AC 2009-293: INTRODUCING HIGH-VOLTAGE DIRECT-CURRENT TRANSMISSION INTO AN UNDERGRADUATE POWER-SYSTEMS COURSE

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Introducing High Voltage Direct Current Transmission into an Undergraduate Power Systems Course

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Abstract

High voltage direct current (HVDC) transmission systems have shown steady growth in capacity addition for the past three to four decades. More than 100,000 MW of HVDC transmission capacity is installed around the globe in more than 100 projects and over 25,000 MW of additional HVDC transmission capacity is under construction. The HVDC system is suitable for interconnecting two asynchronous power systems, as well as for undersea and underground electric transmission systems. For bulk power transmission over long distances, HVDC systems are less expensive and suffer lower losses compared to high voltage alternating current (HVAC) transmission systems. Multi-terminal HVDC systems may provide a better alternative for underground transmission systems in urban areas and large cities. As a power systems engineer it is important to have a basic understanding of HVDC transmission system operation, control features, advantages and disadvantages compared to HVAC transmission systems. This paper discusses the HVDC transmission system can be introduced into a power systems course. Introduction to the HVDC transmission system is designed for the last three class sessions of an undergraduate power systems class. By the end of the semester, students have the necessary background on power systems to understand the basics of HVDC system operation.

Class one:

- Introduction to HVDC transmission systems,
- Advantages and disadvantages of HVDC transmission systems,
- Assignment: comparative economic evaluation of the HVDC and HVAC systems.

Class two:

- Detailed study of a two-terminal HVDC transmission system,
- Control features and modeling with software such as Matlab/Simulink.

Class Three:

- Simulation study,
- Assignment: simulate a three-terminal HVDC system.

Introduction

Alternating current (AC) is the most convenient form of electricity for industry/residential use and in electric distribution systems. Direct current (DC) has some distinct advantages over AC for high power long distance electric transmission systems, underground and undersea electric transmission systems, and for interconnecting two asynchronous power systems^{1,2}. Flexible AC transmission system (FACTS) is an emerging technology in electric transmission which enhances controllability and increases the power transfer capability of the network^{3,4}. Typically a FACTS is an electric power system controlled by power electronics. HVDC technology was first

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used for the undersea cable interconnections to Gotland (1954) and Sardina (1967), and for the long distance transmission to Pacific Intertie (1970) and Nelson River (1973). All of the early HVDC schemes were developed using mercury arc valves. The introduction of thyristor valves was demonstrated in 1972 with the first back-to-back asynchronous interconnection at the Eel River between Quebec and New Brunswick. Since then thyristor valve technology has completely replaced mercury arc valve technology. By 2008, a total transmission capacity of 100,000 MW HVDC has been installed in over 100 projects worldwide, more than 25,000 MW HVDC is under construction in 10 projects, and an additional 125,000 MW HVDC transmission capacity has been planned in 50 projects⁵. To account for the rapid growth of DC transmission and its technology it is necessary to include the HVDC transmission into the undergraduate power systems curriculum. Most undergraduate curricula have only one course on power systems which is typically devoted to AC transmission systems. The Electrical and Computer Engineering program at York College of Pennsylvania has four concentration areas: power systems/energy conversion, embedded systems, signal processing/communication, and control systems. Every student is required to complete two of these four concentration areas for graduation. Each concentration area consists of a two-course sequence. For example, the power systems/energy conversion concentration area consists of a power systems and a power electronics course. Most of the electrical engineering program graduates start working in industry right after the completion of their undergraduate degree. Consequently students who are interested in power engineering but who do not want to go on to graduate study can easily miss out on the rapidly growing HVDC system technologies. This paper discusses a method to introduce an HVDC transmission system module into the undergraduate power systems course using only three lecture periods. The first lecture consists of an introduction to HVDC systems and comparison to HVAC transmission; the second lecture consists of the study of a two terminal HVDC system and modeling with Matlab/Simulink; and the third lecture consists of simulation study of a two terminal HVDC with various AC/DC faults. Finally, students are asked to model and simulate a three terminal HVDC system using Matlab/Simulink. The second lecture appears longer than other two lectures due to the control and system descriptions combined with the simulation modeling. However, the simulation model is built in advance and is distributed to the students before class to save time during the lecture. Different building blocks of the model are then highlighted during class.

