NTNU
Norwegian University of
Science and Technology

Cross-border transmission line between Nepal and India: a test-case for the analysis of HVDC integration into an existing HVAC system

Praveen Shrestha

Master of Science in Electric Power Engineering
Submission date: February 2016
Supervisor: Elisabetta Tedeschi, ELKRAFT
Co-supervisor: Jon Are Wold Suul, ELKRAFT
Bergna Diaz Gilbert, ELKRAFT
Navaraj Karki, Tribhuvan University

Norwegian University of Science and Technology
Department of Electric Power Engineering

Problem Description

Nepal has tremendous hydro power potential but at present there is a huge power deficit that is crippling the country. Last year, 2015, Nepal imported 224.21 MW of electric power from India and there was up to 11 hours of load shedding in the capital Kathmandu. A 400 kV Dhalkebar-Muzaffarpur cross border transmission line is under construction, which is designed to bring power up to 1200 MW when charged at 400 kV and 500 MW when charged at 220 kV. In the future, when there will be surplus power in Nepal, the same transmission line can be used to transmit power back to India.

HVDC can be another option for HVAC. It can either be connected in parallel with HVAC or can replace it. When used in parallel, it can increase the reliability, transfer capability of the transmission line, mitigate inter-area low frequency oscillations and improve voltage stability and transient stability.

Preface

This master thesis is the work required for the completion of the Master in Electrical Power Engineering at Norwegian University of Science and Technology.

I would like to thank my supervisor prof. Elisabetta Tedeschi at the Department of Electrical Power Engineering, for accepting my thesis proposal and guiding me throughout my work. I would also like to thank my co-supervisor Jon Are Wold Suul and Navaraj Karki for providing me with literatures. Also, my special thanks goes to co-supervisor Gilbert Bergna-Diaz for me with the HVDC simulation model and for guiding me with my simulations.

Finally, many thanks to all the peoples who provided me the parameters of Nepalese power system and thesis related with it.

Abstract

Nepal has huge hydropower potential of 83,000 MW, of which 42,000 MW is technically and economically feasible. According to the annual report of Nepal Electricity Authority, the total installed capacity of hydropower in Nepal is only 733.57 MW. Although bestowed with tremendous hydropower resources, only about 40% of Nepal’s population has access to electricity and remaining 60% faces severe load shedding. In this scenario, the cross border transmission links between Nepal and India serves two purposes. First, since Nepal still is short of electric power, these transmission links can be used to import power from India. Second, in future when there is surplus electric power in Nepal, it can be used to transfer power to India.

In the thesis, a model of integrated power system of Nepal is made in the Matlab Simulink. All the major power plants with capacity above 30 MW has been considered. The plants are connected to major loads with the transmission lines. In the start of the thesis, it was planned to find the real parameters of generators, governors, excitation systems, power transformers, transmission lines and loads. But later because of difficulty in finding the real parameters, the standard values were used. The grid on the Indian side is represented by three phase voltage source.

The best place for transmission link with India is in the central region between Butwal and Dhalkebar. Among different options for putting cross border transmission line, Dhalkebar-Muzaffarpur link is considered for the thesis. Different possible configuration were made using HVAC and HVDC in the cross border link. The HVAC link is considered first and then HVDC is kept in parallel. The power through the HVDC transmission line is regulated by setting the parameter values in the controller of the HVDC model. The simulation result shows that the system is unstable when there is HVAC in the cross border link. With HVDC only, the system is stable and also the control of the power flow through cross border is possible. Different condition of power transfer has been obtained and presented.

Even though the values of generators parameters were taken as standard parameters, the excitation and governor parameters were same for all power plants. Either real value of the parameters should be used or standard values should be used according to the size and location of the power plant. The location of hydropower plants and load center are exact. The rated capacity of Upper Tamakoshi hydro plant is taken as 100 MVA, although its actual capacity is 540 MVA. It was because for its rated capacity above 100 MVA, the system becomes unstable. During the simulation, the control of power flow through HVAC was not possible. The model involving HVAC was not stable also. Stable condition were found using HVDC only.

Abbreviation

AC	:	Alternating Current
DC	:	Direct Current
GMD	:	Geometric Mean Distance
GMR	:	Geometric Mean Radius
HVAC	:	High Voltage Alternating Current
HVDC	:	High Voltage Direct Current
INPS	:	Integrated Nepal Power System
IPS	:	Integrated Power System
mmf	:	Magnetic Motive Force
NEA	:	Nepal Electricity Authority
pu	:	Per unit

Contents

List of Figures

List of Tables

Chapter 1. Nepal's Hydro Power

1.1. Introduction

Nepal has huge hydropower potential due to its perennial nature of rivers and the steep gradient of the country's topography. Nepal has hydropower potential of 83,000 MW of which 42,000 MW is of technically and economically feasible [1]. The Government of Nepal sees hydropower as critical to the nation's sustainable economic and social growth and is committed to its development for domestic use and to generate valuable foreign exchange through exports. However, by 2013/2014, the total installed capacity is of 787.087 MW only, out of which hydroelectric holds its share of only 733.577 MW [2]. It has been more than 100 years, in 1911, that Nepal started producing hydroelectric power from Pharping Power station. The remaining contributions are from thermal and solar plants. Therefore, bulk of the economically feasible generation has not been realized yet. Besides, the multipurpose, secondary and tertiary benefits like flood control, irrigation, drinking water supply, transportation have not been realized from the development of its rivers. Although bestowed with tremendous hydropower resources, only about 40% of Nepal's population has access to electricity.

