MODELLING AND SIMULATION OF HIGH VOLTAGE DIRECT CURRENT TRANSMISSION SYSTEM

By

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FINAL PROJECT REPORT

Submitted to the Electrical & Electronics Engineering Programme
in Partial Fulfillment of the Requirements
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Bachelor of Engineering (Hons)
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CERTIFICATION OF APPROVAL

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Approved:

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UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

December 2007

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Nor Azizi bin Azizan

ABSTRACT

High voltage direct current (HVDC) is one of the technologies in electrical transmission system. It is established as an alternative to AC transmission system. The main purpose of this project is to model and simulate the HVDC system by using software. The scope of this project is to cover the concepts about transmission system, specifically HVDC. In fact, familiarization with software such as ATP will be covered too as it will assist in the modeling and simulation stage. The systematic approaches such as research, modeling, simulation, validation and troubleshooting in accomplishing this project are discussed in the chapter of methodology. Assessments on several softwares were conducted in order to identify the best software in studying the behavior of HVDC system. Besides that, data taken from real HVDC project, which is EGAT/TNB HVDC Interconnection Project, will be discussed too. Comparison between the simulated results and the real data were carried out in order to validate the findings from the simulation. Based on the evaluation made on the relevant software, it is found that ATP is the best software to be utilized in this project. Subsequently, simulations were conducted by using ATP and desired waveforms were obtained since they managed to resemble the real data and consistent with the theoretical concept.

ACKNOWLEDGEMENTS

بِسْمِ ٱللَّهِ ٱلرَّحْمَٰنِ ٱلرَّحِيمِ

In the name of Allah, The Beneficent, The Merciful.

Alhamdulillah, all praises to Him that I have been able to complete the two-semester final year project of Modeling and Simulation of High Voltage Direct Current Transmission System.

Highest appreciation and sincere gratitude regarded to the project supervisor, Mr. Mohd. Fakhizan bin Romlie, for the guidance and attention in helping me to complete this project. All comments given had urged me to struggle hard in fulfilling the required deliverables of the project.

Apart from that, I also want to express my appreciation to my beloved parents whose supportive spirit never faded in supporting me to accomplish this project. In addition, thanks to all my peers, for the continuous support and willingness to share their ideas regarding this task.

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LIST OF ABBREVIATIONS

HVDC	- high voltage direct current
DC	- direct current
AC	- alternating current
GTO	- gate turn off
DCCT	- DC current transductor
DCPT	- DC potential transductor
ATP	- alternative transient program
TACS	- transient analysis of control system
emf	- electromotive force
rms	- root mean square

CHAPTER 1
INTRODUCTION

1.1 Background of Study

The main purpose of the transmission system is to carry bulk quantities of electrical energy to or between convenient points. At these points, the electrical energy may be subdivided for eventual delivery to one or more distribution systems. The voltage of transmission line is usually determined by economics. Higher voltages are generally desirable since smaller, less expensive conductor may be used. In fact, high voltage transmission often permits transmitting large block of power more economically than lower voltage transmission.

HVDC transmission uses a lighter and cheaper construction, with one or two conductors instead of three, but requires complex and expensive terminal arrangements. However, where power is to be transmitted over long distances, either overhead or with cables, or when a connection is required between systems operating at different frequency, HVDC may well become economic. This has led to the installation worldwide of a number of HVDC links operating at powers of gigawatts. A typical HVDC system is shown in Figure 1.

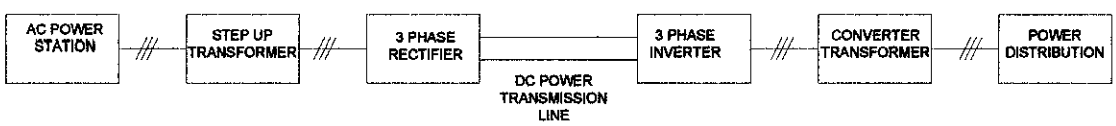

Figure 1 : HVDC power transmission system [1]

HVDC is an application of the power electronics and due to the economic and technical aspects; this technology has started to be developed. Generally HVDC has its own terminal design, basic configuration and equipment in order to establish the transmission system. In fact, it is predicted that in future HVDC will be improved by using advanced technology such as multiterminal configuration, Gate Turn Off (GTO) devices, forced commutation converters and control electronics.

1.2 Problem Statement

Modeling refers to the process of generating a model as a conceptual representation of some systems. The usual approach to model development is to characterize the system, make some assumptions about how it works and translate these into equations and a simulation program. Pertaining to the modeling of HVDC, which has a very complex system, its whole system must be characterized and divided into small chunks so that the modeling task can be executed easier. In fact, the most crucial part that plays major role in HVDC transmission system must be identified and modeled first because at least it can represent important part of the performance of the HVDC system.

Subsequently, a computer simulation will take place in completing the modeling task. The computer simulation is an attempt to model a real-life or hypothetical situation on a computer so that it can be studied to see how the system works. Simulation has become a useful part of modeling in engineering in order to gain insight into the operation of those systems. Usually, certain software is used to carry out simulation.

To perform the simulation of HVDC transmission system, the most suitable computer software needs to be identified. This is because in the study of engineering, there are many engineering software available in the market that can be used for simulation purpose. However, among these software, there are only few software that are specially designed to study the behaviors of power transmission especially HVDC transmission system. Thus, the selection of right software is essential in order to obtain the best result from the simulation.

1.3 Objectives and Scope of Study

The objectives of this project are:

- To study the HVDC system concepts and its application in power system.
- To model and perform simulation on HVDC system.
- To compare the obtained simulation results with the existing available data.

The scope of study will cover several aspects. Firstly, it is to cover the concepts of transmission system and HVDC itself. Complete understanding about the system is vital before the next stage can take place. Software will be used to carry out modeling and simulation of the system. Thus, knowledge about the software needs to be developed. After thorough investigation has been made, Alternative Transient Program (ATP) is chosen as the best software to undertake the role in the modeling and simulation of the HVDC transmission system.

CHAPTER 2
LITERATURE REVIEW

2.1 HVDC Power Transmission System

2.1.1 Introduction

HVDC transmission systems have been developed worldwide. In fact, there is boost in utilization of the technology in 1970s and 1980s. The trend is shown in Figure 2. The economic and technical benefits are the two reasons that have been identified which contribute towards the phenomenon [2].

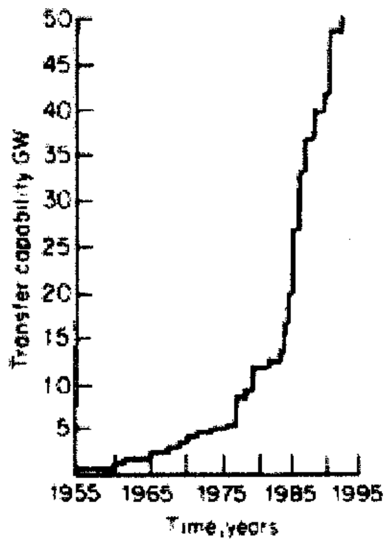

Figure 2 : Increased in utility interest in HVDC transmission. [2]

HVDC transmission is described as economical due to some reasons. Firstly, HVDC is better than AC for overhead line especially when the transmission distance is 500km or more. This is because the lower cost of the DC transmission lines offset the high cost of the converter terminals. In term of cables, its break-even distance is 30km. This is because higher voltage AC cables require excessive capacitive charging current. Although intermediate costly shunt reactor can be applied to compensate the underground cables, it is not practical for submarine cables. Since DC cables do not have capacitive charging currents, no shunt compensation is needed. A more detailed cost comparison of 3000MW transmission system between DC and AC alternatives is shown in Appendix A [3].

Apart from that, HVDC can provide technical and performance characteristics which do not posses by AC such as asynchronous interconnection between two large AC systems, control of power flow and power modulation control. This is because in AC, it is technically difficult and impossible to connect two independent controlled power systems, which on the other hand can be catered by asynchronous HVDC tie. In fact, interconnection of power systems with different nominal frequency can be done in HVDC [2].

2.1.2 Terminal Design and System Configuration

2.1.2.1 Terminal Design

Rectifier is a terminal that converts AC to DC while inverter is a terminal that converts DC to AC. In HVDC, these two terminals are referred as converter. The converter terminals consist of the following components:

- converter (valve) and its controls,
- converter transformers,
- reactors,
- filters,
- reactive power supplies and
- protective, monitoring, measuring, communications and auxiliary equipments.

Major elements of bipolar transmission system are shown in Figure 3. The system indicates the arrangement with the sending end at point of generation; the receiving end connected to AC system via bipolar DC line and ground return is used as a spare conductor. An example of HVDC converter station design is depicted in Appendix B [3]. Six pulses Converter Bridge are used to convert the power from AC to DC and DC to AC. The six pulses converter is depicted in Figure 4.

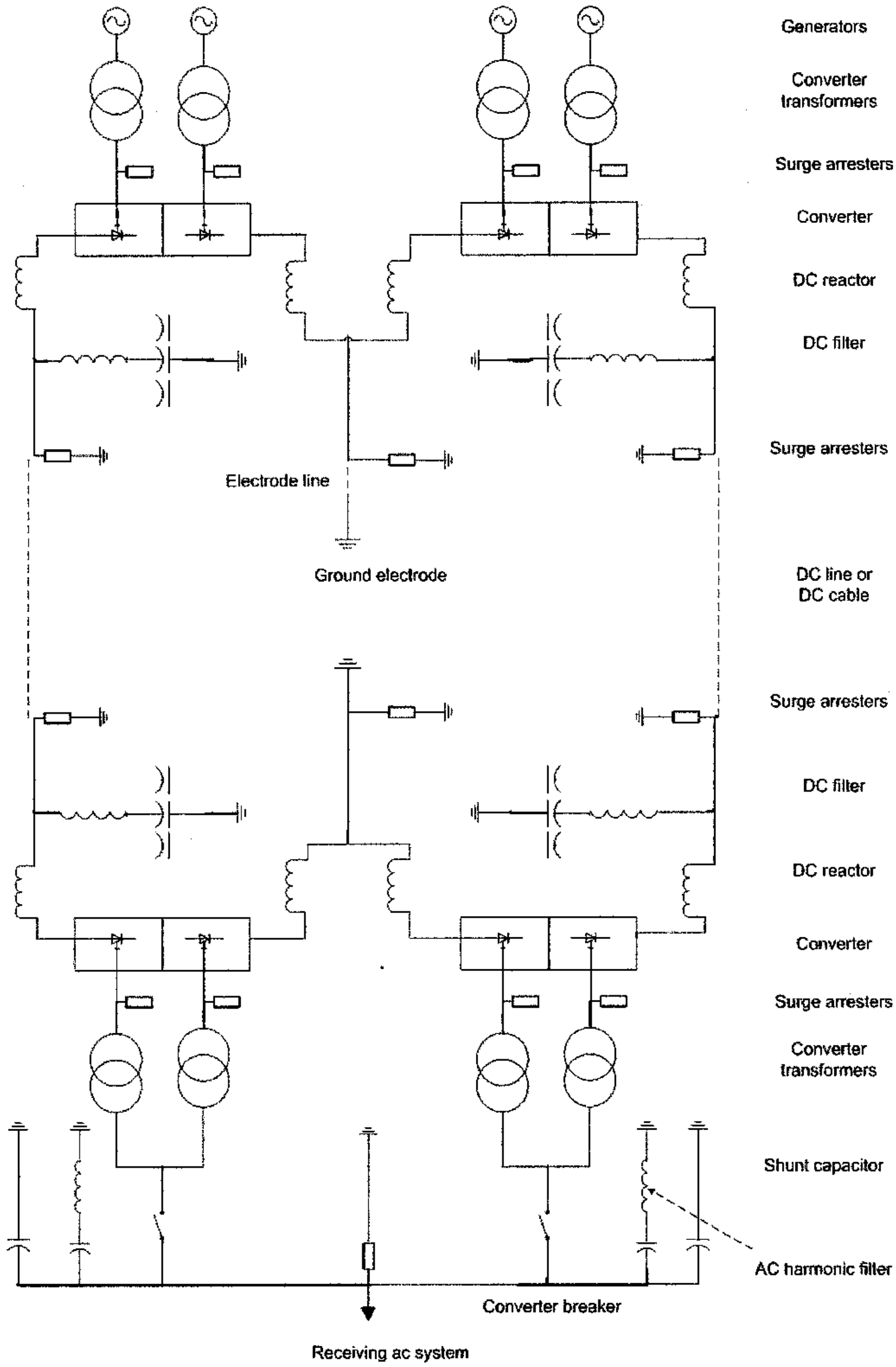

Figure 3 : Major elements of bipolar transmission system [2]

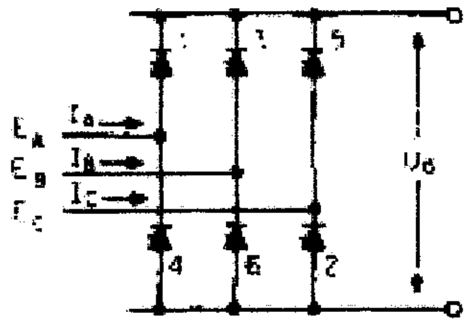

Figure 4 : 6 pulse converter bridge [2]

Each element in the six pulses converter represents an optimized number of solid-state thyristors connected in series, and sometimes in parallel, to form a solid-state valve. The DC output voltage of a 6-pulse bridge contains even voltage harmonics of order 6, 12, 18. . , 6n, while the valve side AC current contains odd current harmonics, 5, 7, 11, 13. . . 6n ± 1. Unless these harmonic voltages are filtered, they will flow into the AC system and the DC line, and can cause voltage distortion and telephone interference.