Lecture 1

High Voltage Direct Current Transmission: An HVDC transmission system consists of three basic parts: 1) A rectifier station to convert AC to DC, 2) A DC transmission line, and 3) An inverter station to convert DC back to AC. Fig. 1 shows the schematic diagram of a typical HVDC transmission system.

Fig. 1: Schematic diagram of an HVDC transmission system

An HVDC transmission system can be configured in many ways based on cost, flexibility, and/or operational requirements. Fig. 2 shows five potential configurations of HVDC transmission systems².

Fig. 2: Basic configurations of HVDC systems

Fig. 2a represents the simplest configuration—the back-to-back interconnection. It has a rectifier and inverter at the same location and there is no transmission line. This type of connection is used as an inter-tie between two different AC transmission systems. Fig. 2b shows the mono-polar link, in which the rectifier and inverter stations are separately located and are connected by a single conductor line with earth or sea used as a return path. The most common HVDC link is shown in Fig. 2c, where the rectifier and inverter stations are connected by bipolar ($\pm$) conductors. Additionally each conductor has its own ground return which can be used for limited

periods in an emergency when one pole is temporarily out of service. Fig. 2d shows a parallel-connected multi-terminal HVDC configuration, where converter 1 operates as a rectifier and converters 2 and 3 operate as inverters. Fig. 2e shows the series-connected multi-terminal HVDC transmission system with four converter stations connected in series. Converter 1 operates as a rectifier and converters 2, 3 and 4 operate as inverters. The series connected scheme has been generally confined to applications with small power taps (less than 20%) where it may be more economical to operate at a higher current and lower voltage than for a full voltage tap.

Comparison of AC versus DC Transmission: Capital investment of a transmission line includes towers, conductors, insulators, and terminal equipment. Assuming similar insulation requirements for peak voltage levels for both the DC and AC lines, an HVDC line can carry as much power with two conductors (with positive/negative conductor with respect to ground) as an HVAC line with three conductors of same size. Fig. 3 shows the comparison of right-of-way (ROW) for HVDC and HVAC transmission systems of approximately 2000 MW power transmission with same current capacity⁷. For DC transmission the peak voltage is ± 500 kV and for AC transmission the peak voltage is 800 kV. The current for the DC transmission can be calculated as:

$$2V_d I_d = 2000 \text{ MW} \quad (1)$$

where V_d is the DC transmission line voltage with respect to ground, and I_d is the DC transmission line current. The line current I_d is 2000 A. For the same line current AC transmission line peak voltage for unity power factor can be calculated as:

$$\sqrt{3} \frac{V_p}{\sqrt{2}} I_L = 2000 \text{ MW} \quad (2)$$

where $I_L = I_d$ and V_p is the peak AC line voltage. The peak AC line voltage is approximately 800 kV depending on the transmission line power factor. HVDC transmission line uses only two conductors to carry the same amount of power and requires a smaller ROW. Therefore tower construction is simpler and cheaper. With only two conductors the HVDC power transmission losses are also reduced to about two-thirds of the comparable HVAC system. DC transmission does not have any skin effect and the dielectric losses are lower for the DC transmission. DC transmission also has less corona effect, which minimizes the losses further. While an HVDC transmission system does not require reactive power compensation, the terminal equipment costs are higher due to the presence of converters and filters.

Fig. 3: Comparison of right-of-way (ROW) for HVDC and HVAC transmission systems for approximately 2000 MW power transmission⁷

The advantages and disadvantages of the HVDC transmission system compared to the HVAC transmission system can be listed as follows⁸:

Advantages:

- Greater power per conductor.
- Simpler line construction.
- Ground return can be used so that each conductor can be operated as an independent circuit.
- No charging current.
- No skin effect.
- Cables can be worked at a higher voltage gradient.
- Line power factor is always unity: line does not require reactive compensation.
- Less corona loss and radio interference, especially in foul weather, for a given conductor diameter and rms voltage.
- Synchronous operation is not required.
- Hence distance is not limited by stability.
- Can interconnect AC systems of different frequencies.
- Low short-circuit current on DC line.
- Does not contribute to short-circuit current of an AC system.
- Tie-line power is easily controlled.

Disadvantages:

- Converters are expensive.
- Converters require significant reactive power.
- Converters generate harmonics and require filters.
- Multiterminal or network operation is complex.