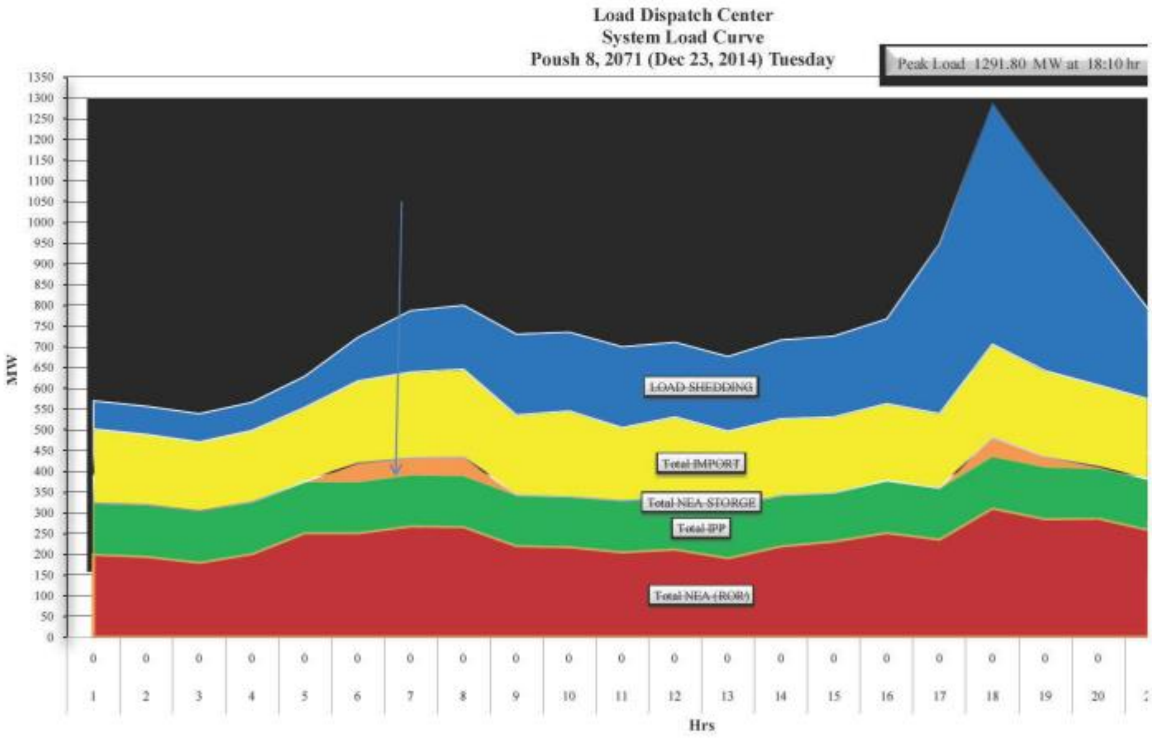

Figure 1.1-1: System load curve of peak load day (Dec 23, 2014) [2]

Most of the hydropower in Nepal are of run of river (ROR) type, the generating capacity reduces to nearly half during dry season when the demand is at its peak. There is only one seasonal storage project in the Nepal. As shown in the Figure 1.1-1, the annual peak demand of the integrated Nepal Power System (INPS) in fiscal year 2014/15 is estimated to be 1,291.8 MW, with 585 MW power estimated to have been shed. Out of the 706.8 MW of power actually supplied, 357.68 MW was contributed by NEA hydro, 124.71 MW by IPP hydro and the rest 224.41 MW was imported from India. The load curve is an estimation and it shows the amount of load that has been shed. The growth in the annual peak power demand of INPS registered to be 9.7%. [2] Energy demand of INPS in fiscal year 2013/14 is estimated at 5,909.96 GWh, out of which only 4,631.51 GWh (78.4%) could be supplied. The rest 1,278.45 GWh (21.6%) was resorted to load shedding. Of the total supplied energy volume, 3,559.28 GWh (76.8%) was contributed by domestic generation and 1,072.23 GWh (23.2%) by import from India. Domestic supply included 1,258.94 GWh (35.4%) from IPPs and the rest 2,300.34 GWh (64.6%) was from NEA owned power stations with a share of 2,290.78 GWh from hydro and 9.56 GWh from thermal [3].

1.2. **Nepal Electricity Authority**

The Nepal Electricity Authority (NEA) is the government-owned utility serving approximately 2.87 million grid-connected customers by 2014/15 [2]. NEA was created on August 16, 1985 under the Nepal Electricity Authority Act. 1984, through the merger of the Department of Electricity of Ministry of Water Resources, Nepal Electricity Corporation and related Development Boards. The primary objective of NEA is to generate, transmit and distribute adequate, reliable and affordable power by planning, constructing, operating and maintaining all generation, transmission and distribution facilities in Nepal's power system both interconnected and isolated [4].

During its dry season (Oct-May), Nepal experiences significant power deficit because of high demand, low water flow in the rivers and the inability to import energy from India because of lack of transmission interconnections. In the fiscal year, 2014/15, NEA was able to limit daily load shedding up to 12 hours per day, which was less than the previous years. This was possible due to sound operation of the power system, to ensure filing up of the Kulekhani reservoir at the onset of the dry season, and comparatively a wet monsoon. Extended load shedding hours for the feeders that reported high percentage of theft was also a contributing factor. NEA resorted to all possible means to minimize load shedding; including purchase of all excess energy from the IPPs and all possible import under power exchange agreement and power trade with India [2].