A 12-pulse converter consists of two 6-pulse bridges in series. The two are identical except that the AC supply voltages of the two are shifted in phase by 30°. This is usually accomplished by supplying one bridge with a wye-wye transformer and the other with a wye-delta connection as shown in Figure 5. As a result of this 30° phase shift, certain harmonics are canceled out, thus leaving even voltage harmonics on the DC side of the converter of order 12, 24, 36, . . ., 12n, and odd current harmonics on the AC side of the converter of order 11, 13, 23, 25, . . . , 12n ± 1. This reduction in filter requirements is a major reason why almost all modern solid-state HVDC systems operate as 12-pulse only.

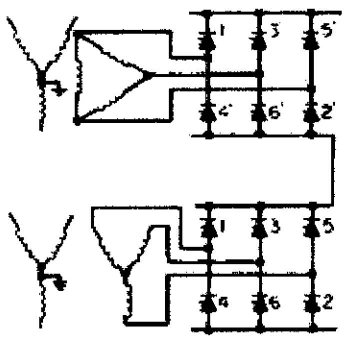

Figure 5 : The pulse converter consists of two 6-pulse bridges in series. [2]

2.1.2.2 System Configurations

In HVDC transmission, ground return can be used as a conductor if current flowing through ground is not objectionable. That is, each separately insulated transmission conductor, together with the ground-return path, would form a separate electric circuit. When ground current is objectionable, a dedicated metallic return is used instead. Utilizing this fundamental principle, the following basic transmission configurations can be considered:

- Back-to-back interconnection [4,5]

This is the simplest configuration in which the two converters are located on the same site. Therefore in this case, it does not require any transmission line or cable between the converter bridges. The two units are identical and each can be used on the rectification or inversion modes as ordered by the system control. Figure 6 shows the configuration of back-to-back interconnection.

Figure 6 : Back-to-back interconnection [5]

- Monopolar Arrangement [2, 4]

In this configuration, which is shown in Figure 7, a single conductor line is used to connect between the two converter stations. In fact, earth or the sea is utilized as the return conductor which requiring two electrodes capable of carrying the full current. Monopolar transmission is often used in systems of comparatively low power rating, primarily with cable transmission.

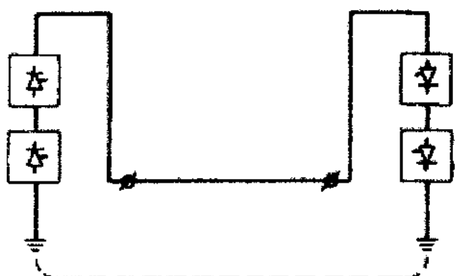

Figure 7 : Direct current monopolar transmission arrangements [2]

- Bipolar Arrangement [4]

It is the most common configuration. As shown in Figure 8, actually bipolar arrangement is the combination of two monopolar systems, one at positive and one at negative polarity with respect to ground.

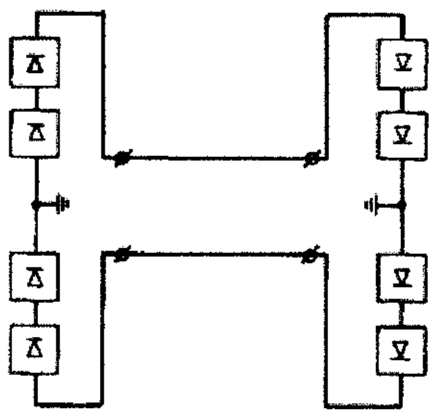

Figure 8 : Direct current bipolar transmission [2]

Other types of configurations are depicted in Appendix C [3].

2.1.3 Equipment Characteristic.

2.1.3.1 HVDC Valve (converter)

The main requirements of HVDC valve in power transmission are:

- Low voltage drop during conduction
- Ability to withstand high negative and positive voltage without breaking down
- Controllable firing instant
- Overcurrent ability to withstand internal and external faults

Converter station has used thyristor that consists of the silicon semiconductor wafer encapsulated in a disc-type porcelain package. The major power loss in a thyristor occurs due to "spreading" phenomena. That is, when the thyristor first turns on, only a small portion of its junction area conducts. The area of conduction spreads with time until maximum conduction area is reached. This minor power loss is due to leakage currents from the impressed voltage on the thyristor.[2,4]

There are several combinations of valve insulation and cooling mediums [2], which are listed as follows:

- air for both insulation and cooling
- oil for both insulation and cooling
- air for insulation and water, oil, Freon, etc., for cooling
- SF6 for insulation and oil, Freon, etc., for cooling

2.1.3.2 Converter Controller

The main objectives of an HVDC control system are:

- to control a system quantity such as DC line current, transmitted power, or frequency of either of the two connected ac networks with sufficient accuracy and speed of response
- to ensure stable converter operation in presence of small system disturbances
- to fulfill the above objectives at minimum reactive power consumption

In HVDC transmission, because of the rather small value of line resistance, the direct current will vary rapidly and drastically with small changes in the direct voltage difference between terminals. The widely accepted method for the control of the voltage difference is to change the ratio between direct voltage and alternating voltage by grid control, that is, change of the converter firing angle α.

To minimize the amount of reactive power consumed, it is usual to operate either the rectifier on minimum firing angle α, or the inverter on minimum margin of commutation γ. A smaller firing angle would give less demand for reactive power, but also would limit the ability to rapidly increase the rectifier voltage by decreasing the firing angle. As the inverter establishes the direct voltage, the suitable firing angle range for the rectifier may be obtained by tap-changer control in the rectifier. [2]

2.1.3.3 Converter Transformer

Converter transformers [2, 6] are the link between the AC and DC systems. They provide a natural barrier between AC and DC systems, preventing DC voltage and current from reaching the AC system. Through their closely matched impedances, a result of careful design and construction, they:

- reduce non-characteristic harmonics
- reduce AC phase imbalance, thus simplifying system regulation

- limit short-circuits currents to tolerable levels for the solid-state converter valve

2.1.3.4 Smoothing Reactor

A smoothing reactor [2, 4] is placed in series with DC converters to smooth DC ripple current and reduce current transients during system contingencies. It serves a secondary purpose of protecting the converter valves from voltage surges coming from the DC line.

2.1.3.5 Transductor

- DC Current Transductor

For an HVDC power system, measurements of direct current are required as an input to the converter controller, and for metering and instrumentation. The DC current transductor (DCCT) measures the direct current and provides a signal in the form of a direct voltage proportional to the direct current. The DCCT also provides isolation between the HVDC line, where the current is measured, and the control system ground.

- DC Potential Transductor

As previously mentioned, measurements of DC line voltage are required as an input to the converter controller and for metering and instrumentation of an HVDC system. The DC potential transductor (DCPT) measures DC line voltage with isolation between the power system and control system ground. The DCPT consists of the following main components:

- current limiting precision resistor
- auxiliary unit
- transductor cores
- distribution and sensor box [2]

2.1.3.6 Arresters

The main purpose of surge arrester is to protect valve from reverse overvoltage. A gapless metal oxide surge arrester connected across the valve does the protection. The surge arrester constitutes the primary protection of the valve against overvoltage of external origin. The arrester has to withstand continuous operation while subjected to the valve OFF state voltage, including the periodic switching transients which happening every cycle. The arrester provides a protective level typically around 70% higher than the peak of the normal operating voltage of the valve. [4]

2.1.3.7 A.C Filters

The filters that are connected to the same AC busbar as the converter transformers have two main functions, which are to absorb harmonic currents and to provide reactive power. In order to have separate maintenance and to restrict the voltage step at switching, it is normal to split filters to several banks. [7]

2.2 Basic Conversion Principle

The mechanism to achieve instantaneous matching of the AC and DC voltage levels must be considered first in the process of static power conversion, given the limited number of phases and switching devices, which are economically feasible. By referring to Figure 9a, theoretically infinite current level transient will occur. This is due to the absence of the energy storing elements on either side and in the presence of a constant DC voltage. In fact, the time variation of the AC voltage waveforms and any voltage supply deviations from the nominal level will contribute to the same phenomenon.

Therefore in order to absorb the continuous voltage mismatch between the two sides, series impedance must be included in the scheme. The switching devices will transfer instantaneous direct voltage to the AC system according to the transformer connection and ratio if such impedance is exclusively located on the AC side, as depicted in Figure 9b. Thus, the circuit configuration is basically a voltage converter, with possibility to altering the DC current by thyristor control.

Pulse of constant direct current will flow through the switching devices into the transformer secondary windings by placing a large smoothing reactor on the DC side, as indicated in Figure 9c. These current pulses are then transferred to the primary side according to transformer connection and ratio; thus the result is basically a current converter with the possibility of adjusting the direct voltage by the thyristor control.

Due to the impossibility of recovering from the arc back disturbances, the usage of the voltage converter was rejected in mercury arc-converter. In fact, it is uneconomical in terms of reactive power compensation to apply the voltage converter with thyristor scheme. This is because it requires large series of impedance and rapid changes in the supply voltage can be accommodated within narrow limits. Therefore, the current conversion principle is generally accepted as the basis of HVDC converter design. [4]

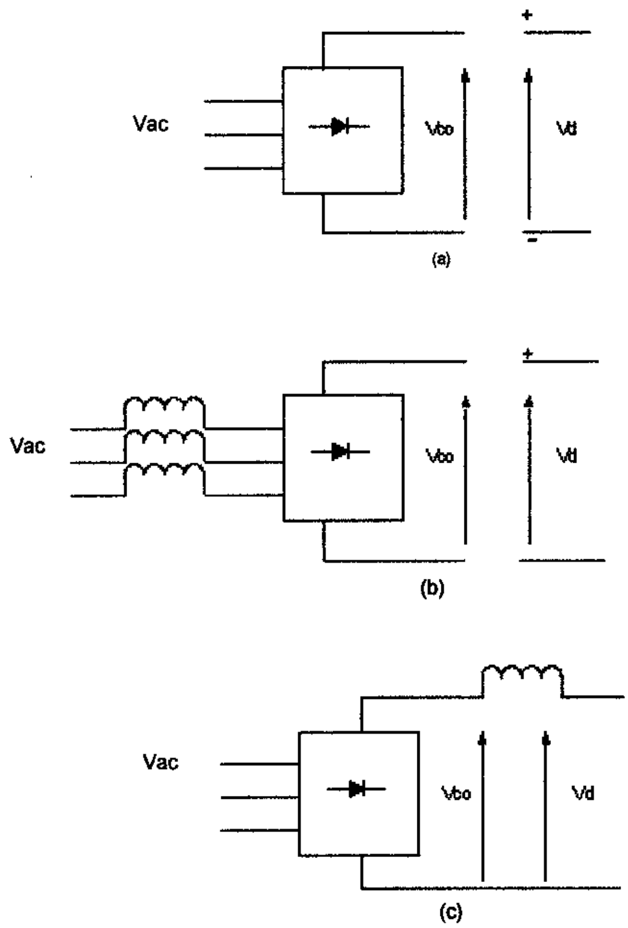

Figure 9 :AC/DC voltage matching: (a) unmatched circuit, (b) circuit for voltage conversion, (c) circuit for current conversion [4]