Fig. 4 shows a graph of the cost versus distance for HVDC and HVAC transmission systems⁷. HVAC transmission systems are economically suitable for shorter distances but more expensive for longer distances. On the other hand, HVDC transmission systems are well suited for bulk power transmission over long distances. This is because of the relative costs of transmission line and terminal equipment. For overhead transmission lines the break even distances can vary from about 500 km to 800 km and with a cable (underground or undersea) system the breakeven distance is approximately 50 km.

Fig. 4: Comparison of HVDC and HVAC transmission systems cost⁷

Take Home Assignment: A high voltage transmission line is planned to transfer 2000 MW over 800 km. The following two options are considered: a ± 500 kV HVDC transmission line and an 800 kV HVAC transmission line. Provide a comparative economic assessment between the two options. The economic comparison between HVDC and HVAC transmission systems consists of terminal cost, transmission line cost, reactive compensation cost, and operation and maintenance cost. The feasibility of the HVDC or HVAC transmission system depends on the break even distance. Based on your analysis identify the preferred transmission system to transfer power over a distance of 800 km.

Lecture 2

Two-Terminal HVDC Transmission Systems: A two-terminal HVDC transmission system consists of converters (rectifier and inverter), DC transmission lines, control systems, and filters.

Converter: A rectifier performs power conversion from AC to DC and an inverter transforms DC to AC. Converters provide a means of controlling power flow through the HVDC link. The major elements of the converter are the valve bridge and a converter transformer. Because the converter transformer provides the key interface between the AC and DC systems it is important to have a clear idea about the converter operation. Fig. 5 shows a six-pulse converter bridge⁶. Even though converter stations can be configured in several ways, six- or twelve-pulse bridge converter (three-phase) configurations are universally used in HVDC systems. The pulse number of a converter is the number of pulsations or cycles of ripple per cycle of alternating voltage. The ripple of the DC system voltage and the harmonics in the AC system depend on the number of pulses of the converter station. A converter of n pulses ideally generates only voltage harmonics of the order nk on the DC side, and current harmonics of order $nk \pm 1$ on the AC side, where k is an integer. The higher the pulse number, the higher the lowest harmonic frequency. For this reason twelve-pulse converters are most commonly used in HVDC systems. Twelve-pulse operation could be easily obtained with wye-wye and wye-delta transformer connections. The higher pulse converter number needs more complicated transformer connections and control systems. Additionally the voltage-to-earth stress on the valve (which is further from the ground point) increases and demands more insulation. Fig. 6 shows a twelve-pulse bridge rectifier connection. All recent converter stations use high power thyristors or silicon controlled rectifiers (SCRs) because of their low cost and reduced maintenance needs compared to mercury arc valves. Fig. 7 shows Manitoba Hydro's Henday converter station and a 2000A 250 kV thyristor valve arrangement.

Fig. 5 A six-pulse converter

Fig. 6 A twelve-pulse bridge rectifier circuit

Fig. 7: Manitoba Hydro's Henday converter station (left) and a 2000A 250 kV thyristor valve arrangement (right)

HVDC Transmission Line: Bipolar HVDC transmission is the most common configuration in HVDC transmission systems. A Bipolar HVDC system has two conductors, one with positive polarity, and the other with negative polarity with respect to ground. Two converter sets with equal ratings are connected in series at each terminal as shown in Fig. 6. The junction between the two sets converters is grounded. During the steady state, the conductors carry equal current and there is zero earth ground current flowing under this condition.

Control Systems: A converter's semiconductor switches are highly controllable and power flow in an HVDC system can be controlled very accurately. However optimum performance of an

HVDC system depends on precise control of these semiconductor switches. Fig 8 shows a schematic diagram of a converter control system. The goal of the converter control system is to provide firing pulses to the thyristor. The steady state DC voltage of the rectifier can be expressed as⁶:

$$V_d = V_{do} \cos \alpha - \frac{3\omega L_c}{\pi} I_d \quad (3)$$

where V_d is the terminal voltage of the rectifier, V_{do} is the ideal no-load direct voltage, α is the firing angle, L_c is the total source inductance, and I_d is the rectifier direct current. The inverter usually operates on constant extinction angle γ , and the relationship between V_d and I_d can be expressed as⁶:

