

A Paper of Determination of Controlling Characteristics of the Monopolar HVDC System

Rajib Baran Roy¹ and Md. Ruhul Amin²

Assistant Professor¹, Lecturer²

*Department of Electrical and Electronic Engineering
University of Information Technology and Sciences (UITS)
Dhaka-1212, Bangladesh*

¹rajib.baran@uits.edu.bd; ²ruhul.amin@uits.edu.bd

Abstract

Due to cost effectiveness and less electrical fault hazards, the HVDC transmission is more suitable for long distance power transmission than that for the conventional AC transmission system. Moreover the utilization of power electronics has made HVDC technology competitive and reliable in comparison to HVAC system. The controlling mechanism of the DC link (either monopolar or bipolar) is the major concern for HVDC technology. Determination of control loop for system operation needs to commensurate with the conduction period of the semiconductor switching device. Generally IGBT and MOSFET are widely used as switching device whose delay angle, advance angle and extinction angle need to be matched with the controlling mechanism of the converter and inverter section. In this paper, the controlling characteristics of a monopolar HVDC system are determined by using MATLAB/Simulink. The Simpower tool box is used for designing the controlling blocks of the HVDC system. The controlling characteristics of the monopolar HVDC system can be determined from the simulation results of the gate currents of IGBT, output voltages of converter and inverter and modulation index.

Keywords: HVDC, monopolar, IGBT, delay angle, advance angle and extinction angle.

1. Introduction

High-voltage direct current (HVDC) transmission is a major user of power electronics technology. HVDC technology first made its mark in the early undersea cable interconnections of Gotland (1954) and Sardinia (1967), and then in long distance transmission with the Pacific Intertie (1970) and Nelson River (1973) schemes using mercury-arc valves. A significant milestone development occurred in 1972 with the first back-to-back (BB) asynchronous interconnection at Eel River between Quebec and New Brunswick; this installation also marked the introduction of thyristor valves to the technology and replaced the earlier mercury-arc valves. The cost of a transmission line comprises the capital investment required for the actual infrastructure like right-of-way (RoW), towers, conductors, insulators, and terminal equipment and costs incurred for operational requirements (i.e. losses). With similar insulation requirements for peak voltage levels for AC and DC lines, a DC line can carry as much power with two conductors as an AC line with three conductors of the same size.

Therefore, for a given power level, a DC line requires smaller RoW, simpler and cheaper towers, reduced conductor and insulator costs. With the DC option, since there are only two conductors (with the same current capacity as three AC conductors), the

power transmission losses are also reduced to about two-third of those of the comparable AC system. The absence of skin effect with DC is also beneficial in reducing power losses marginally, and the dielectric losses in the case of power cables are also very much less for DC transmission. Corona effects tend to be less significant for DC than for AC conductors. The other factors that influence line costs are the costs of compensation and terminal equipment. DC lines do not require reactive power compensation but the terminal equipment costs are increased because of the presence of converters and filters. The DC transmission system is more cost effective for long distance power transmission in comparison to that of AC transmission [2- 4].

The three phase fully controlled bridge converter has been probably the most widely used power electronic converter in the medium to high power applications. Three phase circuits are preferable when large power is involved. The controlled rectifier can provide controllable output DC voltage in a single unit instead of a three phase autotransformer and a diode bridge rectifier. The controlled rectifier is obtained by replacing the diodes of the uncontrolled rectifier with thyristors. Control over the output DC voltage is obtained by controlling the conduction interval of each thyristor. This method is known as phase control and converters are also called phase controlled converters [1-2]. Since thyristors can block voltage in both directions it is possible to reverse the polarity of the output DC voltage and hence feed power back to the AC supply from the DC side. Under such condition the converter is said to be operating in the inverting mode". The thyristors in the converter circuit are commutated with the help of the supply voltage in the rectifying mode of operation and are known as "Line commutated converter". The same circuit while operating in the inverter mode requires load side counter emf for commutation which is referred to as the "Load commutated inverter" [5-6].

In phase controlled rectifiers though the output voltage can be varied continuously the load harmonic voltage increases considerably as the average value goes down. Of course the magnitude of harmonic voltage is lower in three phase converter compared to the single phase circuit. Since the frequency of the harmonic voltage is higher and thereby inductive load goes into continuous conduction. Input current wave shape become rectangular and contain fifth higher order odd harmonics. The displacement angle of the input current increases with the firing angle whereas the frequency of the harmonic voltage and current can be increased by increasing the pulse number of the converter which can be achieved by series and parallel connection of basic 6 pulse converters[2,7]. With the introduction of high power IGBTs the three phase bridge converter has all but been replaced by DC link voltage source converters in the medium to moderately high power range [1, 5]. However in very high power application such as HVDC transmission system, cycloconverter drives and load commutated inverter synchronous motor bridge converter is still used. In this paper, the control characteristics of the HVDC system are determined. The AC-DC-AC block of the HVDC system is designed by MATLAB Simulink toolbox. The Simpower tool box is used for design and analysis of the converter and inverter block of the HVDC system. The determination of control characteristics of the DC link is also discussed in this paper because the controlling of the DC link is the major concern of any HVDC system.

2. Main components of the HVDC system

All printed material, including text, illustrations, and charts, must be kept within the parameters of the 8 15/16-inch (53.75 picas) column length and 5 15/16-inch (36 picas)

column width. Please do not write or print outside of the column parameters. Margins are 1 5/16 of an inch on the sides (8 picas), 7/8 of an inch on the top (5.5 picas), and 1 3/16 of an inch on the bottom (7 picas). The major components of an HVDC transmission system are the converter stations at the ends of the transmission system. In a typical two-terminal transmission system, both converter and an inverter are required. The role of the two stations can be reversed, as controls are usually available for both functions at the terminals. The major components of a typical 12-pulse bipolar HVDC converter station are as follows [2, 8-9]. The main components of a conventional HVDC system is shown in Figure 1.