2.3 Phase Controlled Converter [8]

Controlled rectifier circuits will use silicon-controlled rectifier (SCR), or called "unidirectional thyristor", instead of the diode. Half-wave uncontrolled and controlled rectifiers are shown in Figure 10 and 11 respectively:

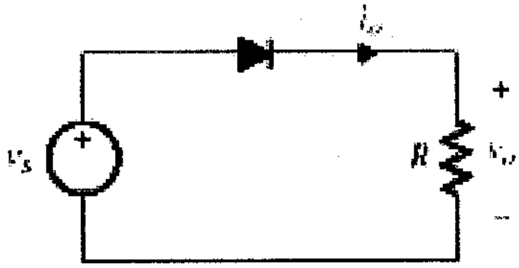

Figure 10 : Half wave uncontrolled rectifier

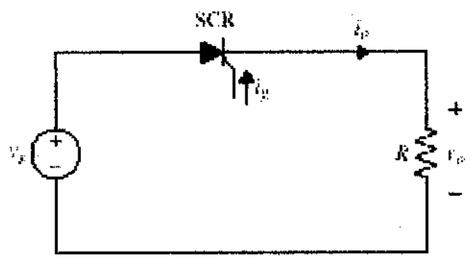

Figure 11 : Half wave uncontrolled rectifier

Unlike in diode rectifier circuits, in controlled circuits the power may flow from the load side (DC side) to the source side (AC side) under some control condition. Such circuits are also known as phase-controlled converters. The source of control stems from the fact that the gate signal can be applied to any time in the period during which the anode-cathode voltage is positive. Negative direction of power flow is known as inversion and the circuits are known as controlled inverter circuits.

2.3.1 Basic Phase Control Concepts

Block diagram for representations for single and three phase SCR controlled circuits are depicted in Figure 12. One or more SCRs and possibly diodes are used in building the SCR circuit block. The SCRs are turned on by using externally applied gating signal, which is regulated by the control circuit. This means that the average output voltage can be controlled.

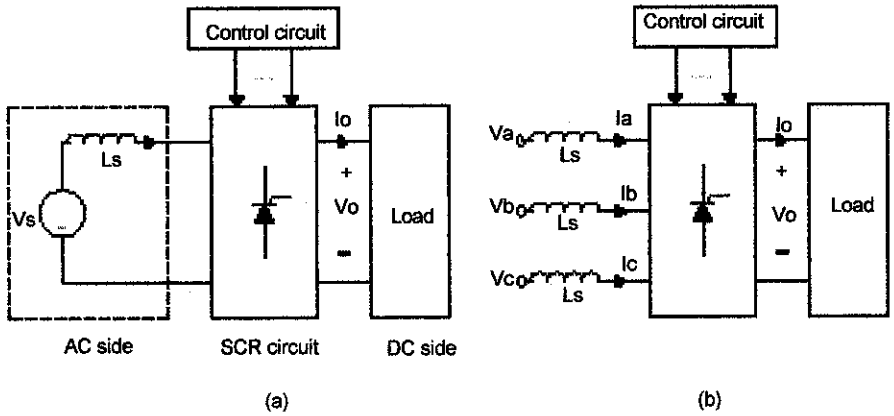

Figure 12 : Block diagram representation for phase controlled converter.
(a) Single-phase. (b) Three- phase

Gate trigger signal as shown in Figure 13 is used in activating the SCRs. The time, t_1, is known as the firing time or the delay time. Firing angle or the delay angle, which is denoted by α, is usually applied to represent this instant. The equation of the firing angle is shown as follow:

$$\alpha = \omega t_1$$

ω is the frequency (rad/s) of the supplied voltage.

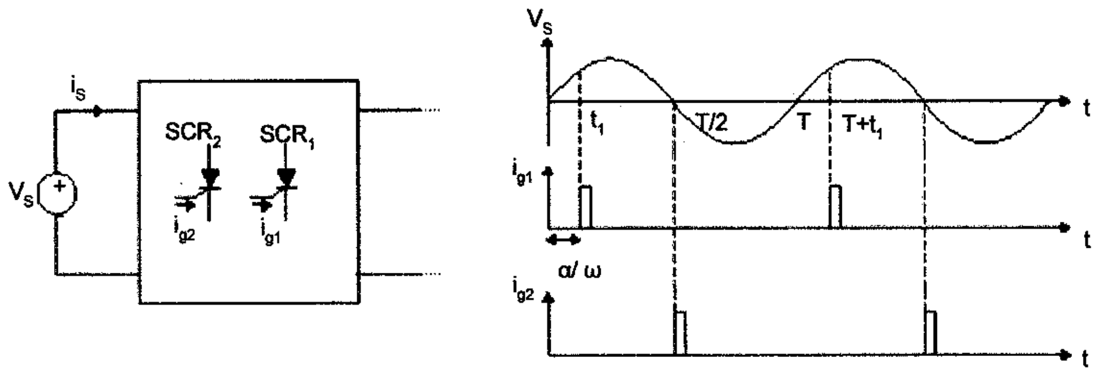

Figure 13 : SCR representation with gate trigger signals i_{g1} and i_{g2}

2.3.2 *Half- wave controlled rectifier (resistive load)*

When the diode is replaced by an SCR in the single-phase half-wave rectifier circuit, the resultant circuit is known as a half-wave phase-controlled rectifier as shown in Figure 11. When the source voltage is positive, the SCR will not conduct until the gate signal is applied at $t = t_1$, as depicted in Figure 14.

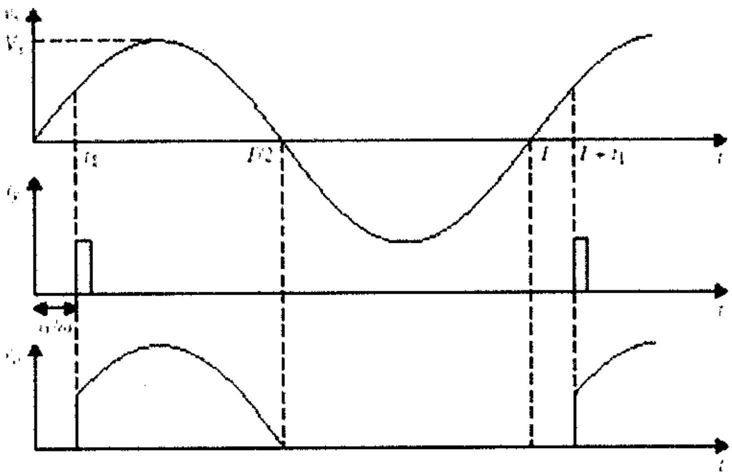

Figure 14 : Waveforms for Figure 11 when the SCR is triggered at $t=t_1$

2.4 Converter Operation: Simplified Case of Zero Commutating Inductance

A three phase full wave bridge which utilizing six controlled (thyristor) valve as shown in Figure 15 is the standard "building block" for HVDC converter. As there are six valve firing pulses and six pulses per power frequency in the output, at the DC terminal, the system is known as a "six pulse" converter bridge.

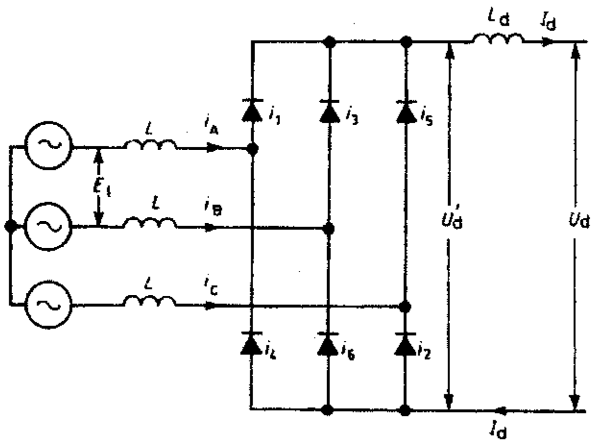

Figure 15 : Basic six pulse converter bridge

The "idealized" current and voltage waveforms which are depicted in Figure 16 are generated by neglecting commutation inductance L in Figure 15. Besides that, it is assumed that the output current, I_d is smooth due to the large DC smoothing reactor, L_d. The time when the uncontrolled (diode) valves start to conduct is used as reference, and the firing angle is defined to be zero at this point on the wave. Figure 16 is drawn by assuming that each valve has the value of firing angle equal to zero, α=0. The effects on the current dependent losses of converters are neglected in the following analysis since they are small and non-linear.

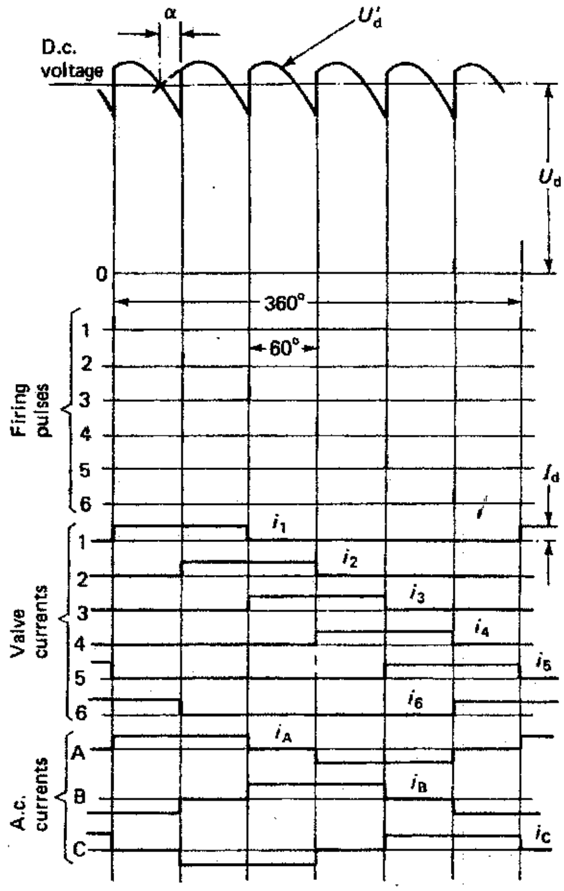

Figure 16 : Idealized waveforms for a six pulse converter [7]

Numerical relationships for this simplified case are shown as follow:

$$U_d = E_l(3\sqrt{2}/\pi)\cos\alpha = 1.35\, E_l \cos\alpha \qquad (2.1)$$

$$I_l = (\sqrt{2}/\sqrt{3})I_d = 0.816 I_d \qquad (2.2)$$

$$I = (\sqrt{6}/\pi)I_d = 0.780 I_d \qquad (2.3)$$

Where U_d is the DC voltage of the six pulse bridge, E_t is the commutation emf (rms line-line), I_d is the DC current, I_l is the rms ac current per phase, and I is the fundamental component of the AC current. The principle control action of the converter is described by the equation (2.1). For instance by changing the firing angle, α, the DC voltage can be varied from the maximum positive (rectification) at α = 0° through zero at α = 90° to negative (inversion) for α approaching 180°. It should be noted that the converter will be operated as inverter when the firing angle exceed 90°. In fact, it will produce similar waveforms as in Figure 16, but DC voltage U_d is negative. [7]

2.5 Alternative Transient Program (ATP) [12, 13]

ATP is a universal program system for digital simulation of transient phenomena of electromagnetic as well as electromechanical nature. With this digital program, complex networks and control systems of arbitrary structure can be simulated. ATP has extensive modeling capabilities and additional important features besides the computation of transients.