The Integrated Power System (IPS) is there for the smooth evacuation of power from the generating stations to the consumers, i.e. taking care of the overall reliability, security, economy and efficiency of the power system. Power generation in the IPS is mostly done by thermal, hydro and nuclear power, depending on the availability of the resources in each nation. Nepal also has its own Integrated Nepal Power System (INPS), and its generation is based entirely on hydropower plants. The government has authorized Nepal Electricity Authority (NEA) to plan, develop/execute, operate and maintain the INPS, mandating it with the study, design and construction of hydropower projects as well.

An Integrated Power System (IPS) should have electrical energy generating plants for base load (e.g., nuclear and thermal plants) and peak load (e.g., hydropower plants) so that they can work in coordination in such a way that the demand is met in time. In Nepal, the Integrated Nepal Power System (INPS) is a hydro-dominated system where the base and intermediate power demands are covered primarily by run-of-river hydropower plants and the peak demand by seasonal storage and several diesel power plants of lower capacity.

INPS has incurred 24.79 % system loss in 2013/14. INPS has challenge towards meeting the growing demand of electricity and it has carried out power purchase agreement with independent power producers. Out of the total consumers served by INPS in 2013/14, domestic consumer stand at 94.37% and industrial consumer is 1.47%. The Government of Nepal made public plans to add 10 GW in 10 years and 25 GW in 20 years. This GON plan requires additional transmission lines, reinforcement in the existing transmission line [3].

Nepal's power system is experiencing insufficient transmission capacity. Often, (N-1) criterion has been violated. Further poor system voltage results in frequent and unusual system collapse. Lack of transmission facilities is the main hurdle for generation capacity expansion. Difficulties in acquisition of land for tower footings, construction of new substations and acquiring Right of way for transmission lines are hindering system expansion. [3]

Existing Nepal's power system utility structure is pseudo competitive generation model. Monopoly of the same utility (NEA) is in transmission and distribution. Due to the absence of standard transmission planning criteria, it will unbalance the development of transmission infrastructure of country covering geographic of state. Figure 1.2-1 shows the pictorial representation of the INPS which shows the power plants, substations, transmission and distribution line up to 11 kV both existing and under construction. The list of major hydropower plants in Nepal are listed below

Table 1.2-1: List of major hydropower plants in Nepal

S. No	Power Plants	Capacity (kW)
1	Kali Gandaki *	144,000
2	Middle Marsyangdi *	70,000
3	Marsyangdi *	69,000
4	Kulekhani I *	60,000
5	Khimti*	60,000
6	Bhotekoshi *	45,000
7	Kulekhani II *	32,000
8	Tirsuli	24,000
9	Gandaki	15,000
10	Modi Khola	14,800
11	Devighat	14,100
12	Sunkoshi	10,050
13	Puwa Khola	6,200

Out of these power plants, only major and which are near to the cross border link (with *), will only be considered for the analysis. Upper Tamakoshi hydropower plant (456 MW), a national pride project, is still under construction and supposed to start generating power from mid-2016 is also considered in the simulation.