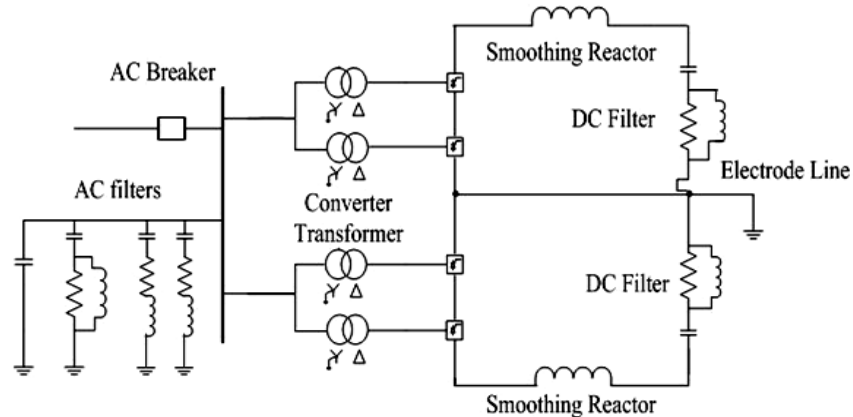


Figure 1. Main components of a conventional HVDC system.

2.1. Converter unit

This unit consists of two three-phase converter bridges connected in series to form a 12-pulse converter unit. The design of valves is based on a modular concept where each module contains a limited number of series-connected thyristor levels. The valves can be packaged as a single-valve, double-valve, or quadruple-valve arrangement. The Converter transformers are generally connected in star-star and star-delta arrangements to form a 12-pulse pair feed the converter. The ratings of a valve group are limited more by the permissible short-circuit currents than by the steady-state load requirements. Valve firing signals are generated in the converter control at ground potential and are transmitted to each thyristor in the valve through a fiber-optic light-guide system. The light signal received at the thyristor level is converted to an electrical signal using gate-drive amplifiers with pulse transformers. However recent trends are to direct optical firing of the valves with LTT thyristors. The valves are protected using snubber circuits, protective firing and gapless surge arrestors.

2.2. Converter transformer

The converter transformer can have different configurations like single phase (two winding and three winding) and three phase (two winding). The valve-side windings are connected in star and delta with neutral point ungrounded. On the AC side, the transformers are connected in parallel with the neutral grounded. The leakage impedance of the transformer which varies between 15 and 18% is chosen to limit the short-circuit current through any valve. The converter transformers are designed to withstand DC voltage stresses and increased eddy-current losses due to harmonic

currents. One problem that can arise is due to the DC magnetization of the core due to unsymmetrical firing of valves.

2.3. Filters

Due to the generation of harmonics by the converter, it is necessary to provide suitable filters on the ac–DC sides of the converter to improve the power quality and meet telephonic and other requirements. Generally, three types of filters are used for this purpose: ac, DC, and high-frequency filters. AC Filters are passive circuits used to provide low impedance shunt paths for AC harmonic currents. Both tuned and damped filter arrangements are used. In a typical 12-pulse station, tuned filters are required for elimination of the 11th and 13th harmonics whereas damped filters (normally tuned to the 23rd harmonic) are required for the higher harmonics. Double- or even triple tuned filters exist to reduce the cost of the filter. DC filters are used for the filtering of DC harmonics. Usually a damped filter at the 24th harmonic is utilized. Modern practice is to use active DC filters. High frequency filters are connected between the converter transformer and the station AC bus to suppress any high-frequency currents. Sometimes such filters are provided on the high-voltage DC bus connected between the DC filter and DC line and also on the neutral side.

2.4. Reactive power source

Converter stations consume reactive power that is dependent on the active power loading (typically about 50% to 60% of the active power). The AC filters provide part of this reactive power requirement. In addition, shunt (switched) capacitors and static var systems are also used.

2.5. DC smoothing reactor

A sufficiently large series reactor is used on the DC side of the converter to smooth the DC current and for converter protection from line surges. The reactor is usually designed as a linear reactor and may be connected on the line side, on the neutral side, or at an intermediate location.

2.6. DC switchgear

This is usually modified AC equipment and used to interrupt only small DC currents (i.e., employed as disconnecting switches). DC breakers or metallic return transfer breakers (MRTB) are used, if required, for the interruption of rated load currents. However AC switchgear and associated equipment for protection and measurement are also part of the converter station.

2.7. DC cables

In contrast to the use of AC cables for transmission, DC cables do not have a requirement for continuous charging current. Hence the length limit of about 50 km does not apply. Moreover, DC voltage gives less aging and hence a longer lifetime for the cable. The new design of HVDC Light cables are based on extruded polymeric insulating material instead of classic paper–oil insulation, which has a tendency to leak. Because of their rugged mechanical design, flexibility, and low weight, polymer cables can be installed underground cheaply with a plowing technique, or in submarine applications can be laid in very deep waters and on rough sea-bottoms. Since DC cables

are operated in bipolar mode, one cable with positive polarity and one cable with negative polarity, very limited magnetic fields result from the transmission. HVDC Light cables have successfully achieved operation at a stress of 20 kV/mm.

3. Operating principal of bridge converter

The reactive power of the system is increased due to the increased load in the transmission line; the current is lagging with respect to voltage. A three phase fully controlled converter is obtained by replacing all the six diodes of an uncontrolled converter by six thyristors which is shown in figure 2. For any current to flow in the load at least one thyristor from the top group (T_1, T_3, T_5) and one thyristor from the bottom group (T_2, T_4, T_6) must conduct. However in case of an uncontrolled converter, one thyristor from these two groups needs to conduct. In order to keep synchronization in three phase system it is necessary that each thyristor conducts for 120° of the input cycle. The thyristors are fired in the sequence $T_1 \rightarrow T_2 \rightarrow T_3 \rightarrow T_4 \rightarrow T_5 \rightarrow T_6 \rightarrow T_1$ with 60° interval between each firing. Therefore thyristors on the same phase leg are fired at an interval of 180° and hence cannot conduct simultaneously.