2.5.1 Operating Principles

ATP is operated based on several principles. These principles are listed as follow:

- Basically, trapezoidal rule of integration is used to solve the differential equations of system components in the time domain.
- Non-zero initial conditions can be determined either automatically by a steady-state, phasor solution or they can be entered by the user for simpler components.
- Interfacing capability to the program modules TACS (Transient Analysis of Control Systems) and MODELS (a simulation language) enables modeling of control systems and components with nonlinear characteristics such as arcs and corona.
- Symmetric or unsymmetric disturbances are allowed, such as faults, lightning surges, and any kind of switching operations including commutation of valves.
- Calculation of frequency response of phasor networks using FREQUENCY SCAN feature.
- Frequency-domain harmonic analysis using HARMONIC FREQUENCY SCAN (harmonic current injection method)
- Dynamic systems also can be simulated using TACS and MODELS control system modeling without any electric network.

2.5.2 Components

ATP provides wide range of components since it support many applications. The components that are stored in ATP are shown as below:

- Uncoupled and coupled linear, lumped R, L, C elements.
- Transmission lines and cables with distributed and frequency-dependent parameters.
- Nonlinear resistances and inductances, hysteretic inductor, time-varying resistance, TACS/MODELS controlled resistance.
- Components with nonlinearities: transformers including saturation and hysteresis, surge arresters (gapless and with gap), arcs.
- Ordinary switches, time-dependent and voltage-dependent switches, statistical switching (Monte-Carlo studies).
- Valves (diodes, thyristors, triacs), TACS/MODELS controlled switches.
- Analytical sources: step, ramp, sinusoidal, exponential surge functions, TACS/MODELS defined sources.
- Rotating machines: 3-phase synchronous machine, universal machine model.
- User-defined electrical components that include MODELS interaction

2.5.3 Integrated Simulation Modules

MODELS in ATP are a general-purpose description language supported by an extensive set of simulation tools for the representation and study of time-variant systems.

- The description of each model is enabled using free-format, keyword-driven syntax of local context and that is largely self-documenting.
- MODELS in ATP allow the description of arbitrary user-defined control and circuit components, providing a simple interface for connecting other programs/models to ATP.
- As a general-purpose programmable tool, MODELS can be used for processing simulation results either in the frequency domain or in the time domain.

TACS is a simulation module for time-domain analysis of control systems. It was originally developed for the simulation of HVDC converter controls. For TACS, a block diagram representation of control systems is used. TACS can be used for the simulation of:

- HVDC converter controls
- Excitation systems of synchronous machines
- Power electronics and drives
- Electric arcs (circuit breaker and fault arcs).

Interface between electrical network and TACS is established by exchange of signals such as node voltage, switch current, switch status, time-varying resistance, voltage and current sources.

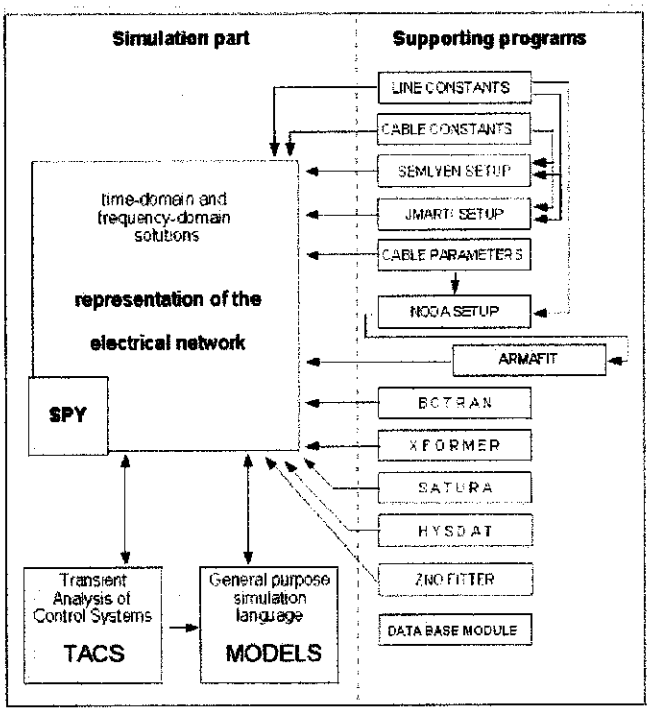

Figure 17 : Integrated simulation modules

2.5.4 Typical Applications

ATP-EMTP is used world-wide for switching and lightning surge analysis, insulation coordination and shaft torsional oscillation studies, protective relay modeling, harmonic and power quality studies, HVDC and FACTS modeling. Typical EMTP studies are:

- Lightning overvoltage studies
- Switching transients and faults
- Statistical and systematic overvoltage studies
- Very fast transients in GIS and groundings
- Machine modeling
- Transient stability, motor startup
- Shaft torsional oscillations
- Transformer and shunt reactor/capacitor switching
- Ferroresonance
- Power electronic applications
- Circuit breaker duty (electric arc), current chopping
- FACTS devices: STATCOM, SVC, UPFC, TCSC modeling
- Harmonic analysis, network resonances
- Protective device testing

CHAPTER 3
METHODOLOGY/ PROJECT WORK

3.1 Procedure Identification

In order to ensure the project can be implemented systematically, the required steps need to be identified. All the methods, which are involved in completing this project, are depicted in Figure 18. All approaches are carried out step by step. However, if any discrepancy is encountered while executing the respective step, the precedent step will be revisited until the desired result is obtained.

3.1.1 Research and Analysis

Research is the prerequisite in the early stage of the project and most of the time of this project has been spent for conducting literature search. This activity is imperative as it helps to understand the problem thoroughly. In fact, by gathering data and information, solutions to overcome the problem can be developed. The sources of literature search comprise of books, journals, conference papers, reports and websites. Literature search will be implemented throughout the project. In the early stage, it is made in order to get general idea on how to approach the project. Later in the middle stage, this activity is very handy in understanding the important theories and concepts of the project as well as developing algorithm and method to solve the problem. At the end, analysis must be done before conclusion can be made.

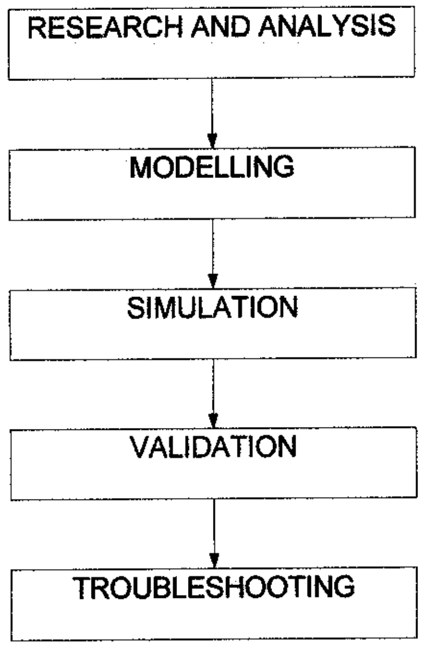

Figure 18 : Procedures in delivering the project

3.1.1.1 Evaluating the Performance of ATP, ATOSEC5 and SIMUSEC in Studying HVDC Transmission System [9]

HVDC simulators are required in order to conduct the simulation studies for HVDC transmission system. There are three software that can be used for that purpose which are ATP, ATOSEC5 and SIMUSEC. All software are designed for time domain analysis of power supply, power electronic converters and converter fed machine respectively.

ATP is an EMTP simulation program that is used in analyzing power system, which includes thyristor converters that are used in HVDC transmission system. There are several reasons that make ETP widely utilized in power simulation studies such as it has list of models for the power system components and its price-wise affordability. The usage of ATP can be applied in the study of power electronic converter and system that use electronic converters.

ATOSEC5 is a simulator that can be used to study power electronic converter too. It has user-friendly schematic capture interface and a novel modelling method for the semiconductor switches.

SIMULINK, which is designed for personal computer, is a simulator that is utilized in studying automatic control system as well as power electronic converter topologies and converter fed DC and AC drive.

Some studies which applying benchmark HVDC transmission systems with a classical regulation scheme have been implemented by using ATP, ATOSEC5 and SIMUSEC. Figure 19, 20, 21 and 22 depict the HVDC scheme and the circuit topology for each simulator. The performance of the system is evaluated comparatively with regards to several aspects, namely:

- user-friendly data preparation
- on-line parameter variations
- computation time requirement
- numerical instability associated with the computation

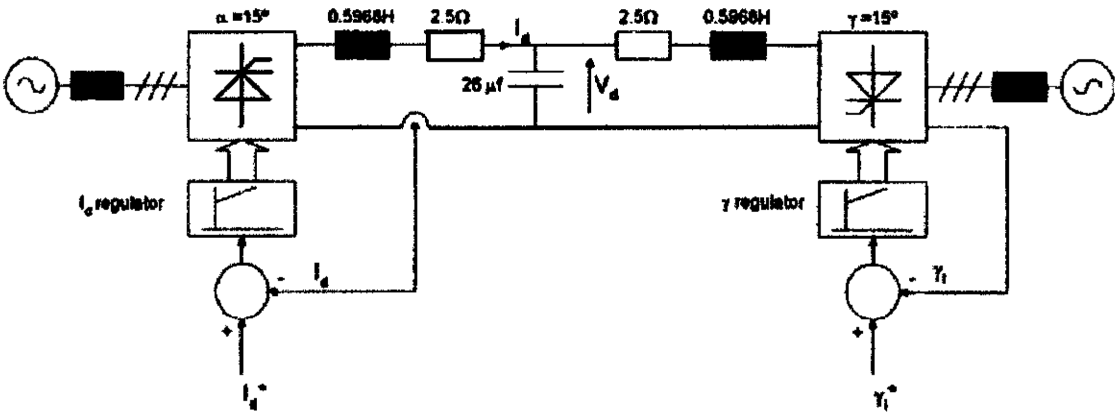

Figure 19 : HVDC transmission scheme [9]

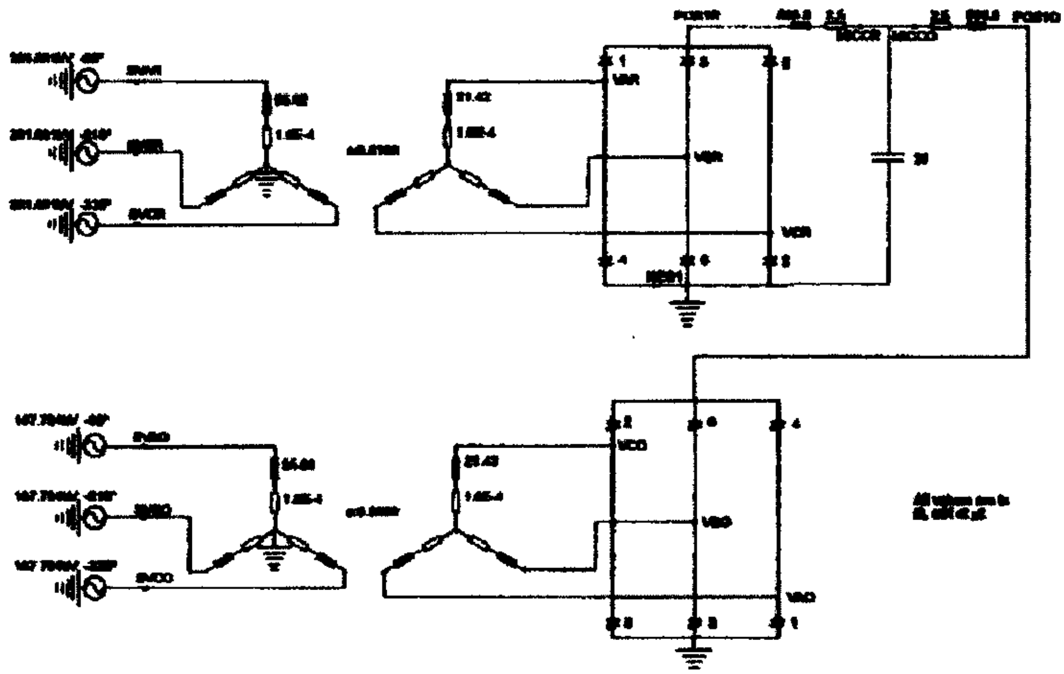

Figure 20 : ATP simulator, system topology without control loops [9]