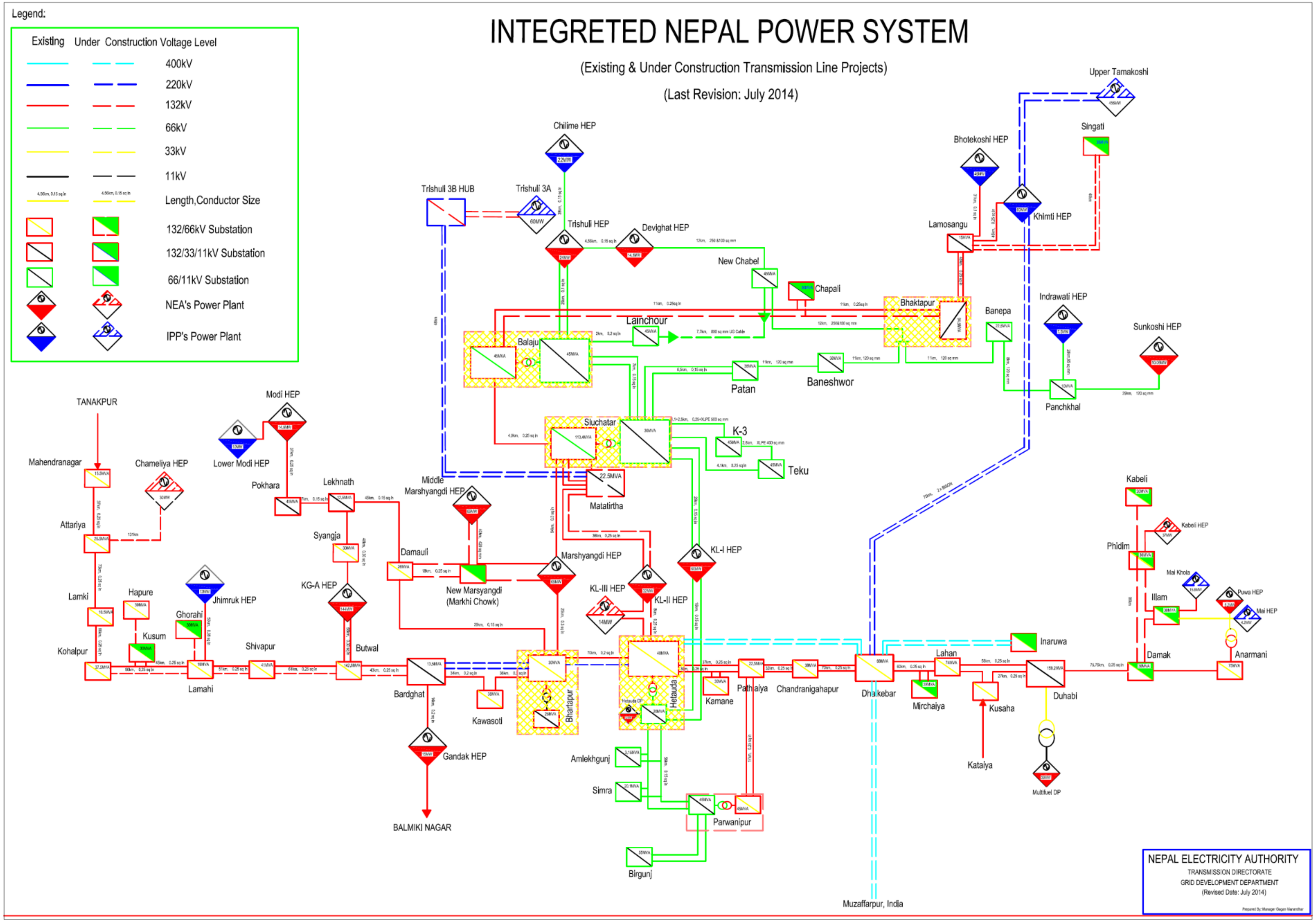

Figure 1.2-1: Existing and under construction transmission line projects of Nepal [3]

1.3. Indo Nepal Power Exchange

The cooperation history between Nepal and India dates back to the 1950s with the Kataiya Powerhouse in the Koshi Canal. Subsequently Trishuli, Devighat and Fewa Hydro projects were built in Nepal with the assistance of India in the 1970s and 80s [5]. The present main objective of building cross-border transmission line at present scenario would be to import electricity from India to reduce the load shedding hours that has crippled the country. Because of the large number of run-of-river plants in NEA's system, significant energy will be available during the monsoon season, which could be exported to India.

The concept of Indo-Nepal Power Exchange was first broached in 1950 AD. There are around 13 radial points along Nepal-India border for power exchange but the main Nepalese and Indian grid are not permanently connected. Out of these transmission lines, three are of 132 kV and rest are of 33 and 11 kV. The electricity brought using 33 and 11 kV lines can only be used in areas near Nepal-India border. To supply electricity from India to places like Kathmandu, NEA is using three 132 kV transmission lines. All the three 132 kV transmission lines, which are shown in Figure 1.2-1 operating in radial (asynchronous) mode. Nepal is importing power from Bihar and Utter Pradesh power grid of India. The three 132 kV cross-border transmission lines are [2] [6] [7] :

1.3.1. Gandak (Nepal) to Ramnagar and Muzaffarpur (India)

This is the first 132 kV cross-border link (constructed in 1979) and is basically export oriented since it was constructed primarily to transfer power generated by Gandak power house to India under Gandak treaty. Now it has been rearranged for the purpose of import also. The 132 kV line runs from the Bardghat substation to the Indian substation at Muzaffarpur via Gandak where there is 15 MW of generation, Ramnagar, Bettiah and Motihari. . The Indian part of this line lies in the state of Bihar. This interconnection is in the center of the country, relatively close to the load center at Kathmandu and most of Nepal's generation facilities. Hence, it can be used for both import and export.

1.3.2. Kusaha (Nepal)-Kataiya (India)

This link was a gift for the first Democratic Government of 1990. This 132 kV, which is located close to Duhabi in eastern Nepal, was implemented for enhancing the power exchange level up to 50 MW. The objective of this project is to reduce load shedding by increasing import power from India and for cross boarder power exchange enhancement. This transmission line is in the east of the country and hence it is of no significant for exporting power from Nepal. Approximately 13km of transmission line from Kusaha to Kataiya near Indo-Nepal Border falls under the Nepalese territory and 3km falls under Indian Territory. The existing ACSR conductor from Kusaha to Kataiya has been upgraded by the equivalent size high current carrying conductors called Aluminum Conductor Composite Reinforced (ACCR).After this the line is now able to import around 150 MW Power from India instead of 80MW. The resistance and reactance of the transmission line are 1.77 and 6.9 ohms/phase. It does not appear suitable for export from Nepal for the following reasons:

- The eastern region of Nepal is a deficit area requiring imports from India; no generation plants are proposed in NEA's recent generation expansion plan
- The market for Nepali power in India is located in the western, northern or southern regional grids; the eastern region of India has a surplus. The power exported from Nepal

to India's eastern region will have to be wheeled back to other regions resulting in significant transmission losses and wheeling charges.

1.3.3. Mahendranagar (Nepal) – Tanakpur (India):

This 16 km long 132 kV link was commissioned in December 1999. This interconnection is at the extreme west of the country and is serving a way for receiving 70 million free units of electricity from Tanakpur hydro power plant as per the Integrated Mahakali Treaty. This is being operated in radial mode up to Kohalpur and is basically an import link owing to the issue of synchronization. This transmission line is in the far west of the country and hence it is also of no significance for exporting power from Nepal for two reasons:

- There is little generation in western Nepal; generation form the 750 MW West Seti project located here will be evacuated to India via a dedicated transmission line
- Exporting significant amounts of power past India's Tanakpur plant may require a significant reinforcement on the Indian system.