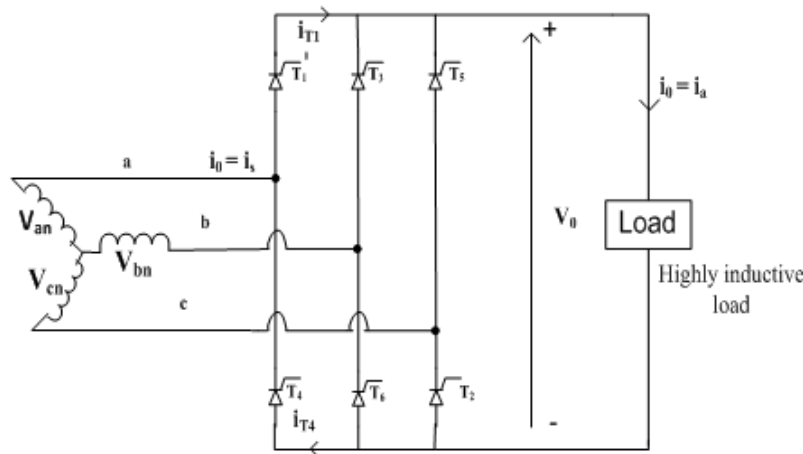


Figure 2. Fully controlled converter

So there are six possible conduction modes for the converter in the continuous conduction mode of operation. These are $T1T2, T2T3, T3T4, T4T5, T5T6,$ and $T6T1$. Each conduction mode is of 60° duration and appears in the sequence mentioned. The diagram of the line voltages and gate currents are shown in Figure 3. Each of these line voltages is associated with the firing of the thyristors. When the thyristor $T1$ is fired at the end of $T5 T6$ conduction interval and during this period the voltage across $T1$ is V_{ac} . Therefore $T1$ is fired α angle after the positive going zero crossing of V_{ac} . Other thyristors are operated in the similar manner. All the thyristors are fired in the correct sequence with 60° interval between each firing.

When the converter firing angle is α then each thyristor is fired α angle after the positive going zero crossing of the corresponding line voltage with which its firing is associated.

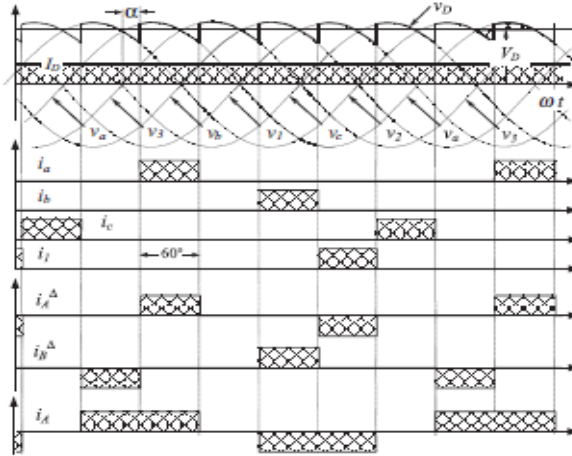


Figure 3. Line voltages and gate currents of converter

It is clear from the waveforms that output voltage and current waveforms are periodic over one sixth of the input cycle. Therefore this converter is also called the six pulse converter.

3.1. Analysis of the converter

The theoretical analysis of a six pulse converter is mentioned below,

$$V_{dr} = V_{dor} \cdot \cos \alpha - R_{cr} I_d \quad (1)$$

Where, $V_{dor} = \frac{3}{\pi} \cdot \sqrt{2} \cdot V_{LL}$ and $R = \left(\frac{3}{\pi}\right) \omega L_{cr}$

For an inverter: There are two options possible, depending on choice of either the advance angle β or extinction angle α for extinction angle γ as the control variable.

$$-V_{di} = V_{doi} \cdot \cos \beta + R_{ci} I_d \quad (2)$$

$$-V_{di} = V_{dor} \cdot \cos \gamma + R_{cr} I_d \quad (3)$$

Where, V_{dr} and V_{di} are the DC voltage at the rectifier and inverter respectively whereas V_{dor} and V_{doi} are the open-circuit DC voltage at the rectifier and inverter respectively.

The I_d is DC current, α is delay angle, β is advance angle at the inverter ($\beta = \pi - \alpha$), γ is extinction angle at the inverter ($\gamma = \pi - \alpha - \mu$) and μ is overlap angle at the inverter.

$$V_{dor} = \left(\frac{3}{\pi}\right) * 1.414 * V_{LLr}, V_{doi} = \left(\frac{3}{\pi}\right) * 1.414 * V_{LLi} \quad (4)$$

$$R_{cr} = \left(\frac{3}{\pi}\right) * \omega * L_{cr}, R_{ci} = \left(\frac{3}{\pi}\right) * \omega * L_{ci} \quad (5)$$

Here V_{LLr} and V_{LLi} are the line-line voltages at the rectifier and inverter, respectively and R_{cr} and R_{ci} are the equivalent commutation resistance at the rectifier and inverter,

respectively. The L_{cr} and L_{ci} are the leakage inductances of the converter transformer at rectifier and inverter, respectively.

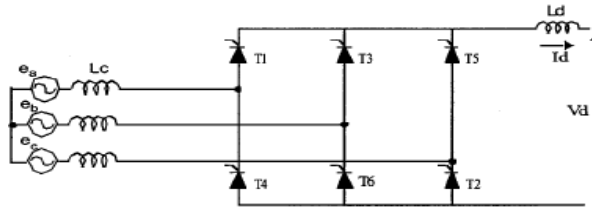


Figure 4. Converter Six pulse bridge circuit

4. Basics of control for a two terminal DC

From converter theory, the relationship between the DC voltage V_d and DC current I_d is given in equations 1 to 3. It is to be noted that the beta characteristics has a positive slope where the gamma characteristics has negative slope. According to the control strategy, the rectifier should be in constant current control mode where as the inverter should be in constant extinction angle (CEA) control mode. The control strategy is illustrated in figure 5. The rectifier characteristic is composed of two control modes, alpha-min (line AB) and constant current (line BC). The alpha-min mode of control at the rectifier is imposed by the natural characteristics of the rectifier AC system and the ability of the thyristors to operate at alpha equal to zero.