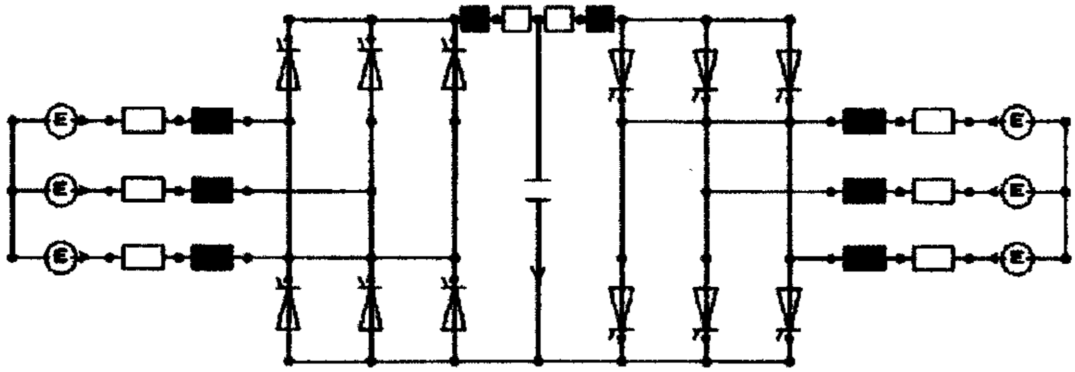

Figure 21 : ATOSEC5 simulator, system topology without control loops [9]

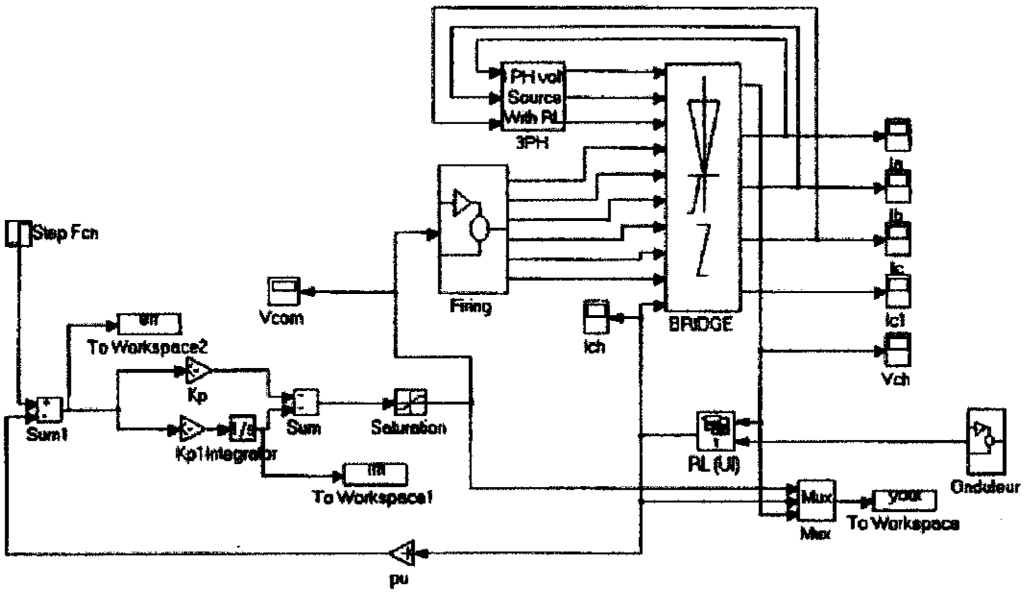

Figure 22 : SIMUSEC simulator, system topology with current control [9]

In order to ensure the study can be executed correctly, a six-pulse scheme was utilized instead of 12-pulse scheme that is generally used for the HVDC transmission scheme and the parameters of the benchmark system were altered so that the requirements were fulfilled. Classical control method that is used in a standard HVDC transmission scheme under normal operating conditions was employed in the studies, which are the converter at the sending end, operates in the rectifier-mode while the receiving end converter operates in the inverter mode.

ATP used a nodal approach in formulating the system equations while the state variable approach is applied in ATOSECS and SIMULINK simulators. ATP and ATOSEC5 require three modules for analysis, namely:

- pre-processor module for data preparation
- simulation module
- a post-processor module

Since ATP version that was used did not have any particular pre-processor module, any ASCII type of text editor could be used for the preparation of data from circuit topology.

A feature in ATOSEC5, which is known as ATOSECG, has enabled it to prepare data for a topology under study. In both cases, data edition was carried out to incorporate the automatic control loop. In the three simulators, modification data is made to include two control loops, which are:

1. a constant current control loop which is for the converter at the sending end that operates under rectifier mode
2. a constant extinction angle control loop which is for the receiving end inverter

SIMULINK is a simulator that has linear and nonlinear control blocks and sources. A library known as SIMUSEC was created for the creation of the circuit topology that will be used in the simulation of the benchmark of HVDC scheme. The library consists of converter topologies and converter fed ac machine systems and control strategies such as cascade speed-current control loops for DC drive, and voltage-frequency and field-oriented controls for AC drives.

Three case studies were implemented in each simulator:

Case study 1: Variation of the current reference by plus or minus 10% for the rectifier end of the scheme.

Case study 2: Operation of the current regulation loop for the rectifier end under short-circuited conditions of the inverter end;

Case study 3: Operation of the complete HVDC scheme with link current control for the rectifier end and extinction angle control for the inverter end, when its mains voltage varies by minus 10%.

The results that were produced by each simulator are compared and tabulated. These results are shown in the following chapter.

3.1.1.2 Modeling of the HVDC Transmission System Links between Thailand-Malaysia Using EMTP/ATP Program [10]

The EGAT-TNB HVDC system interconnects the asynchronous 230 kV 50 Hz AC system of Thailand and 275 kV 50 Hz AC system of Malaysia. Two 12-pulse converter stations, which are connected by 110 km long DC transmission line, are used in the Thailand-Malaysia HVDC link. In order to transfer continuous power from 60 to 600 MW, bipolar system is incorporated in designing the HVDC interconnection project. However the early stage would be the monopolar system with metallic return scheme, and extended to the bipolar operation later.

Each converter station can be both rectifier converter station and inverter converter station depending on the transferring direction of the power. The rate of continuous operation power is from 30 to 300 MW with short time overload capability at 450 MW for 10 minutes daily. The operating voltage of the DC system rates at 300 kV and reduced to 210 kV, should the insulation withstand capability of DC line be reduced due to contamination. During the initial monopolar stage, the EGAT-TNB HVDC system normally connects the high voltage pole to the first conductor and connects the low voltage pole in parallel with the neutral line (which are directly grounded at the Khlong Nage station) to reduce losses as shown in Figure 23.

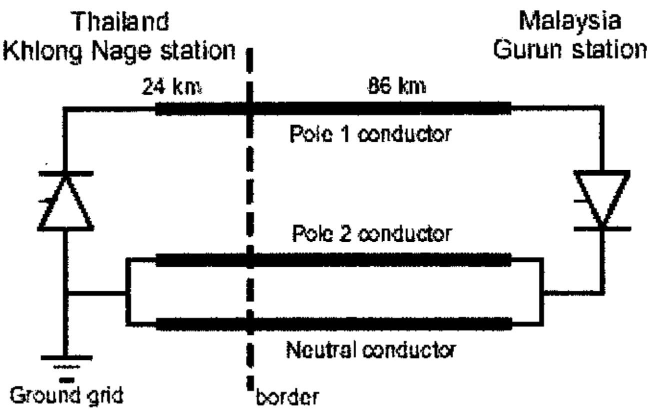

Figure 23 : Normal operating configurations [10]

Figure 24 depicts the equivalent circuits of the EGAT- TNB HVDC Interconnection Project, which have been modeled by using ATP. It is important that the AC system is equivalent so that the simulation study accurately reflects the behavior of the AC system. The resistors, inductors and capacitors contribute to the impedance of the AC system. By having the equivalent circuit, the demonstration of the DC control response as well as the verification of the HVDC performance can be executed.

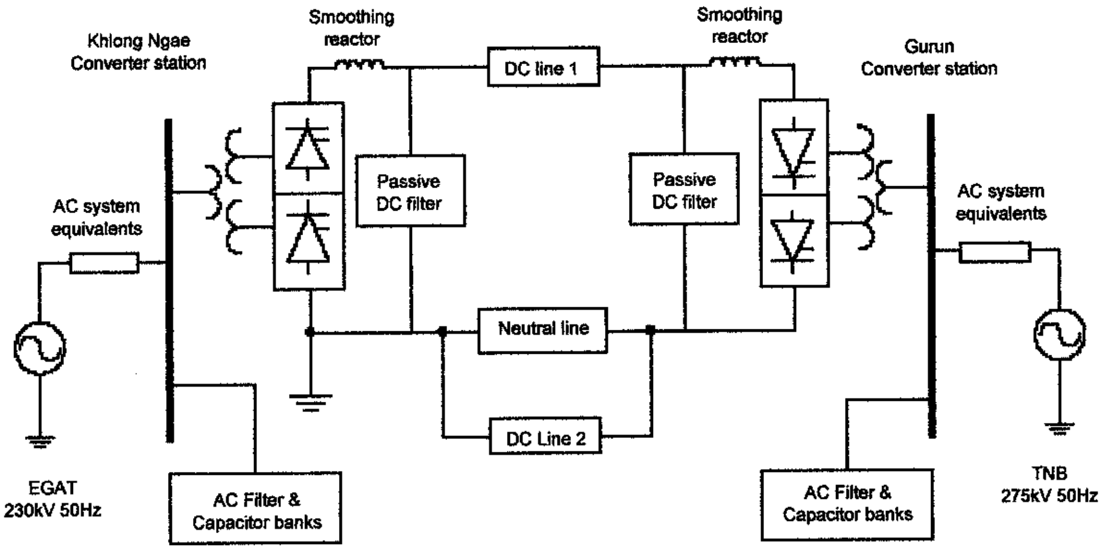

Figure 24 :The modelling of EGAT-TNB HVDC Interconnection Project [10]

The triple-tuned AC filters and shunt capacitor banks are connected to the high voltage AC busbars at both converter stations. The main purpose of shunt capacitor banks is to supply reactive power during HVDC operating. In order to reduce the flow of harmonic currents into the AC system, AC filters are utilized in the HVDC transmission system. The converter transformers, which are connected between the AC network and the thyristor valves, provide voltage matching between the AC system and the thyristor valves group. For interconnection project, the converter transformers are single-phase, three windings rated 116/58/58 MVA with a 122.24 kV valve winding voltage. So, for 12-pulse operation, three units of converter transformer are required. The connections of windings are star to ground at primary, star at the first secondary and delta at the last one.

Thyristor valves are main equipment for conversion of AC and DC system. Both converter stations consisted of 12 thyristor valves, which are connected as series of two 6-pulse bridge converters. The first 6-pulse converter bridge is connected directly to the star secondary winding, whereas the other one is connected to the delta secondary winding. Each thyristor valve is consisted of thyristors, snubber circuits, reactors, grading resistors and grading capacitors.

100mH smoothing-reactors were installed at the both stations and they were connected in series with the converter bridges. The main purposes of the installation are for reducing DC voltage harmonics on DC transmission line, protecting the stations from lighting and switching surge. The hybrid DC filter consists of passive and active part. The passive part is a double tuned filter, tuned harmonics at 12th and 24th. The active DC filter is a device which injects harmonic currents into the DC line at the same magnitude but opposite in phase 180°. Since the impedance of the smoothing reactor is high compared to the DC line, the generating current would flow into the DC line. So, the sum of harmonic currents in the DC line would nearly zero.

3.1.2 Modeling

The modeling of HVDC transmission system was done on the converter part only. This is because the fundamental process that occurs in an HVDC system is the conversion of electrical current from AC to DC (rectifier) at the transmitting end and from DC to AC (inverter) at the receiving end [11]. This step was executed by using ATP software. The model of the converter is shown in Figure 25. The whole transmission system which connects between rectifier and inverter was not designed since such model requires control system. The control system is necessary in order to control the mode of each converter. Since the design and concept of HVDC control system are very complex, its model is omitted from this project. Also, time constraint has contributed towards the issue.