Different 33 kV transmission lines are given below, some of which are not in use today: [8]

1. Siraha – Jaynagar (3 MW)
2. Birpur – Kataiya (10 MW)
3. Jaleswar - Sursand (6MW)
4. Birgunj – Raxaul (10 MW)
5. Bhairahwa – Nautanawa (5MW)
6. Koilabas – Lamhi (Not in Use)
7. Nepalgunj – Nanpara (8 MW)
8. Dhangadhi – Paliya
9. Mahendranagar – Lohiahed
10. Chandragadhi – Thakurgunj

In 2014, NEA imported 230 MW of electricity from India. It is planning to import 35 MW of additional electricity from India in the coming year to limit the load shedding hours as energy production here starts to fall with the advent of winter season. For this 132 kV transmission lines Kusahar-Kataiya and Gandak-Ramnagar are to be used to bring additional 25 MW to 33 MW of electricity from India.

Chapter 2. Background Theory

2.1. Transmission Lines

In the 19th century most of the distribution system used direct current to supply power over the copper lines. This method of distribution was very inefficient because of power loss in the conductor. Due to this the power plants had to be built within a mile of the load. In 1890s, many developments were made in the field of power distribution. Among them the most important development was high voltage power transmission lines using alternation current (AC). In 1896, George Westinghouse built 11,000 Volt AC line to connect a hydroelectric generating station at Niagara Falls to Buffalo, 20 miles away. AC offered much better efficiency, since it could easily be transformed to higher voltages with less loss of power. AC transmission allowed power lines to transmit power over much longer distance than the DC system. After 11 kV, as years passed, the transmission voltage level grew rapidly in the US as illustrated in following table. [9]

Table 2.1-1: Development of voltage level with years

Date	Voltage Level (V)
1896	11,000
1900	60,000
1912	150,000
1930	240,000

Voltages adopted for transmission of bulk power have to conform to standard specifications formulated in all countries and internationally. They are necessary in view of import, export and domestic manufacture and use.

In modern practice, line losses caused by I^2R heating of the conductors is gaining in importance because of the need to conserve energy. When line resistance is neglected, the power that can be transmitted over the transmission line depends upon (a) magnitude of voltages at the ends (E_s, E_r), (b) their phase difference δ and (c) the total positive sequence reactance X_d per phase when the shunt capacitive admittance is neglected [10]. Single line representation is shown in Figure 2.1-1.

Thus,

$$P = \frac{E_s E_r}{L x_d} sin\delta$$

Where,

P= Power in MW, 3-phase

E_s, E_r = Voltages at the sending end and receiving end respectively, in kV line-line

δ= phase difference between E_s and E_r

x_d= positive sequence reactance per phase, ohms/km

L= line length, km

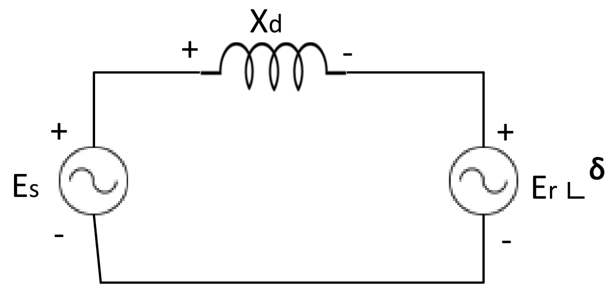

Figure 2.1-1: Single line representation of sending and receiving end

For the preliminary estimate of P, $E_s = E_r = E$. Accordingly, the power handling capacity of a single circuit is

$$P = \frac{E^2}{Lx} sin\delta$$

At unity power factor, at the load P, the current flowing is

$$I = \frac{E}{\sqrt{3}Lx} sin\delta$$

And the total power loss in 3-phase will amount to

$$p = 3\, I^2 rL = E^2 sin^2\delta \frac{r}{Lx^2}$$

Where, r is resistance per unit length of the transmission line.

Hence the percentage power loss is,

$$\%\, p = \frac{p}{P}.100 = \frac{r}{x} \sin\delta\,.\,100$$

From above property, if the conductor size is based on current rating as line length increases, smaller size of conductor will be necessary. However, the percentage power loss in transmission remains independent of line length since it depends on the ratio of conductor resistance to the positive sequence reactance per unit length and the phase difference δ between E_s and E_r. The power loss decreases as the system voltage is increased.

From the above discussion it becomes apparent that the choice of a transmission voltage depends upon (a) the total power transmitted (b) the distance of transmission (c) the % power loss allowed and (d) the number of circuits permissible from the point of view of land acquisition for the line corridor.

The stability limit of a transmission line is the maximum amount of power that can be transmitted for which the system will remain synchronized if a disturbance occurs. Maximum power transfer occurs at δ=90° and is

$$P_{max} = \frac{E_s E_r}{Lx}$$

The reactance between the sending and receiving end is proportional to the length of the line. Thus power per circuit of an operating voltage is limited by steady-state stability, which is inversely proportional to the length of line. The load angle is kept small around 30°, for the reason of stability. In an uncompensated line the phase angle varies with the distance when the line operating at natural load and puts a limit on the distance. For 30° phase angle the distance is 258 miles at 60 Hz. The line distance can be increased using series capacitor, whose reactance compensates a part of series capacitor. [11]

2.2. **Synchronous Generator**

Synchronous generator is the major electric power generating source in power systems. The rotor of the synchronous machine moves at a speed which bears a constant relationship to the frequency of the armature winding current. The stator of the synchronous generator is a stationary hollow cylinder as shown in Figure 2.2-1, which consists of hollow cylinder containing longitudinal slots in which armature windings are kept. The armature winding carries the load current. Figure 2.2-1 also shows the rotor, which is mounted on the shaft and rotates inside the hollow cylinder. The field winding is kept on the rotor and is supplied with DC current in order to generate rotor mmf. The armature and rotor mmf combines to generate voltage in the armature windings and electromagnetic torque between the stator and rotor.