However since a minimum positive voltage is desired before firing of the thyristors to ensure conduction, an alpha-min limit of about 2° to 5° is imposed. The inverter characteristics is composed of two modes, gamma min (line PQ) and constant current (line QR). The operating point for the DC link is defined by the crossover point X of the two characteristics. In addition a constant current characteristic is also used at the inverter. However the current demanded by the inverter I_{di} is usually less than the current demanded by the rectifier I_{dr} by the current margin ΔI that typically about 0.1p.u.

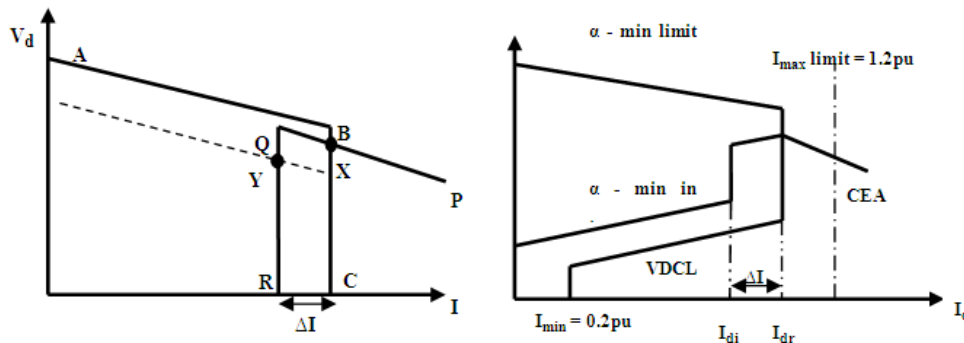


Figure 5. Control characteristics of two terminal DC link

The current margin is selected to be large enough that the rectifier and inverter constant current modes do not interact because of any current harmonics which may be superimposed on the DC current. This control strategy is termed as the current margin method. The advantage of this control strategy becomes evident if there is a voltage decrease at the rectifier AC bus. The operating point then moves to point Y. Consequently the current transmitted will be reduced to 0.9 pu of its previous value and voltage control will shift to the

rectifier. However the power transmission will be largely maintained near to 90% of its original value. The control strategy usually employs the following modifications in order to improve the behavior during system disturbances.

At the converter side, the modification is required to limit the DC current as a function of either the DC voltage or AC voltage. This modification assists the DC link to recover from faults which is called the voltage dependent current limit (VDCL). The I_d -min limit (0.2 ~ 0.3 p.u) is to ensure a minimum DC current to avoid the possibility of DC current extinction caused by the thyristor current dropping below the hold on current which could arise harmonics superimposed on the low value of the DC current. The resultant current chopping would cause high over voltages to appear on the converter. The magnitude of I_d -min is affected by the size of the smoothing reactor employed.

At the inverter side, the inverter is not allowed to operate inadvertently in the rectifier region i.e. a power reversal occurring because of an inadvertent current margin sign change. In order to ensure this an alpha minimum limit of about 100 -1100 is imposed in inverter mode. When the inverter operates into a weak AC system, the slope of the CEA control mode characteristics is quite steep and may cause multiple crossover points with the rectifier characteristics is quite steep and may cause multiple crossover points with the rectifier characteristic. To avoid this possibility, the inverter CEA characteristic is usually modified into either a constant beta characteristic or constant voltage characteristic within the current error region.

The equidistant pulse firing control systems used in modern HVDC system uses independent voltage controlled oscillator (VCO) to decouple the direct coupling between the firing pulses and the commutation voltage, V_{com} . In order to synchronize the firing pulses, an independent oscillator can be used which is synchronously locked to the AC commutation voltage frequency. The advantage of using independent oscillator is to provide an ideal sinusoidal for synchronizing and timing purposes which can be operated on fixed frequency and variable frequency modes. The control loop for frequency tracking purposes would also need to consider the mode of operation for the DC link. The method widely adopted for DC link operation is called current margin method.

5. Current control loops

In conventional HVDC systems, a PI regulator is used for the converter current controller. For constant I_d and small changes in α ,

$$\Delta V_d / \Delta \alpha = -V_d \sin \alpha$$

From the above equation it can be said that the maximum gain ($\Delta V_d / \Delta \alpha$) occurs when $\alpha = 90^\circ$. Thus the control loop must be stabilized for normal operation within the range of 12-180. However the PI regulator is used with fixed gains and it is difficult to select the optimal gain. The similar current control loop is used at the inverter which has a gamma controller and the selection between the control loops of converter and inverter is made via a minimum select block. Moreover in order to bias the inverter current controller off, a current margin signal ΔI is subtracted from the current reference I_{or} received from the rectifier via a communication link. The current control loops for converter and inverter are shown in figures 6 and 7. It is necessary to coordinate the converter and inverter to maintain a current margin of about 10 between the two terminals at all times otherwise there is a risk of loss of margin and the DC voltage could run down. At the inverter end there are two known methods for a gamma control look for determining the extinction angle which are predictive and direct

method. In either case, a delay of one cycle occurs from the indication of actual gamma and the reaction of the controller to this measurement.