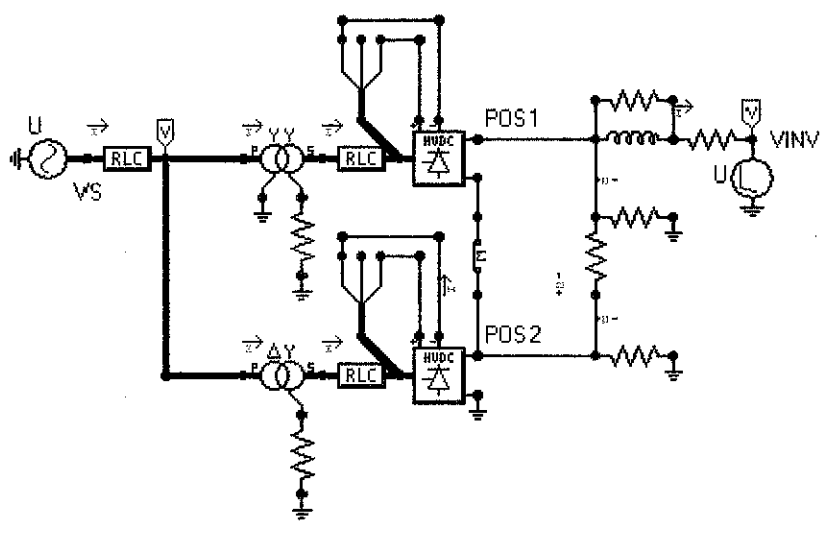

Figure 25 :The 12-pulse HVDC converter station

In the modeling task, some of the ATPDraw components were used. Figure 26 indicates most of the predefined object in ATPDraw. Among these components, just few of them were utilized in constructing the model of the HVDC converter, namely:

- AC type 14 which is an AC source
- Probe volt which is used to specify voltage output request in the ATP file
- Splitter that is used as a transformation between a 3-phase node and three single-phase nodes.
- RLC which is R, L and C in series
- Ramp type 12, which is a ramp source.
- Measuring switch
- Transformers
- HVDC converter bridge
- Resistor and Inductor

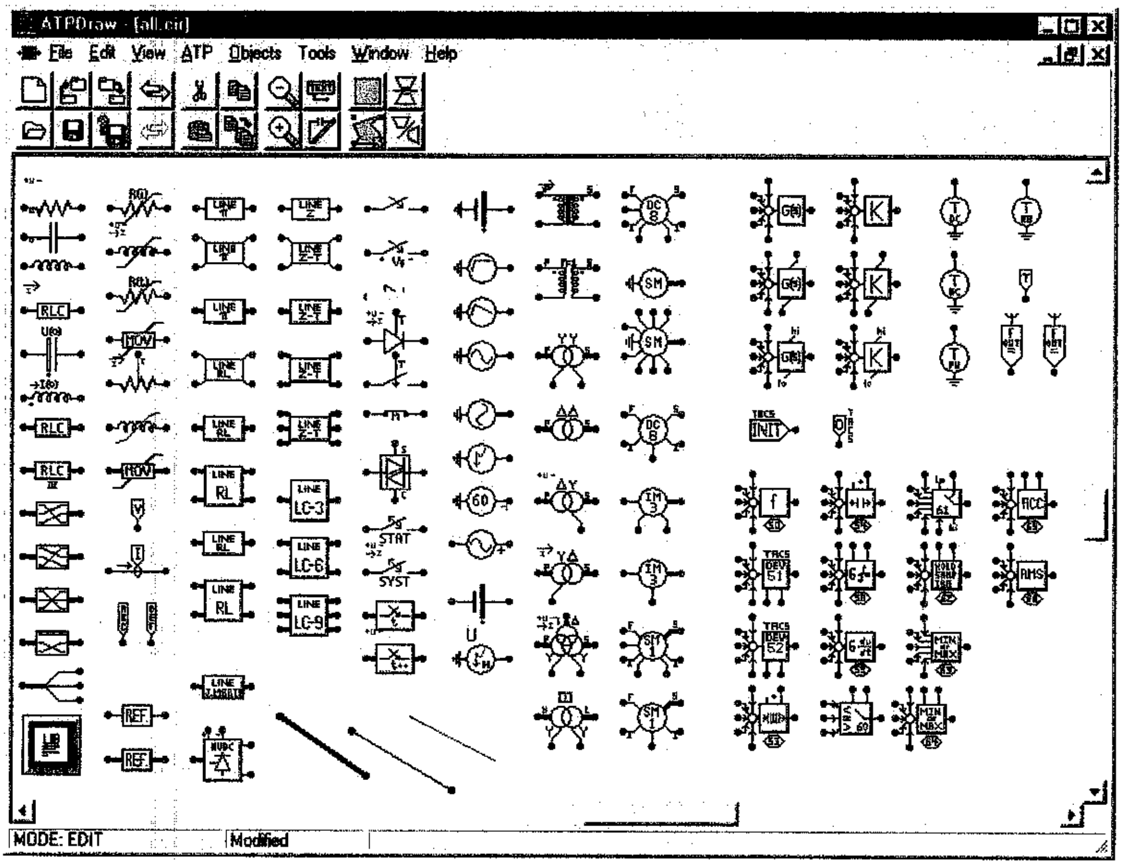

Figure 26 : ATPDraw main windows showing most of the predefined components. [13]

3.1.3 Simulation

Using "run" command in the ATPDraw ran the simulation of the model. Subsequently, calculation on the model will be performed in MS-DOS format. Once the computation was completed, the output waveform from the HVDC converter is plotted using the ATPDraw plotting features, which is known as PlotXY. Figure 27 depicts the interface of the plotting tool.

3.1.3.1 Varying Firing Angle

During the simulation process, the firing angle of the HVDC converter was varied. This was done in order to observe the effect on the voltage output that will occur once the firing angle is changed. In fact, this step is important in determining the right angle to operate the HVDC converter.

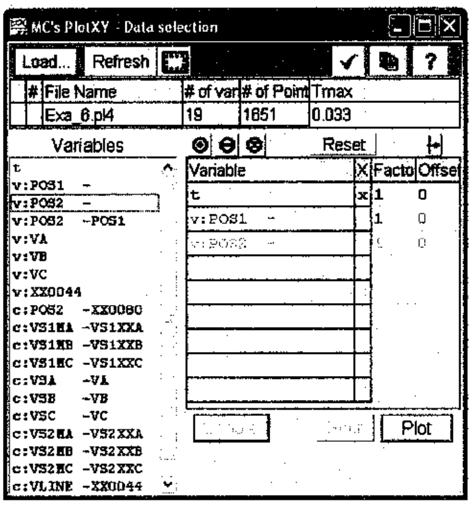

Figure 27 : Plotting tool used in generating the output waveforms

3.1.4 Validation

In general, validation is the process of checking if something satisfies a certain criterion. Validation implies one is able to testify that a solution or process is correct or compliant with set standards or rules. In this project, the validation was conducted by comparing the simulated results with the real data, which was obtained from the EGAT-TNB HVDC system. From this step, it will determine whether the model and simulation of the HVDC converter is correct or vice versa.

Apart from that, the validation was executed by comparing the results obtained with the theoretical results too. For instance, in the case when the firing angle was varied, the simulated outputs were compared with the theoretical results and concept.

3.1.5 Troubleshooting

This step is optional, which means that it will be executed when the results obtained are not behave as expected. This is because inputs to the system are expected to generate specific results or outputs. Therefore, if the outputs that are produced are wrong, troubleshooting will be implemented. Generally troubleshooting is a form of problem solving. It is the systematic search for the source of a problem so that it can be solved.

3.2 Tools [12, 13]

Basically all the tools that were utilized in this project are those that were provided by the Alternative Transient Program. These tools are mainly used to develop the model of HVDC transmission system and simulate the model in order to obtain the results. The tools that were applied throughout the project are listed as follow:

3.2.1 ATPDraw (graphical preprocessor to ATP)

ATPDraw is a graphical preprocessor to the ATP-EMTP on the MS Windows platform. In the program the user can build up an electric circuit, using the mouse, by selecting predefined components from an extensive palette. Based on the graphical drawing of the circuit, ATPDraw generates the ATP file in the appropriate format based on "what you see is what you get". All kinds of standard circuit editing facilities (copy/paste, grouping, rotate, export/import) are supported. ATPDraw administrates circuit node naming and the user only needs to give name to "key" nodes. More than 65 standard components and 25 TACS objects are available, and in addition the user can create new objects based on MODELS or Data Base Modularization.

ATPDraw has a standard Windows layout, supports multiple documents and offers a large Windows help file system, which explains the most basic rules. Other facilities in ATPDraw are: a built-in editor for ATP-file editing, support of Windows clipboard for bitmap/metafile, output of MetaFiles/Bitmaps files or PostScript files not limited to circuit window size, a new module for using Line/Cable Constant punch files directly in ATPDraw, a tool-bar below the main menu containing the most used selections together with the last 9 selected components, an extensive UnDo/ReDo handling with up to 100 steps, etc.

3.2.2 PlotXY (Plotting program)

It is a plotting program to generate easy and fast scientific line plots using data collected from PL4 file after running. Main program features are listed as follow:

- up to 8 plots per sheet.
- allows plots versus time.
- allows linear and logarithmic scales.
- scaling, offsets and zoom support.
- automatic axis scaling and labeling.
- cursor to see values in numerical format.
- printing and Windows Metafile export facilities.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Evaluating the Performance of ATP, ATOSEC5 and SIMUSEC in Studying HVDC Transmission System [9]

As mentioned previously, the three simulators/software which are ATP, ATOSEC5 and SIMUSEC were applied in three different case studies, namely:

- Case study 1: Variation of the current reference by plus or minus 10% for the rectifier end of the scheme

- Case study 2: Operation of the current regulation loop for the rectifier end under short circuited conditions of the inverter end

- Case study 3: Operation of the complete HVDC scheme with link current control for the rectifier end and extinction angle control for the inverter end, when its mains voltage varies by minus 10%

Then, from the results obtained, the performances of the system are evaluated with respect to certain features, specifically:

- user-friendly data preparation
- on-line parameter variations
- computation time requirement
- numerical instability associated with the computation

Table 1 : Performance evaluation of ATP, ATOSEC5 and SIMUSEC simulators for case study 1. [9]

All simulations were done using a 486-50 MHz PC compatible machine with 8MB of RAM			
	ATP	ATOSEC5	SIMUSEC
Data file name	SIXATP.DAT	SIXATO.DAT	SIXSIM.M
Data file length	9881 bytes	4287 bytes	192385 bytes
Integration algorithm	Trapezoidal	Euler backward	Gear
Tolerance	N/A	N/A	5e-4
Minimum step length	2e-5	2e-5	2e-5
Maximum step length	N/A	N/A	N/A
Simulation interval	550ms (27.5 cycles)	550ms (27.5 cycles)	550ms (27.5 cycles)
Simulation time	1'11"	12'00"	67'10"

Table 2 : Performance evaluation of ATP, ATOSEC5 and SIMUSEC simulators for case study 2. [9]

All simulations were done using a 486-50 MHz PC compatible machine with 8MB of RAM			
	ATP	ATOSEC5	SIMUSEC
Data file name	SIXATP.DAT	SIXATO.DAT	SIXSIM.M
Data file length	9698 bytes	4659 bytes	192484 bytes
Integration algorithm	Trapezoidal	Euler backward	Gear
Tolerance	N/A	N/A	5e-4
Minimum step length	2e-5	2e-5	2e-5
Maximum step length	N/A	N/A	2e-4
Simulation interval	550ms (27.5 cycles)	550ms (27.5 cycles)	550ms (27.5 cycles)
Simulation time	3'48"	12'27"	97'42"

Table 3 : Performance evaluation of ATP, ATOSEC5 and SIMUSEC simulators for case study 3. [9]

All simulations were done using a 486-50 MHz PC compatible machine with 8MB of RAM			
	ATP	ATOSEC5	SIMUSEC
Data file name	SIX2X2C1.DAT	SIX2X2C1.DAT	N/A
Data file length	14947 bytes	4659 bytes	N/A
Integration algorithm	Trapezoidal	Euler backward	N/A
Tolerance	N/A	N/A	N/A
Minimum step length	2e-5	2e-5	N/A
Maximum step length	N/A	N/A	N/A
Simulation interval	800ms (40 cycles)	800ms (40 cycles)	N/A
Simulation time	3'20"	79'54"	N/A

Comparative performance of the three simulators for the case studies 1 and 2 are shown in Table 1 and 2. Based on the results, it can be stated that the simulation studies gave comparable results (within a relative accuracy of 5%). SIMUSEC was facing numerical instability problems in the third case; this was found to be true when both the control loops were included for the simulation. Due to the problem, SIMUSEC was excluded for the third case studies. Table 3 summarizes the comparative performance of the two simulators, ATP and ATOSECS for the case study 3.