$$V_d = V_{do} \cos \gamma - \frac{3\omega L_c}{\pi} I_d \quad (4)$$

Fig. 8: A converter control system

In a typical HVDC system, the rectifier station controls DC current through firing angle, α , which is called constant current (CC) control. The inverter station controls voltage through extinction angle, γ , which is called constant extinction angle (CEA) control. In addition to the CEA, the inverter station also consists of a CC control. The rectifier has a minimum α limit of about 5° to ensure adequate voltage across the valve before firing. The rectifier normally operates at a value of α within the range of 5° to 15° in order to leave some room for increasing rectifier voltage to control DC power flow. In the case of inverter operation, it is important to have a minimum γ limit to prevent commutation failure. The minimum value of γ is typically between 15° and 25° for successful operation.

Filters: AC filters are used to provide a low impedance shunt path for AC harmonic currents and DC filters are used to filter out the DC harmonics. For a 12-pulse station AC filters are typically set at the 11th, 13th, and 23rd harmonics. A DC filter is set at the 24th harmonic.

Modeling with Matlab/Simulink: Matlab/Simulink is a high performance multifunctional software system for numerical computation, system simulation and application development. SimPowerSystems (SPS), a toolbox in Simulink, extends Simulink with tools for modeling and simulating basic electrical circuits and detailed electrical power systems. It contains a block

library with all common components and devices found in electrical power systems with models based on electromagnetic and electromechanical equations. The SPS toolbox also contains the necessary control blocks for both continuous and discrete models. The SPS solves the system equations through state-variable analysis using either fixed or variable integration time step. The linear dynamics of the system are expressed through continuous- or discrete-time domain state space equations. It also offers the flexibility of choosing from a variety of integration algorithms⁹.

The well known CIGRE HVDC Benchmark system is used in this paper for modeling and simulation. A single-line diagram of the CIGRE HVDC Benchmark system is shown in Fig. 9 and the system's data is provided in Appendix I¹⁰. The model descriptions are as follows:

Fig. 9 CIGRE HVDC Benchmark system¹⁰

The AC side of the HVDC system consists of a supply network, filters, and converter transformers. The AC supply network is modeled by a Thevenin equivalent voltage source with equivalent source impedance. The filters are added to attenuate the harmonics generated by the converter and to supply the reactive power needed by the converter. The Simulink/SPS model is shown in Fig. 10. Data for each block can be entered by double clicking on the block. The DC side of each converter consists of a smoothing reactor. The DC transmission line connected to each converter station is represented by a T network.

The 12-pulse converter station is configured by two universal bridge blocks in series. The universal bridge block implements a universal three-phase power converter that consists of up to six power switches connected in a bridge configuration. The type of power switch and converter configuration can be selected from the dialog box. In actual construction, every valve is implemented using many thyristors in series. Series RC snubber circuits are connected in parallel with each switching device. The gating signals are the vector of six pulse trains corresponding to the natural line commutation. Converter transformers are three-phase two-winding with a grounded wye-wye connection and a grounded wye-delta connection. The converter station is interconnected through the transmission line. Fig. 11 shows the rectifier configuration using Simulink/SPS.

Fig. 10: Simulink/SPS model of AC filters.

Fig. 11: Simulink/SPS model of converter with transformer and input/output signals

The control model mainly consists of a constant current controller and a constant extinction angle controller¹¹. The firing pulses are generated depending on current and γ measurements. The equidistant firing pulses are realized using a phase-locked-loop (PLL) synchronized on the positive-sequence of the fundamental voltage.

The rectifier is equipped with a constant current controller (CCC) to maintain the DC link current constant. The reference current for the CCC is obtained from the inverter controller output. This protects the converter in situations when the inverter side does not have sufficient DC voltage (due to a fault) or does not have sufficient load requirement (load rejection). The DC link current at the rectifier end is measured and passed through an appropriate filter before comparing with the reference to produce the error signal. The error signal is then passed through the PI controller to produce a firing angle order α . The firing circuit uses the angle order α to produce the necessary equidistant pulses for the valves. Fig. 12 shows the rectifier side control with the pulse generator.

Fig. 12: Rectifier side control with the pulse generator

The inverter is provided with a constant extinction angle, (CEA) or γ (gamma) control and the CCC. The CCC is implemented with a voltage dependent current order limit (VDCOL). The current reference for the CCC is obtained through a comparison between the external reference (provided by the operator or load requirement) and VDCOL output (implemented through a lookup table). The error signal is obtained by subtracting the measured current from the reference current and passed through the PI controller to produce firing angle order α .