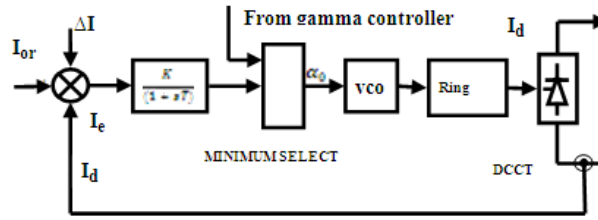


Figure 6. Current control loop of converter

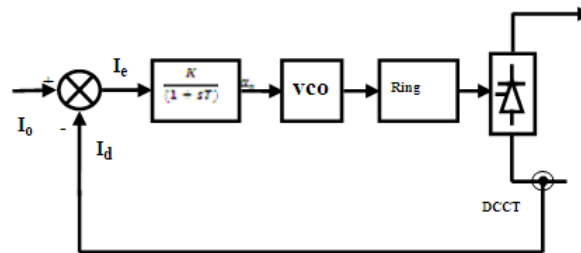


Figure 7. Current control loop of inverter

The predictive measurement tries to maintain the commutation voltage-time area after commutation larger than a specified minimum value. Since the gamma prediction method corrects gamma by means of a feedback loop that calculated the error between the predicated value and actual value of gamma. The predictor calculates continuously by triangular approximation where the overlap commutation voltage-time area is directly proportional to direct current and the leakage impedance value of the converter transformer. In case of direct measuring method, the gamma measurement is derived from a measurement of the actual value voltage. An internal timing waveform consisting of a ramp function of fixed slope is generated after being initiated from the instant of anode current zero. This value corresponds to a direct voltage proportional to the last value of gamma which is compared to a gamma reference value and a PI regulator defines the dynamic properties of the controller. The 12 pulse circuit generates 12 gamma measurements from which the minimum gamma value is selected and then used to derive the control voltage for the firing pulse generator with symmetrical pulses. The waveforms for the gamma measuring are shown in figure 8.

The bipole (master) controller is usually located at one end of the DC link and receives its power order from a centralized system dispatch center. The bipole controller derives a current order for the pole controller using a local measurement of either AC or DC voltage. Other inputs may also be used by the bipole controller such as frequency control for damping or modulation purposes.

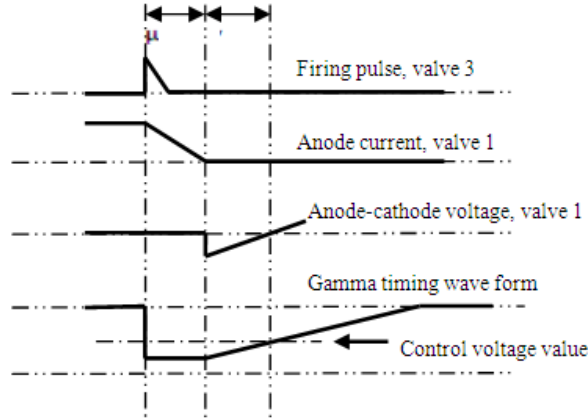


Figure 8. Waveforms for measuring gamma

The converter group controllers generate the firing pulses for the converter and receive measurements of DC current, DC voltage and AC current into the converter transformer. These measurements assist in the rapid alternation of firing angle for protection of the converter during perturbations. The gamma feedback controller is shown in figure 9.

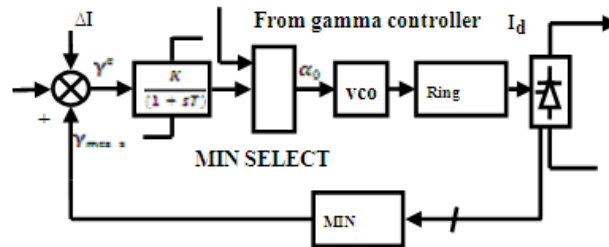


Figure 9. Gamma feedback controller

5.1. Operation of multiterminal DC system

Most HVDC transmission systems are two terminal systems, A multiterminal DC system (MTDC) has more than two terminals and there are two existing installations of this type. There are two possible ways of tapping power from an HVDC link. A monopolar version of a three terminal series DC link is shown in the figure 10. In a series DC system, the DC current is set by one terminal and is common to all terminals; the other terminals are operated at a constant delay angle for a rectifier and constant extinction angle for inverter operation with the help of transformer tap changers. Power reversal at a station is achieved by reversing the DC voltage with angle control. From an evaluation of ratings and costs for series taps it is not practical for the series tap to exceed to 20% of the rating for a major terminal in the MTDC system. A monopolar version of a three terminal series and parallel DC link is shown in figure 11. In a parallel MTDC system, the system voltage is common to all terminals. There are two possible configuration for a parallel MTDC system, radial and mesh which is shown in figure 12.