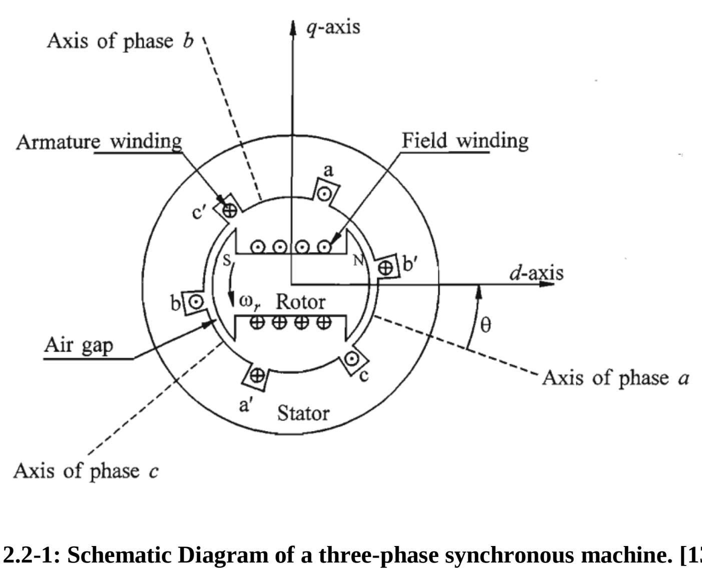

Figure 2.2-1: Schematic Diagram of a three-phase synchronous machine. [13]

Based on the type of rotor used, synchronous generators are categorized into two types. Cylindrical rotor construction has practically uniform air-gap length while salient pole type has much larger air gap length in the quadrature axis than in the direct axis. The hydraulic turbines operate at low speed compared to steam plants. Due to this low speed, it requires larger number of poles to generate the rated frequency. Salient pole type generators can have larger number of poles and are suited for low speed operation. Hydro electric generators falls in low speed types and hence almost all of hydro electric generators are of salient pole type.

There are different reactances and time constants which are important in machine design, machine testing and in system stability model studies. The axis of the field poles is called the direct axis or simply d-axis, while the centerline of interpolar space is called the quadrature axis or simply q-axis. [12]

2.2.1. Direct axis reactance (X_d):

The ratio of the sustained value of the fundamental AC component of armature voltage, which is produced by the total direct-axis primary flux due to direct-axis armature current and the value of the fundamental AC component of this current, the machine running at rated speed

2.2.2. Quadrature axis reactance (X_q):

The ratio of the sustained value of that fundamental AC component of armature voltage, which is produced by the total quadrature axis primary flux due to quadrature-axis armature current, and the value of the fundamental AC component of this current, the machine running at rated speed.

2.2.3. Direct-axis transient reactance (X_d'):

The ratio of the initial value of a sudden change in the fundamental AC component of armature voltage, which is produced by the total direct-axis primary flux, and the value of the simultaneous change in fundamental AC component of direct-axis armature current, the machine running at rated speed and the high decrement components during the first cycles being excluded.

2.2.4. Direct axis sub-transient reactance (X_d''):

The ratio of the initial value of a sudden change in the fundamental AC component of armature voltage, which is produced by the total direct-axis armature flux, and the value of the simultaneous change in fundamental AC component of direct-axis armature current, the machine running at rated speed.

2.2.5. Negative sequence reactance (X_2):

The ratio of the reactive fundamental component of negative sequence armature voltage, due to the presence of fundamental negative sequence armature current at rated frequency, by the value of that component of current, the machine running at rated speed.

2.2.6. Zero sequence reactance (X_o):

The ratio of the reactive fundamental component of zero sequence armature voltage, due to the presence of fundamental zero sequence armature current at rated frequency, by the value of that component of current, the machine running at rated speed.

2.2.7. Direct-axis transient short-circuit time constant (τ_d):

It is the time, in seconds, required for the transient alternating component of the short-circuit current to decrease to 0.368 times its initial value.

2.2.8. Direct-axis sub-transient short-circuit time constant (τ_d'):

It is the time, in seconds, required for the sub-transient alternating component of the short-circuit current to decrease to 0.368 times its initial value.

2.2.9. Direct-axis transient open circuit time constant (τ_d''):

It is the time, in seconds, required for the transient alternating component of the open-circuit current to decrease to 0.368 times its initial value.

2.3. **Governor**

The basic function of a governing system is to control the turbine-governor speed and hence the frequency and active power. The governor controls the position of the governor-controlled gates and finally controls the amount of water flow into the turbine. The frequency/active power control mechanism senses the actual speed and power of generator units, compares with the reference speed and sends the error as a feedback to control the flow of water to the turbine.