Gamma, γ is the time expressed in degrees from the thyristor current extinction to the time when the thyristor commutation voltage becomes positive. The system frequency is used to convert time values in electrical degrees. The current extinction time is determined from the current threshold. The six gamma angles are determined using six thyristor currents and the six commutation voltages are derived from the three-phase-to-ground AC voltages measured at the

primary of the converter transformer. The minimum gamma value is considered for the control action. For a 12-pulse converter, two gamma measurement units are used, and the smaller of the two gamma outputs is compared with the reference gamma to produce the error signal. The gamma uses another PI controller to produce the firing angle order for the inverter. The firing angle orders from the CCC and from the gamma controller (CEA) are compared and the minimum is used to produce firing pulses for the valve. Fig. 13 shows the inverter side control with gamma measurement technique¹². Appropriate voltmeters and ammeters are used to measure the DC voltages and currents, and three-phase VI measurement blocks is used to measure the three phase voltages and currents. Signals are routed using “From” and “Goto” blocks and displayed by the scope. Fig. 14 shows the Simulink/SPS model of the CIGRE HVDC Benchmark system

Fig. 13: Inverter control with gamma measurement technique¹²

Fig. 14: Simulink/SPS model of the CIGRE HVDC Benchmark system

Lecture 3

Simulation: The HVDC system simulated in this study is modeled based on the CIGRE HVDC Benchmark system. For the simulation, a time-step of $50 \mu\text{s}$ is customarily chosen, which is slightly less than 1° for a 50 Hz waveform. To implement the model with Simulink/SPS, a total of 109 states; 37 inputs; 86 outputs; 31 switches were used. Matlab 7.6.0 (R2008a) was used to conduct the simulation. The normal operation of the HVDC system is affected by faults on the DC line, converters, or the AC system. The impact of a fault is reflected through the action of converter controls. In an AC system, relays and circuit breakers are used to detect and remove faults. On the other hand, the faults associated with an HVDC system are cleared through the action of converter controls. The converter controls thus play a vital role in the satisfactory operation of an HVDC system subject to faults on the DC as well as the AC side.

HVDC System Responses without any Fault: To make sure that the HVDC model is working, a simulation is conducted without any fault as shown in Fig. 15. DC currents and AC voltages reach the steady state within 300 ms after the initial transient. The initial overshoots for DC currents are 2.75 pu for a very brief period of time. The initial overshoot for inverter side AC voltage is 1.75 pu. Once the system reaches the steady state, it stays in the steady state as long as there is no further disturbance.

Single Line-to-Ground Fault on the AC Side of the Inverter: An unsymmetrical single line-to-ground fault is applied at 1.0 seconds for a duration of 50 ms on the AC side of the inverter to

observe the system response during the disturbance and once the disturbance is cleared. Fig. 16 shows DC current and AC voltage response of the system and Fig. 17 shows an enlarged view of the system response. Fig. 18 shows the DC voltage of the system. It can be seen from Fig. 17 that the recovery time is about 300 ms. The overshoot in the inverter DC current is 2.5 pu and for the rectifier DC current, 2.0 pu. The rectifier side AC voltage is not affected by this fault. The AC voltages on the inverter side are also restored to normal within 300 ms. The DC voltages are reversed for a few moments but recovered quickly after the fault is removed as shown in Fig. 18.

Fig. 15: DC current and AC voltage without any fault.

Fig. 16: DC current and AC voltage for a single phase-to-ground fault on the AC side of the inverter

Fig. 17: Enlarged view of DC current and AC voltage for a single phase-to-ground fault on the AC side of the inverter

Fig. 18: DC voltage for a single-phase-to-ground fault on the AC side of the inverter

DC Line Fault: A DC line fault is applied at the midpoint of the DC line at 1.0 seconds for 50 ms duration. The system responses are shown in Fig. 19 and 20. The rectifier side AC voltages are not affected by the DC fault but the inverter side AC voltages are affected with overshoots of less than 10%. The rectifier DC current reduces to zero during the fault and recovers quickly after the fault is removed. The inverter side DC current also reduces during the fault despite the initial spike. Fig. 20 shows that both the DC voltages are kept to zero during the fault and recover smoothly from the fault after the fault is cleared.