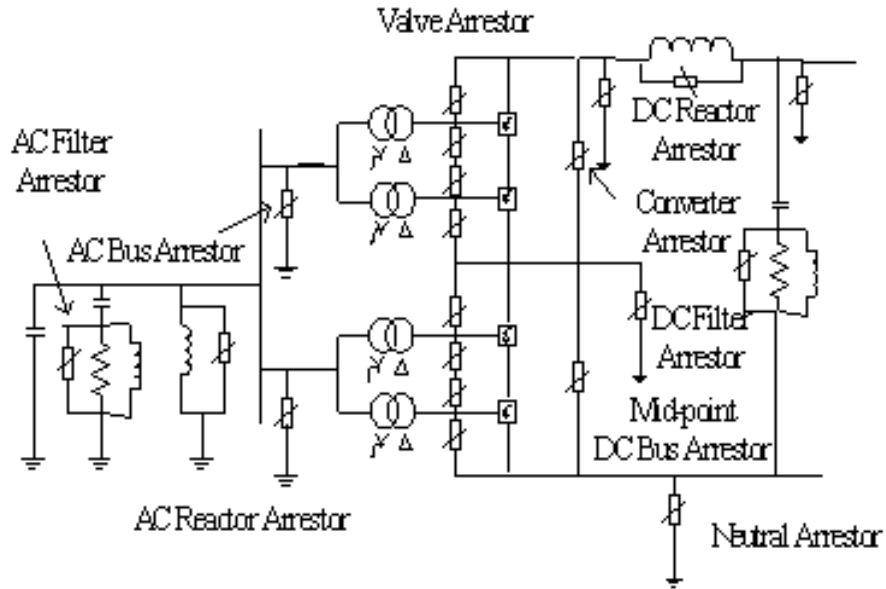


Figure 10. Surge arrestors of monopolar version of three terminal DC series link

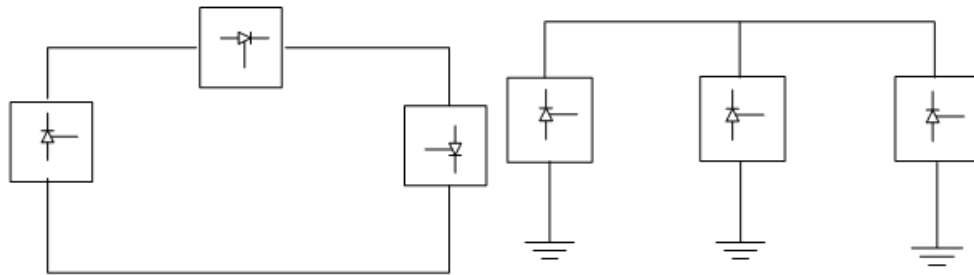


Figure 11. Block diagram of monopolar version of series and parallel DC link

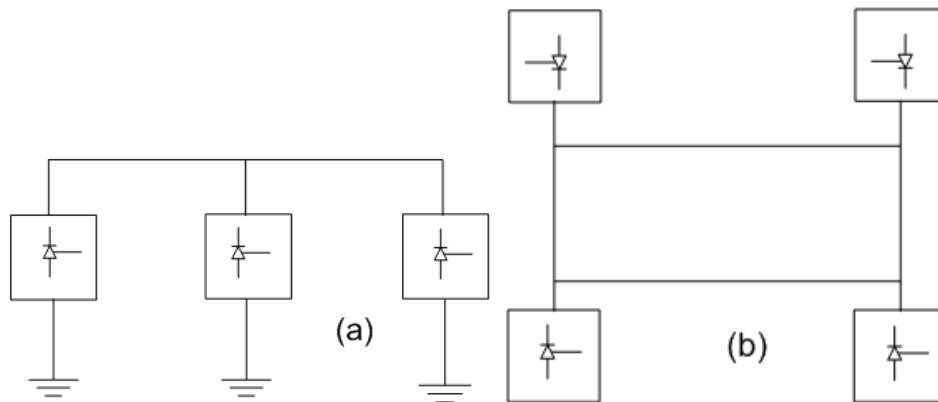


Figure 12. Block diagram of (a) radial type and (b) mesh type DC link

In a radial system, disconnection of one segment of the system will interrupt power from one or more terminals. In a mesh system, the removal of one segment will not interrupt power flow, provided the remaining links are capable of carrying the required power. The power reversal in a parallel system will require mechanical switching of the links, as the DC voltage cannot be reversed. From an evaluation of ratings and costs for parallel taps it is not practical for the parallel top to be less than 20% of the rating for a major terminal in the MTDC system.

6. Design of AC-DC-AC PWM converter and inverter for HVDC system

The AC-DC-AC PWM converter and inverter for HVDC system are designed by using MATLAB Simulink and Simpower tools in order to determine the controlling characteristics of the monopolar HVDC system. A 60 Hz, voltage source feeds a 50 Hz, 50 kW load through an AC-DC-AC converter. The 600V, 60 Hz voltage is obtained at secondary of the Y- Δ transformer which is first rectified by a six pulse IGBT bridge. The filtered DC voltage is applied to an IGBT two-level inverter generating 50 Hz. The IGBT inverter uses Pulse Width Modulation (PWM) at a 2 kHz carrier frequency. The circuit is discrete at a sample time of 2 μ s. The load voltage is regulated at 1 pu (380 V rms) by a PI voltage regulator. The first output of the voltage regulator is a vector containing the three modulating signals used by the PWM Generator to generate the 6 IGBT pulses. The second output returns the modulation index. The multimeter block is used to observe IGBT currents. In order to allow further signal processing, signals displayed on scope1 block (sampled at simulation sampling rate of 2 μ s) are stored in a variable named 'psbbridges_str' (structure with time). The figure 13 shows the block simulated block diagram of the AC-DC-AC PWM Converter and Inverter for monopolar HVDC system. When the simulation is done it is observed that after a transient period of approximately 50 ms, the system reaches a steady state.