Mechanical-hydraulic governor are traditional one in which speed sensing, permanent droop feedback and computing functions are achieved through hydraulic components. In order to provide transient droop compensation, a dashpot is used. In electro-hydraulic governor speed sensing, permanent droop, temporary droop, measuring computing functions are performed electrically. The electric/electronic apparatus provides greater flexibility and improved performance in both dead band and dead time. [13] [14]

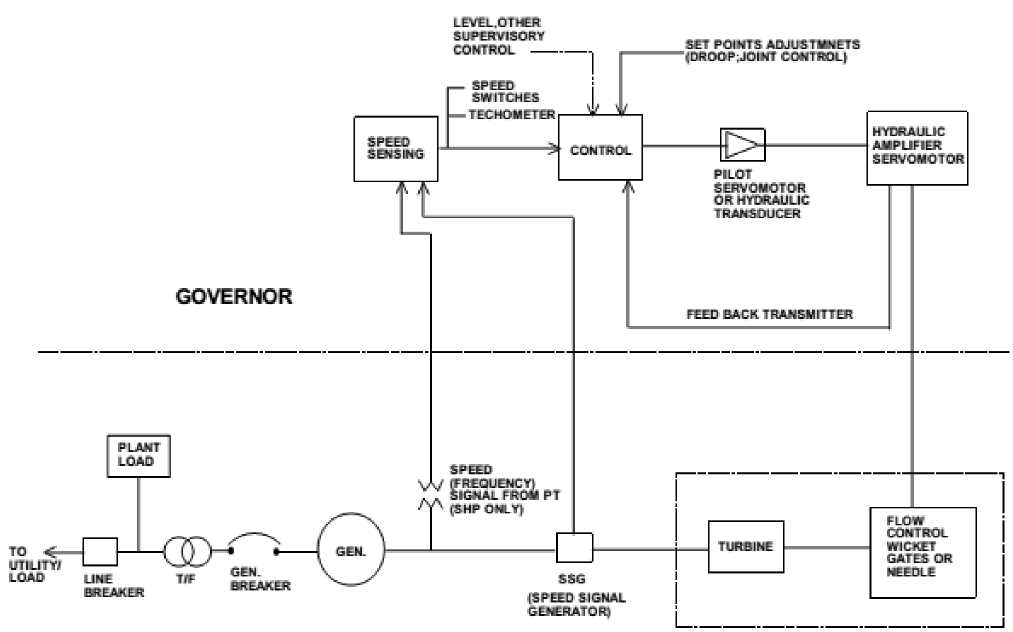

Figure 2.3-1: A typical diagram of a Governor system

Figure 2.3-1 shows a block diagram of a governor system which includes:

a. Speed sensing elements.
b. Governor control actuators.
c. Hydraulic pressure supply systems.
d. Turbine control servomotors.

The electro hydraulic governing system uses proportional-integral-derivative action, PID controller as shown in Figure 2.3-2. The proportional terms produces an immediate response to an error level input. The proportional term response has a significant influence on the stability of the governed system. The derivative action is beneficial for isolated operation and helps to extend the stability limits of the governed system by allowing higher proportional and integral gains while maintaining a stable control system.

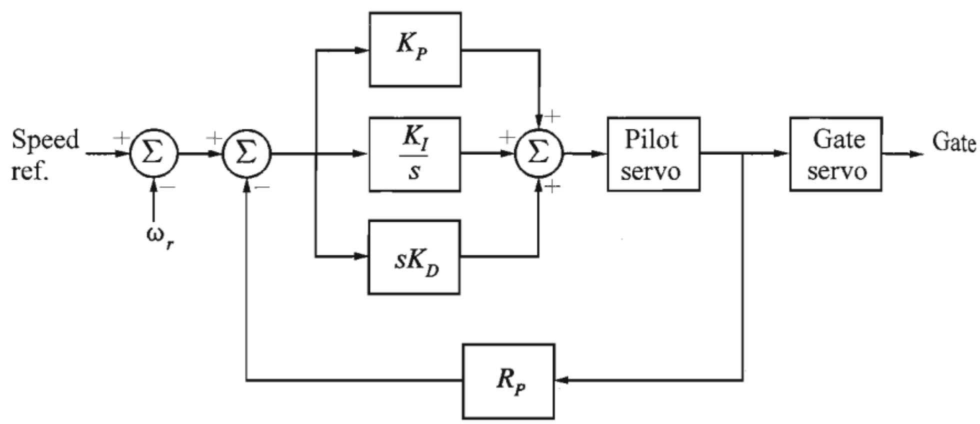

Figure 2.3-2: PID Governor Controller. [13]

The transfer function of the PID governor expressed in terms of proportional, integral and derivative gains is [15]

$$\frac{y}{\omega_{ref} - \omega_s} = \frac{1}{R_p}\left[\frac{K_d S^2 + K_p s + K_i}{K_d S^2 + (K_p + 1/R_p)s + K_i}\right]$$

Where,

y= gate position

ω_{ref} = reference angular speed

ω_S= feedback angular speed

R_P = Permanent Droop

The use of a high derivative gain results in excessive oscillation and possibly instability when the generating unit is connected to an interconnected system. When derivative gain is set to zero, the transfer function of PID-controller is equivalent to that of mechanical hydraulic governor. [13] The transfer function of PI governor yields [15]

$$\frac{y}{\omega_{ref} - \omega_s} = \frac{1}{R_p} * \frac{K_p S + K_i}{(K_p + 1/R_p)S + K_i}$$

Adding a small time constant on above equation,

$$\frac{y}{\omega_{ref} - \omega_s} = \frac{1}{R_p} * \frac{1 + (K_P/K_i)S}{\left(1 + (K_p R_P + 1)/(K_i K_P)\right)S * (1 + 0.1S)^2}$$

2.4. **Excitation System**

Excitation system supplies DC field current to the synchronous machine field winding. Furthermore, the excitation system controls the field voltage and field current which there by performs control and protective functions essential to the satisfactory performance of the power system. The power rating of the exciter is in the range of 0.2 to 0.8 % of the generator's megawatt rating.