Fig. 19: Enlarged view of DC currents and AC voltages for a DC fault

Fig. 20: DC voltages for a DC fault

The Simulink/SPS model of the CIGRE HVDC Benchmark system shows the desired operation of an HVDC system under both normal and fault conditions. Further study can be conducted using this model with some minor changes. To give students a better idea about HVDC systems the following assignments are considered.

In-Class Assignment: Apply a three-phase-to-ground fault on the AC side of the rectifier at 2.0 seconds for 50 ms. Capture AC/DC voltages and currents using the Simulink scope. Briefly describe the system responses due to the fault.

Take Home Assignment: Model a three terminal HVDC system using this two terminal HVDC system and simulate the system for DC and AC faults. Capture AC/DC voltages and currents using the Simulink scope. Describe the system responses due to the faults.

Conclusions

A lecture by lecture approach is presented in this paper to introduce high voltage direct current (HVDC) transmission systems into an undergraduate power systems course. The HVDC system has been and is being considered as an alternative to the high voltage alternating current (HVAC) transmission due to economic, technical, and environmental factors. Students find the HVDC system very interesting and are able to make comparisons between the HVDC and the HVAC systems. The lecture by lecture introduction to HVDC systems (including the simulations) gives students a broad understanding of HVDC operations. The economic and technical advantages and disadvantages of the HVDC systems are also presented. The study of the HVDC system with a traditional power systems course will help students pursue a career in HVDC systems operation, planning, and design. Students may also be stimulated to conduct graduate research on HVDC systems.

Appendix I

CIGRE HVDC Benchmark System Data

Parameters	Rectifier	Inverter
AC Voltage Base	345 kV	230 kV
Base MVA	1000 MVA	1000 MVA
Transformer tap (HV side)	1.01 p.u.	0.989 p.u.
Voltage source	$1.088 \angle 22.18^0$	$0.935 \angle -23.14^0$
Nominal DC Voltage	500 kV	500 kV
Nominal DC Current	2 kA	2 kA
Transformer X_l	0.18 p.u.	0.18 p.u.
Source Impedance	$R=0.4158\Omega$, $L=0.0206$ H	$R = 0.7406 \Omega$, $L = 0.0365$ H
System Frequency	50 Hz	50 Hz
Nominal Angle	$\alpha = 15^0$	$\gamma = 15^0$

References

1. Edward W. Kimbark, Direct Current Transmission Volume I, John Wiley & Sons, Inc., 1971, ISBN 0-471-47580-7.
2. Jos Arrillaga, High Voltage Direct Current Transmission, 2nd Edition, IEE Power and Energy Series 29, 1998, ISBN 0-85296-941-4.
3. N.G. Hingorani, "Power Electronics in Electronic Utilities: Role of Power Electronics in Future Power Systems," Proceeding of the IEEE, Vol. 76, No. 4, April, 1988, pp. 481-482
4. N.G. Hingorani, and L. Gyugyi, "Understanding FACTS – Concepts and Technology of Flexible AC Transmission Systems," IEEE Press, New York, 1999
5. Working Group on HVDC and FACTS Bibliography and Records, HVDC Projects Listing 2008, DC and Flexible Transmission Subcommittee, IEEE Transmission and Distribution Committee
6. P. Kundur, Power System Stability and Control, Power System Engineering Series, EPRI, 1994, ISBN: 0-07-035958-X
7. M. H. Rashid, "Power Electronics Handbook," Second Edition, Academic Press, 2007, ISBN: 0-12-088479-8
8. Kala Meah, Sadrul Ula, "Comparative Evaluation of HVDC and HVAC Transmission Systems," IEEE 2007 Power and Energy Society General Meeting, 20-24 June, Tampa, Florida, USA.
9. SimPowerSystems User's Guide (The Mathworks, Natick, MA, 2004).
10. M Szechtman, T. Wess and C.V. Thio, "First Benchmark Model for HVDC Control Studies," Electra, No. 135, April 1991, pp. 55-73.
11. A. Ekstrom and G. Liss, "A Refined HVDC Control System," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-89, No. 5, May/June 1970, pp. 723-732.
12. Kala Meah, A.H.M. Sadrul Ula, "Simulation Study of the Frontier Line as a Multi-Terminal HVDC System," IEEE PES General Meeting, July 20- 24, 2008, Pittsburg, PA, USA.