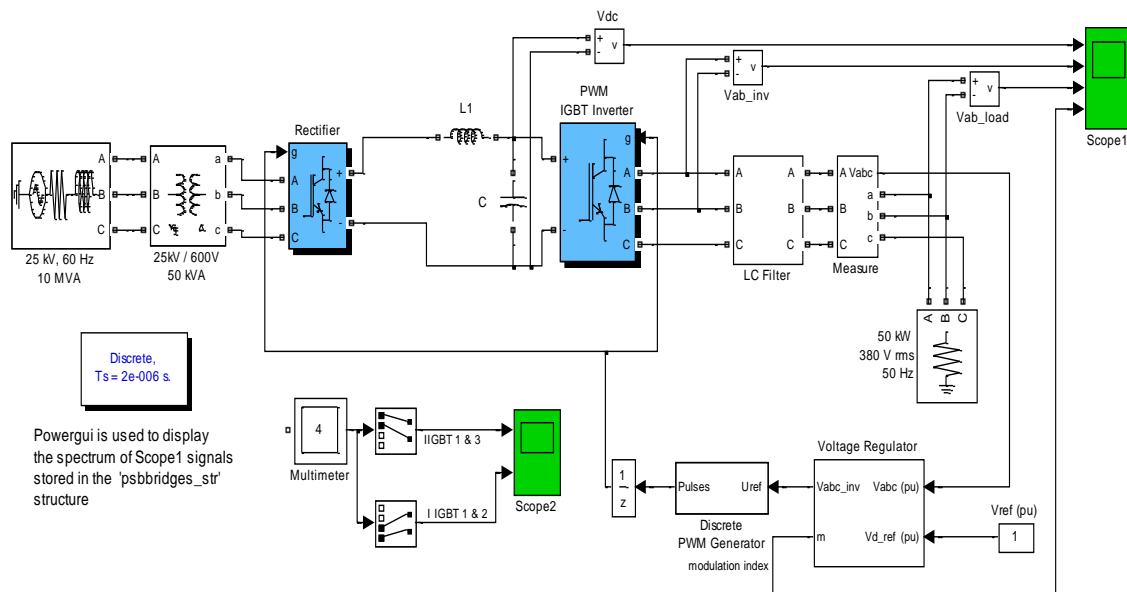


Figure 13. IGBT controlled Converter and Inverter

The voltage waveforms at DC bus, inverter output and load are observed on Scope1. The harmonics generated by the inverter around multiples of 2 kHz are filtered by the LC filter. The peak value of the load voltage is 537 V (380 Vrms). In steady state, the mean value of the modulation index, m is 0.80 and the mean value of the DC voltage is 778 V. The fundamental component of 50 Hz voltage buried in the chopped inverter voltage is about 381 V rms. The FFT Analysis is used to display the 0 - 7000 Hz frequency spectrum of signals saved in the 'psbbridges_str' variable.

The FFT will be performed on a 2-cycle window starting at $t=0.1-2/50$ (last 2 cycles of recording). It is to be noted that the harmonics around multiples of the 2 kHz carrier frequency. Maximum harmonic is 1.4 % of the fundamental frequency and THD(total harmonic distortion) is 2%. The IGBT currents of inverter and the IGBT currents of converter are complementary.