Based on the findings, it can be stated that SIMUSEC-based simulator is the user-friendliest software. Nonetheless, due to numerical instability problems that were encountered during the computation, SIMUSEC takes a long time (several orders of magnitude) for simulation. SIMUSEC has been successfully used for the study of a number of power electronic converter systems but it has not proved to be a useful tool for the study of a HVDC Transmission scheme.

On the other hand, ATOSECS simulator has proved to be a useful tool for the studies though it is not as user friendly as the SIMUSEC simulator. This is because it produces reliable computation especially when it deals with complex converter schemes including their control loops. In term of computation time, ATOSEC5 is faster than SIMUSEC but it is slower when it is compared to ATP. ATOSECS-based simulation was very useful in analyzing a complex circuit such as a HVDC scheme quickly on a simplified representation basis.

From the results, it has proven that ATP-based simulation is the best tool in studying HVDC transmission system; but if one takes into account the time for data preparation or modification, ATP-based simulation may not be the favourite choice for many applications other than power systems.

4.2 Validation

4.2.1 Simulation of HVDC converter

The main focus of the simulation is to see the waveform of the voltage of the HVDC converter. The waveform is depicted as below:

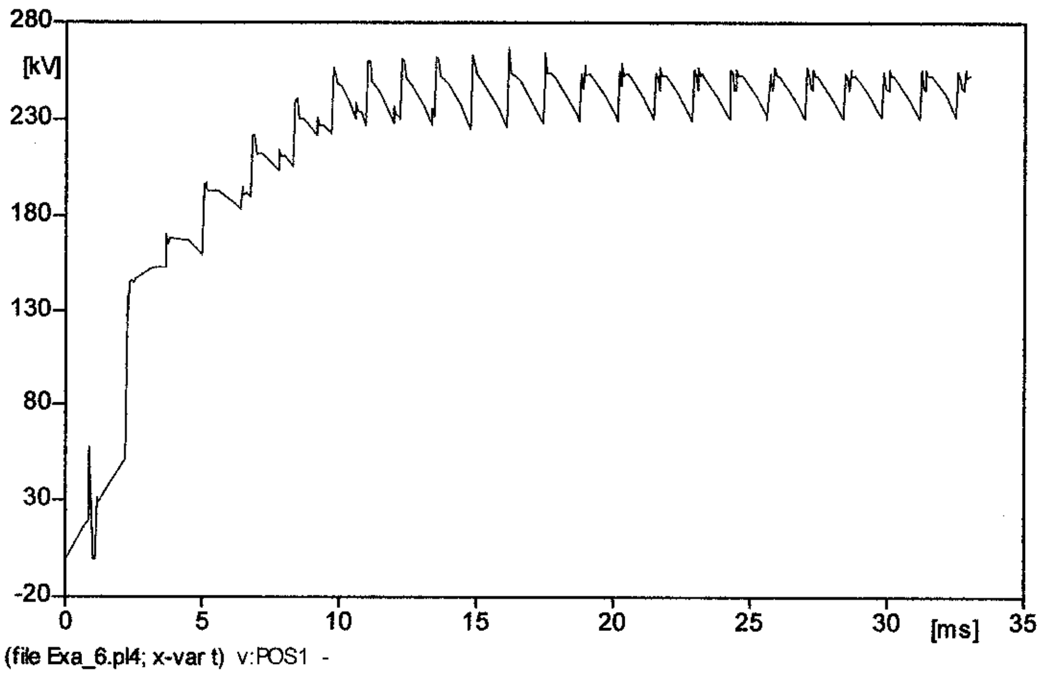

Figure 28 : The voltage and current waveforms

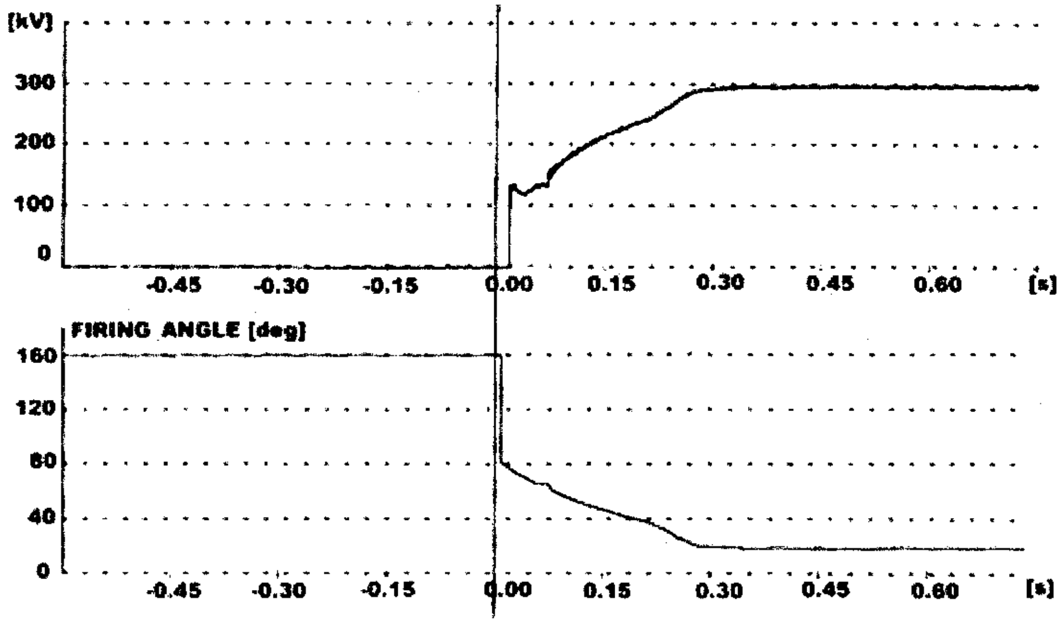

Figure 29 : The real recording signals from EGAT-TNB field-testing [10]

From the waveform in Figure 28, it can be stated that when the valve is fired up (deblocking), the voltage waveform starts to increase until it reached it steady state. After short time interval, the waveform seems to be constant with the value of 250kV. Besides that, it can be seen that the voltage waveform that is produced is not purely constant. This is because it has some ripples in the signal. The most probable solution in order to generate a smooth voltage waveform is by placing a smoothing reactor, which could be a very large magnitude of inductor.

Although the simulated waveforms are not smooth, it actually manages to resemble the real results. This is proven when the simulated results are compared with the real recording signals, which were obtained from the EGAT-TNB field-testing. Therefore, it can be stated that the results are proven.

