THD of voltage is 0.05%, where it is 0.08% for the 6-pusle converter. The phase voltage and phase current are observed in phase with each other as the displacement factor at the supply side is maintained unity during both steady state and dynamic operating conditions.

5. Conclusions

The two-level converter has been analyzed for HVDC systems. Simulation of performance of a two-level voltage source converter has been carried out in MATLAB. Two-level voltage source converter has been a robust for power flow control of high power transmission HVDC system. The presented results have shown that only small variation in dc voltage is required to maintain the unity power factor at the AC mains for wide variation in active power, with zero reactive power. Moreover, the proposed VSC system has exhibited the performance similar to a synchronous machine with bi-directional active power flow.

Appendix

Rated Power = 100 MW, Rated voltage = 33 kV, frequency = 50 Hz, DC-link voltage = 2.7 kV, AC link inductor = 0.2 pu, resistance 9R$_s$) = 0.0015 pu, C_{dc} = 15000 μF, converter switching device = GTO, switching frequency = 50 HZ, transformer voltage ration = 33/2.1 kV

References

[1] C. Adamson and N. G. Hingorani, "High voltage direct current power transmission", *Garraway Ltd*, London, 1960.

[2] C. Adamson, J. D. Ainsworth, B. J. Cory, L. L. Freris, L. A. Harris and J. H. M. Sykes, "High Voltage Direct Current Converters and Systems", *Macdonald & Co (Pub) Ltd*, 1965.

[3] E. W. Kimbark, "Direct Current Transmission", Wiley-Inter-Science, Vol. 1, New York, 1971.

[4] Erich Uhlmann, "Power Transmission by Direct Current", Springer- Verlag Berlin Heidelberg New York – 1975.

[5] K. R. Padiyar, "HVDC Power Transmission Systems: Technology and System Interactions", *New Age International (P) Limited Publishers*, New Delhi, 2007.

[6] J. Arrillaga, "High Voltage Direct Current Transmission", 2nd Edition, *IEE Power and Energy Series 29*, UK, 1998.

[7] Vijay K. Sood, "HVDC and FACTS Controller, Applications of Static Converters in Power Systems", *Kluwar Academic Publishers*, The Netherlands- 2004.

[8] J. Arrillaga, Y. H. Liu and N. R. Waston, "Flexible Power Transmission, The HVDC Options", *John Wiley & Sons*, Ltd, 2007.

[9] Z. Zhao and M. R. Iravani, "Applications for GTO voltage- source inverter for tapping HVDC power", *IEE Genert. Transn. Distri*, Vol. 141, No. 1, pp. 369-377, Jan-1994.

[10] Gunnar Asplund, Kjell Eriksson and kjell Svensson, "DC Transmission based on Voltage Source Converters", in Proc. of CIGRE SC14 Colloquium in South Africa 1997.

[11] Hirokazu Suzuki, Tatsuhito Nakajima, Kunikazu Mino, Sigeyuki Sugimoto, Yoshiaki Mino and Hideyuki Abe, "Development and Testing of Prototype Models for a High-Performance 300 MW Self-Commuated AC/DC Converter", *IEEE Trans. on Power Delivery*, Vol. 12, No. 4, pp. 1589-1601, Oct. 1997.

[12] Tatsuhito Nakajima and Shoichi Irokawa, "A Control System for HVDC Transmission by Voltage Sourced Converters", *in Proc. Rec. Power Engineering Society Summer Meeting*, Vol. 2, pp. 1113-1119, 1999.

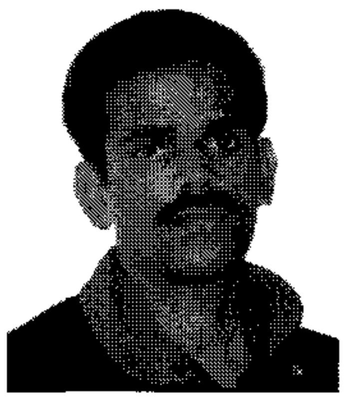
[13] Y. H. Liu R. H. Zhang, J. Arrillaga and N. R. Watson, "An Overview of Self-Commutating Converters and their Application in Transmission and Distribution", *in Conf. IEEE/PES Trans. and Distr.Conf. & Exhibition*, Asia and Pacific Dalian, China. 2005.

[14] José Rodríguez, Jih-Sheng Lai, and Fang Zheng Peng, "Multilevel Inverters: A Survey of Topologies, Controls, and Applications", *IEEE Trans. on Industrial Electronics,* Vol. 49, No. 4, pp.724-739. Augest 2002.

[15] Yong She H. Liu, Jos Arrillaga and Neville R. Waston, "A New High-Pulse Voltage-Sourced Converter for HVDC Transmission", *IEEE Trans. on Power Delivery*, Vol. 9 No.

4, pp. 1388-1393, Oct.2003.

[16] Makoto Hagiwara, Hideaki Fujita and H. Akagi, "Performance of a Self-Commutated BTB HVDC Link System under a Single-Line to-Ground Fault Condition", *IEEE Trans. on Power Electronics*, Vol. 18, No. 1, pp. 278-285, Jan. 2003.



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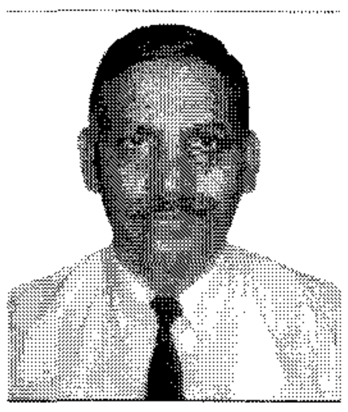
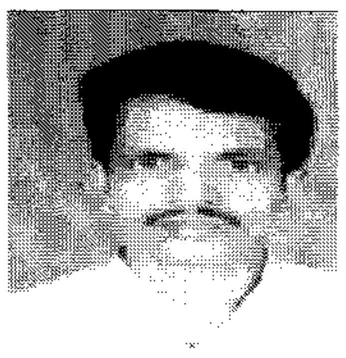


Bhim Singh was born in Rahamapur (UP), India, in 1956. He received B.E (Electrical) degree from the University of Roorkee, Roorkee, India, in 1977 and M.Tech and Ph.D. degrees from the Indian Institute of Technology (IIT) Delhi, New Delhi, India, in 1979 and 1983, respectively. In 1983, he joined the Department of Electrical Engineering, University of Roorkee, as a Lecturer, and in 1988 became a Reader. In December 1990, he joined the Department of Electrical Engineering, IIT Delhi, as an Assistant Professor. He became an Associate Professor in 1994 and Professor in 1997. His area of interest includes power electronics, electrical machines and drives, active filters, FACTS, HVDC and power quality. Dr. Singh is a fellow of Indian National Academy of Engineering (INAE), the Institution of Engineers (India) (IE (I)), and the Institution of Electronics and Telecommunication Engineers (IETE). He is also a life member of the Indian Society for Technical Education (ISTE), the System Society of India (SSI), and the National Institution of Quality and Reliability (NIQR) and Senior Member of Institute of Electrical and Electronics Engineers (IEEE).



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