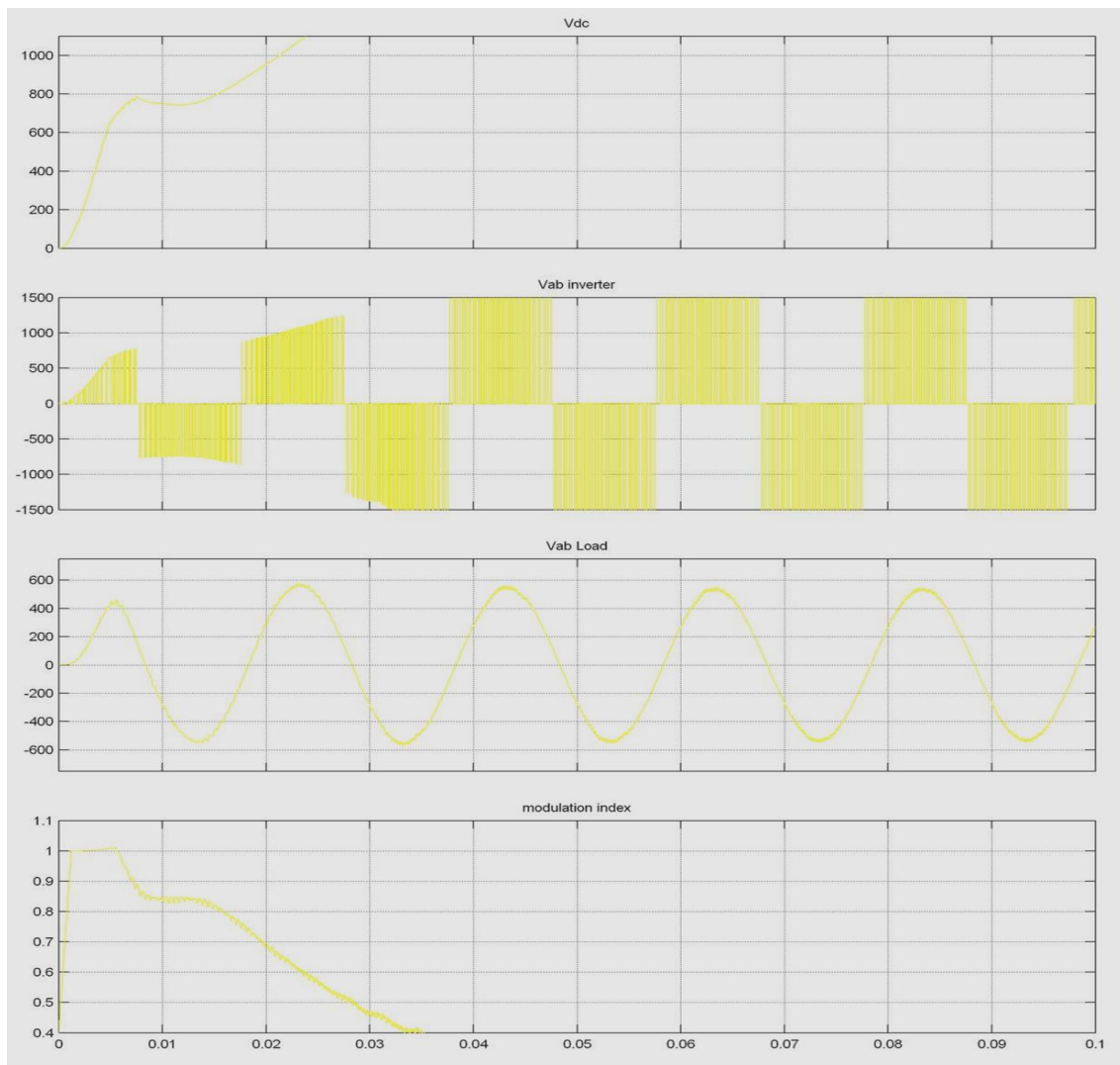


Figure 14. AC-DC-AC PWM converter and inverter for monopolar HVDC system

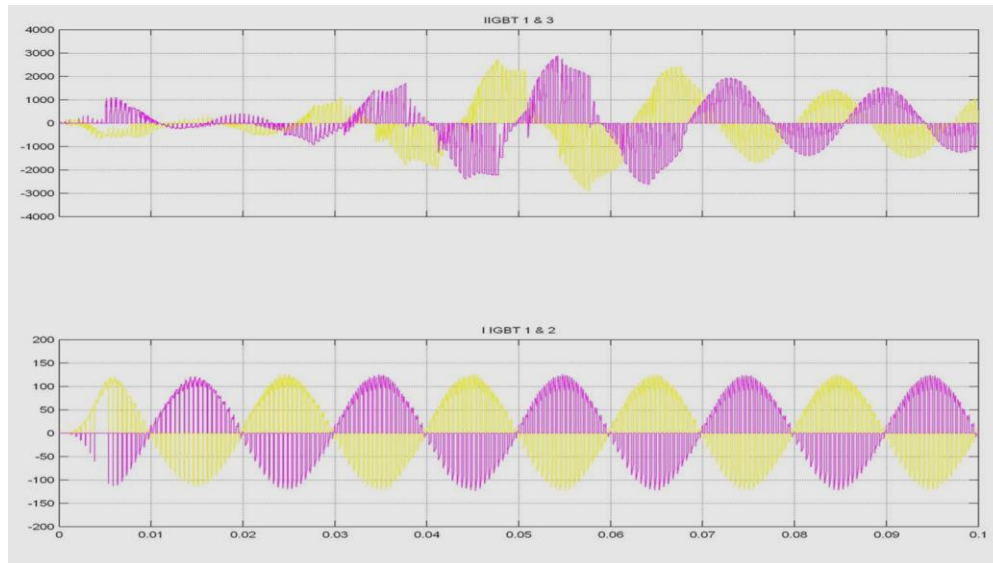


Figure 15. DC output voltage, V_{ab} of inverter, V_{ab} of load and modulation index

A positive current indicates a current flowing in the IGBT, whereas a negative current indicates a current flowing in the anti-parallel diode. The figure 14 shows the gate currents of the IGBT whereas the figure 15 shows the DC output voltage after converter, AC output voltage after inverter and load and modulation index

7. Conclusion

The HVDC technology is now mature, reliable, and accepted all over the world. From its modest beginning in the 1950s, the technology has advanced considerably and maintained its leading-edge image. The encroaching technology of flexible AC transmission systems (FACTS) has learned and gained from the technological enhancements made initially by HVDC systems. FACTS technology may challenge some of the traditional roles for HVDC applications, since the deregulation of the electrical utility business will open up the market for increased interconnection of networks. HVDC transmission has unique characteristics that will provide it with new opportunities. However integration of green electricity will enhance the scope of HVDC for bulk power. In this paper the control characteristics of DC link of HVDC transmission system is discussed. The design and simulation of the converter and inverter block of a conventional HVDC system is designed according to the control topology of the DC link. The Simpowersys toolbox of MATLAB Simulink is used for the design and simulation. The simulated diagram shows the current and voltage wave shapes of converter and inverter block of the designed system which matches with the monopolar series DC link control characteristics of the HVDC system.

References

- [1] M. H. Rashid, "Power Electronics Circuits, Devices and Application", San Diego, CA: Academic Press. (2001).
- [2] M. H. Rashid, "Power Electronics Handbook", A harcourt science and technology company, San Diego, California 92101-4495, USA, (2001), pp.564-585.

- [3] K. R. Padiyar, "HVDC Power Transmission Systems —Technology and System Interactions", John Wiley & Sons, (1990).
- [4] J. Ainsworth, "The phase-locked oscillator—A new control system for controlled static converters", IEEE Trans. Power Apparatus and Systems PAS-87, (1968), pp. 859–865.
- [5] Ekstrom and G. Liss, "A refined HVDC control system", IEEE Trans. on Power Apparatus and Systems PAS-89, (1970), pp. 723–732.
- [6] L. Carlsson, G. Asplund, H. Bjorklund and H. Stomberg, "Recent and future trends in HVDC converter station design," IEE 2nd International Conference on Advances in Power System Control, Operation and Management, (1993) December, pp. 221–226, Hong Kong.
- [7] C. Gagnon, V. K. Sood, J. Belanger, A. Vallee, M. Toupin, P. Mercier and M. Tetreault, "Hydro-Quebec power system simulator," IEEE Canadian Review, no. 19, (1994), pp. 6–9, Spring–Summer.
- [8] Z. Gang, Z. Jianchao and C. Xiangxun, "Study on commutation failure in an HVDC inverter", International Conference on Power System Technology, vol. 1, (1998), pp. 503-506.
- [9] E. Rahimi, A. M. Gole, J. B. Davies, I. T. Fernando and K. L. Kent, "Commutation failure in single- and multi-infeed HVDC systems", The 8th IEEE International Conference on AC and DC Power Transmission, (2006), pp. 182-186.
- [10] G. M. Kristmundsson and D. P. Carroll, "The effect of ac system frequency spectrum on commutation failure in HVDC inverters", IEEE Trans. on Power Delivery, vol. 5, no. 2, (1990), pp. 1121-1128.
- [11] C. V. Thio, J. B. Davies and K. L. Kent, "Commutation failures in HVDC transmission systems, IEEE Transaction on Power Delivery, vol. 11, no. 2, (1995), pp. 946-957.

Authors



Rajib Baran Roy, he has completed Bachelor of Science in Electrical Electronic Engineering from Chittagong University of Engineering and Technology (CUET), Chittagong, Bangladesh and Master's of Science in Sustainable Energy System and Management from University of Flensburg, Germany. He is currently working as an Assistant Professor in the Electrical and Electronic Engineering department of the University of Information Technology and Sciences (UITS), Dhaka, Bangladesh. So far he has five publications in international journals. His research interests are electrical power system analysis, reactive power compensation, hybrid power system, and renewable energy based distributed power system and application of industrial electronics in power system.



Md. Ruhul Amin, he has been working as a Lecturer at the Department of Electrical and Electronic Engineering in the University of Information Technology & Sciences (UITS), Dhaka, Bangladesh since January 2013. He holds a Bachelor of Science degree in Electrical and Electronic Engineering with specialization on Power Systems Engineering from UITS'2012, Dhaka. He has several national and international publications in his area of expertise. His research area addresses the issues related to Electrical Power System and Engineering; FACTS, Distributed Generation and Control; HVDC; Renewable Energy; Smart Grid; Power Electronics.