4.2.2 Varying Firing Angle

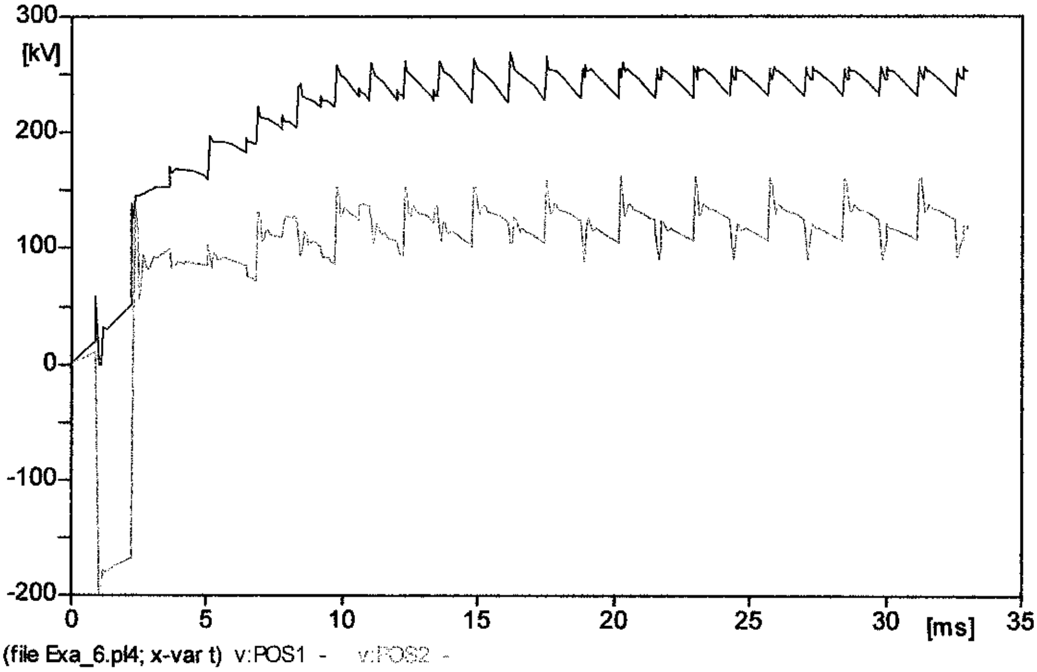

Figure 30 : Output waveforms for firing angle 18.2°

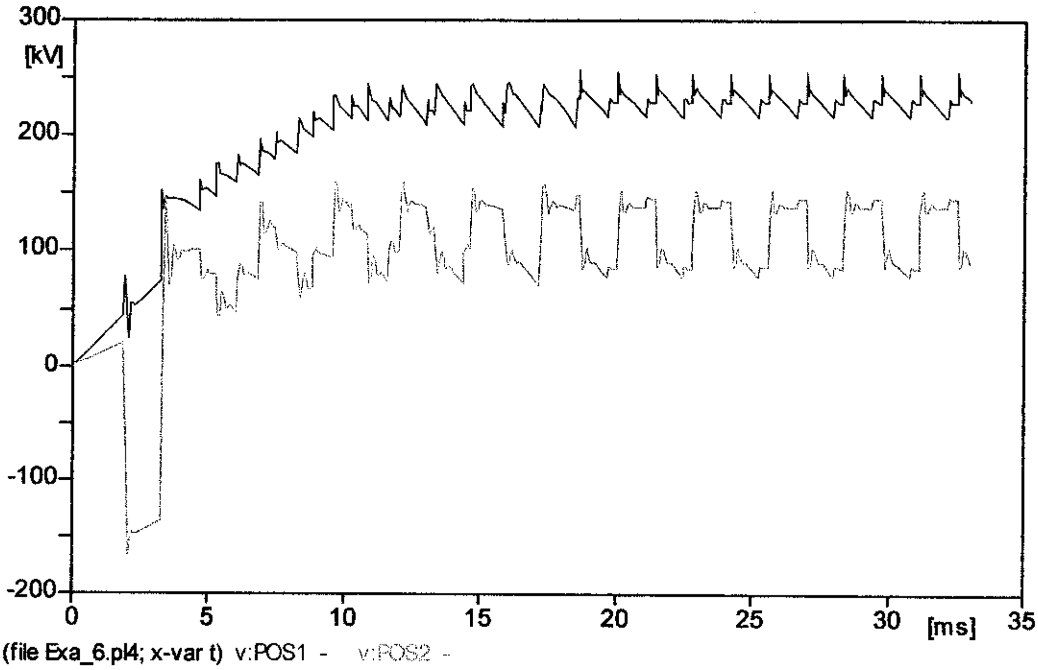

Figure 31 : Output waveforms for firing angle 40°

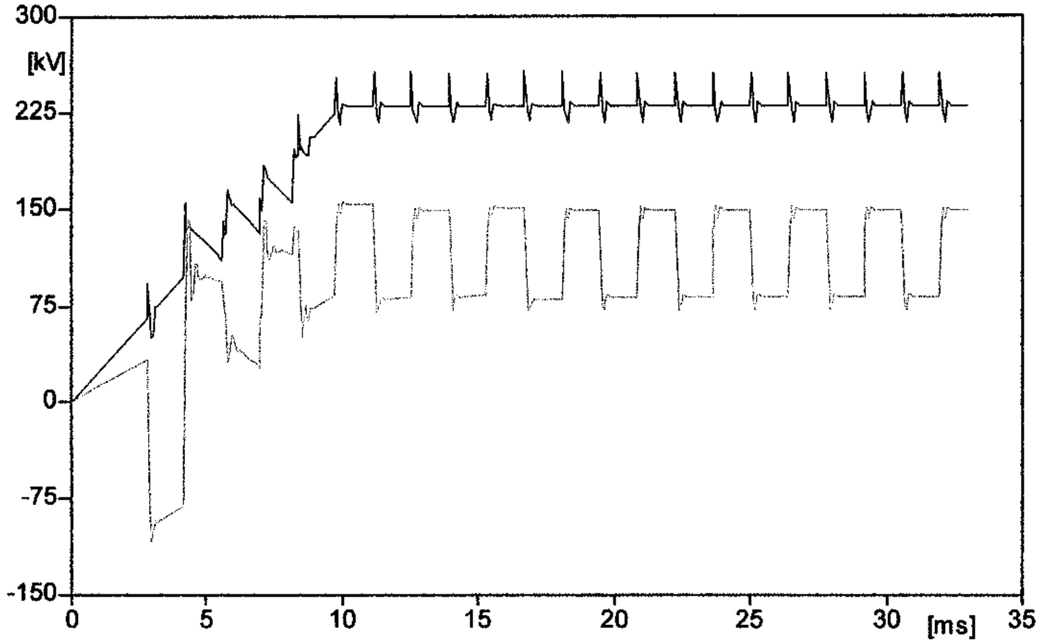

Figure 32 : Output waveforms for firing angle 60°

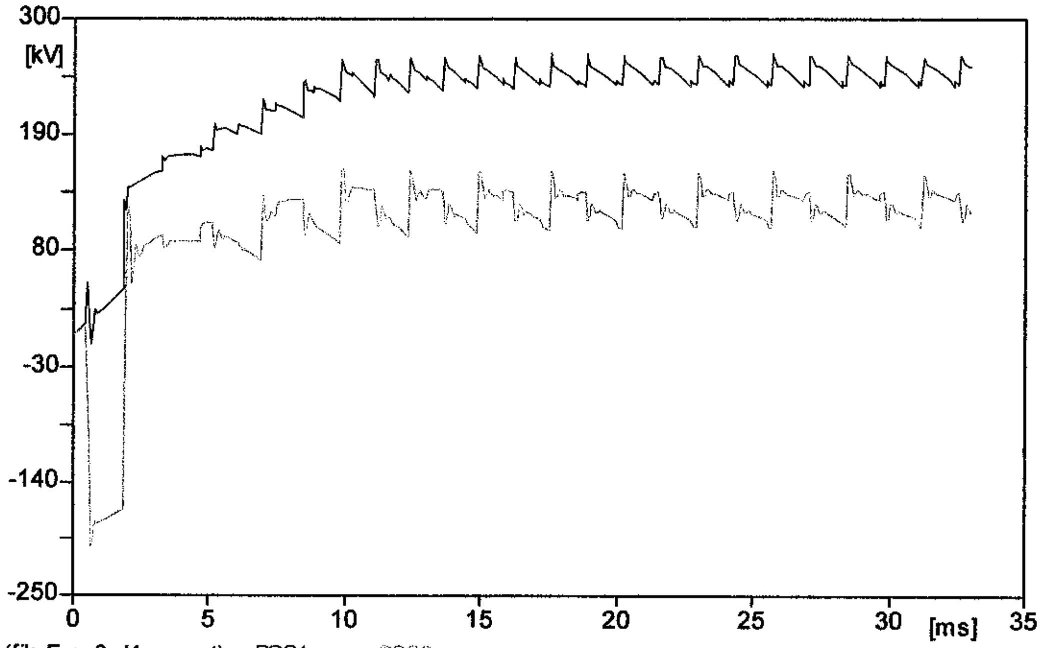

Figure 33 : Output waveforms for firing angle 10°

From the results obtained, it can be stated that small firing angle will produce larger voltage output compared to large firing angle. These results are proven true because theoretically the faster the SCR is fired up, the earlier it will conduct the current and therefore more output voltage will be produced. In fact, by referring to equation (2.1), it obviously indicates that maximum output voltage will be produced when α is at zero degree. Thus, having small firing angle, α will generate large output voltage. Apart from that, having minimum firing angle can minimize the consumption of reactive power.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

This project manages to achieve its objectives. In this project, HVDC transmission system was modeled and simulated by using ATP software. Although the modeling and simulation were conducted on the converter part, it was adequate since fundamental process that occurs in an HVDC system is the conversion of electrical current from AC to DC (rectifier) at the transmitting end and from DC to AC (inverter) at the receiving end.

The project was executed by following several systematical approaches. In the initial stage, research and analysis were conducted in order to gather data and relevant information. All the data were taken from reliable sources such as journals, conference papers and textbooks. Later, modeling and simulation have taken place. ATP software is used to carry out the above step. Subsequently, the results were verified by comparing simulated waveforms with the field-testing data.

From the results obtained, it can be stated that ATP is the best software to study HVDC. This is due to its capability to perform the simulation in stable manner. Apart from that, based on the simulated results, it was found that the waveforms, which were produced by the model, were correct since it almost identical to the field-testing waveforms of EGAT-TNB HVDC.

Nevertheless, there are some portions of the project that can be improved. For instance, the control system of the converter station can be included in the model of the HVDC transmission project. Such system is quite challenging to be implemented by using ATP, but there is other software known as PSCAD that can be used for that purpose, provided that the configuration of the control system that regulates the rectifier and inverter of the HVDC system is known.

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APPENDICES

APPENDIX A

COST COMPARISON OF 3000MW TRANSMISSION SYSTEM

Alternative	DC Alternatives				AC Alternatives			Hybrid AC/DC Alternative		
	± 500 kV Bipole	2 x ± 500 kV 2 Bipoles	± 600 kV Bipole	± 800 kV Bipole	500 kV 2 Single Ckt	500 kV Double Ckt	765 kV 2 Single Ckt	± 500 kV Bipole	500 kV Single Ckt	Total AC+DC
Capital Cost										
Rated Power (MW)	3000	4000	3000	3000	3000	3000	3000	3000	1500	4500
Station costs including reactive compenstation	$420	$680	$465	$510	$542	$542	$630	$420	$302	$722
Transmission line cost (M$/mile)	$1.60	$1.60	$1.80	$1.95	$2.00	$3.20	$2.80	$1.60	$2.00	
Distance in miles	750	1,500	750	750	1,500	750	1,500	750	750	1,500
Transmission Line Cost (M$)	$1,200	$2,400	$1,350	$1,463	$3,000	$2,400	$4,200	$1,200	$1,500	$2,700
Total Cost (M$)	**$1,620**	**$3,080**	**$1,815**	**$1,973**	**$3,542**	**$2,942**	**$4,830**	**$1,620**	**$1,802**	**$3,422**
Annual Payment, 30 years @10%	$172	$327	$193	$209	$376	$312	$512	$172	$191	$363
Cost per kW-Yr	$57.28	$81.68	$64.18	$69.75	$125.24	$104.03	$170.77	$57.28	$127.40	$80.66
Cost per MWh @ 85% Utilization Factor	$7.69	$10.97	$8.62	$9.37	$16.82	$13.97	$22.93	$7.69	$17.11	$10.83
Losses @ full load	193	134	148	103	208	208	139	106	48	154
Losses at full load in %	6.44%	3.35%	4.93%	3.43%	6.93%	6.93%	4.62%	5.29%	4.79%	5.12%
Capitalized cost of losses @ $1500 kW (M$)	$246	$171	$188	$131	$265	$265	$177	$135	$61	$196

Parameters:

Interest rate %	10%
Capitalized cost of losses $/kW	$1,500

Note:

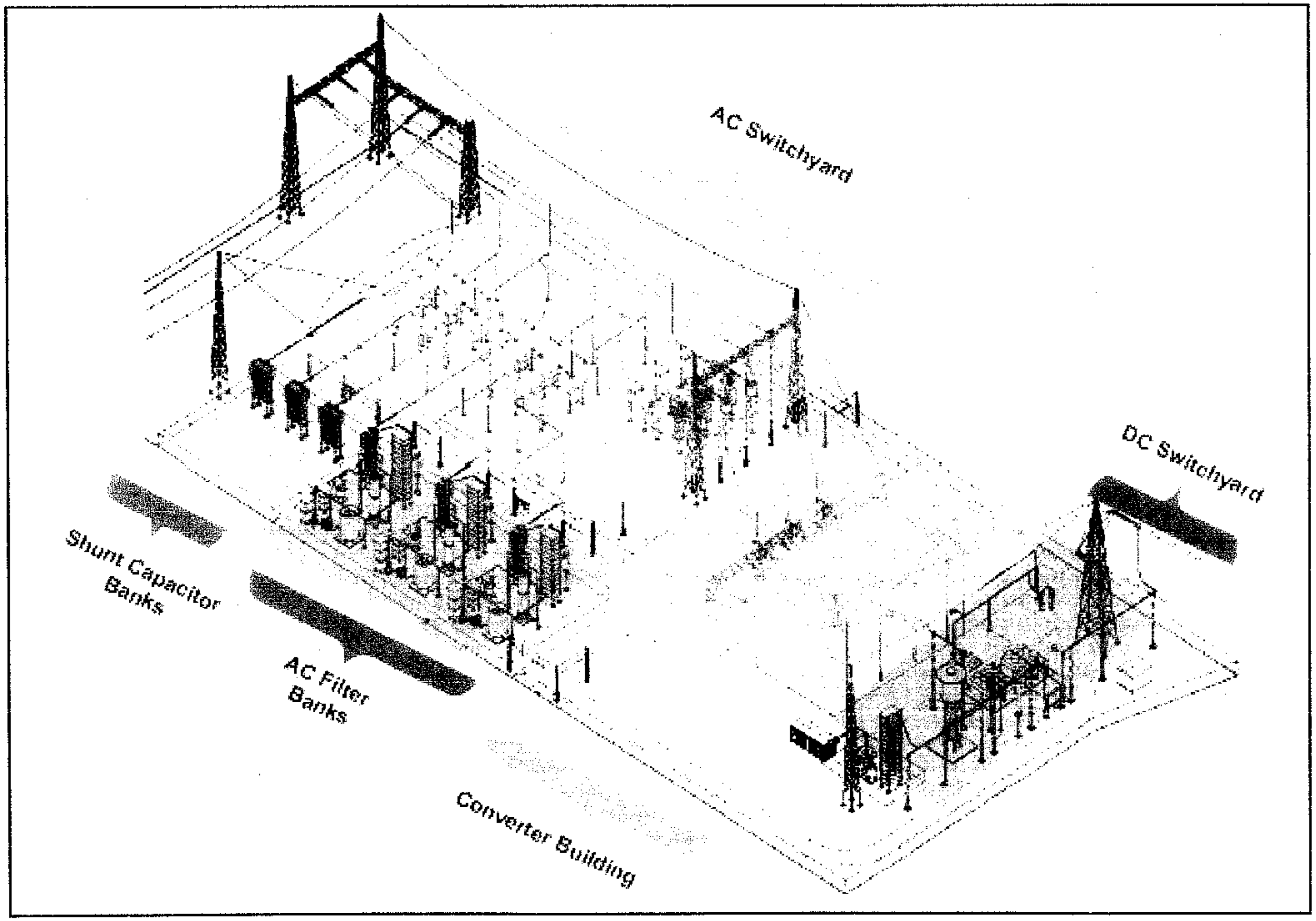
AC current assumes 94% pf

Full load converter station losses = 0.75% per station

Total substation losses (transformers, reactors) assumed = 0.5% of rated power

APPENDIX B

HVDC CONVERTER STATION DESIGN



APPENDIX C

HVDC OPERATING CONFIGURATIONS AND MODES