The excitation system should contribute to effective control of voltage and enhancement of system stability. It should be capable of responding rapidly to a disturbance so as to enhance transient stability and of modulating generator field so as to enhance small-signal stability. The excitation system uses auxiliary stabilizing signals, in addition to terminal voltage error signal to control field voltage to damp system oscillations. This part of excitation system is referred to as power system stabilizer.

The general functional block diagram shown in Figure 1 indicates various synchronous machine excitation subsystems. These subsystems may include a terminal voltage transducer and load compensator, excitation control elements, an exciter, and in many instances, a power system stabilizer (PSS). Supplementary discontinuous excitation control may also be employed.

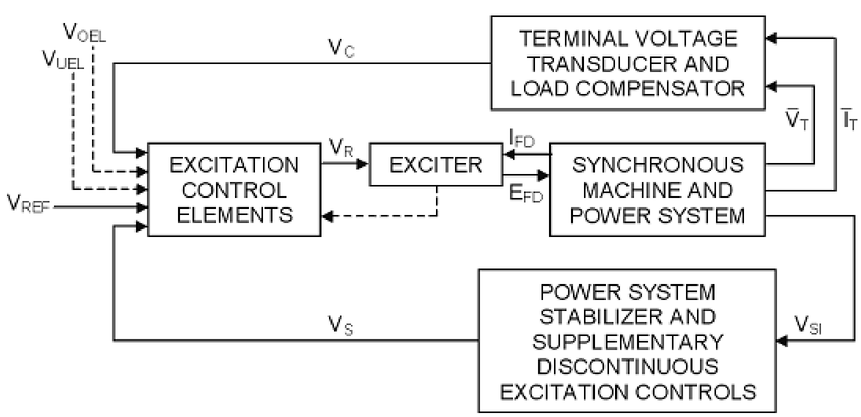

Figure 2.4-1: General functional block diagram for synchronous machine excitation control system. [26]

2.4.1. Excitation System Type

On the basis of construction, the excitation system can be divided in to two categories: static and rotating excitation system. Modern static excitation have completely replaced older shaft mounted rotating exciters with DC filed current controlled by motor operated field rheostat. Brushless excitation system and static excitation systems are being used in modern systems.

2.4.2. Brushless Exciter:

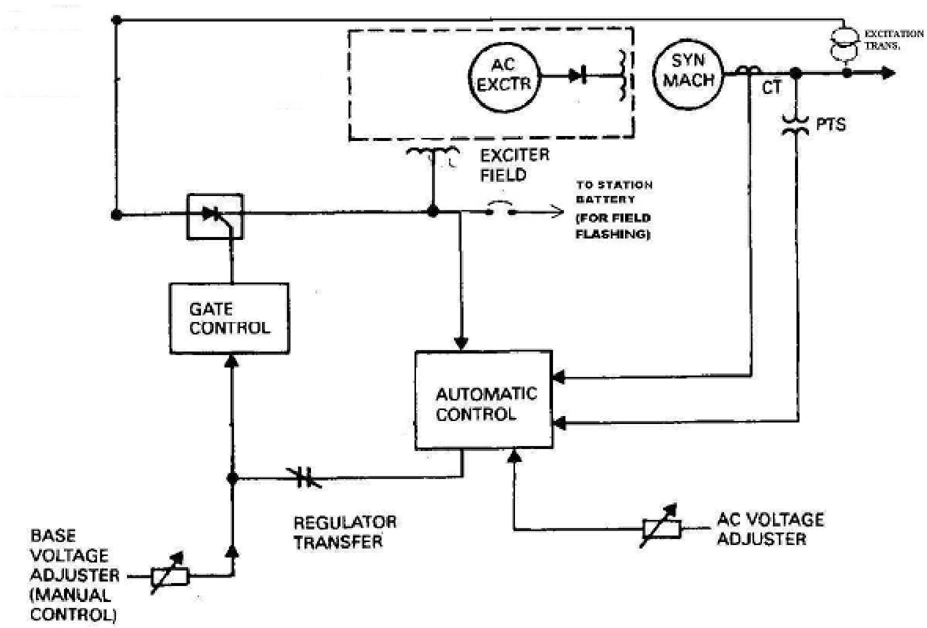

Figure 2.4-2: Typical diagram of a brushless exciter [26]

Figure 2.4-2 shows an alternator-rectifier exciter employing rotating rectifiers with a direct connection to the synchronous machine field thus eliminating the need for field brushes. Brushless system may be used for small hydro generators up to about 10 MVA where large DC current capacity is not required. A provision for field flashing the field of the rotating exciter for startup purposes is required.

2.4.3. Static excitation system

The static excitation system is the most commonly used excitation system for hydro generators. In this type of excitation system, all the components are static or stationary. Depending upon the speed of generator field suppression required, static excitation system can be categorized into two types. Many systems consist of full inverting bridge type which uses six thyristors connected in a three-phase full wave bridge arrangement. This system allows negative field voltage forcing to force faster field suppression, thereby quickly reducing the generator terminal overvoltage during a full load rejection. The semi-inverting type uses three thyristors and three diodes connected in a three-phase full wave bridge. This system drives the positive DC voltage to zero during a full load rejection, but does not allow negative field forcing. Among different types of static excitation system, ST1A excitation system is described below. [16]

Model of Type ST1A potential-source controlled rectifier excitation system represents a system in which excitation power is supplied through a transformer from the generator terminals and is regulated by a controlled rectifier. The excitation power is supplied through a transformer from the generator terminals and is regulated by a controlled rectifier. The maximum exciter voltage available for such system is directly related to generator terminal voltage.

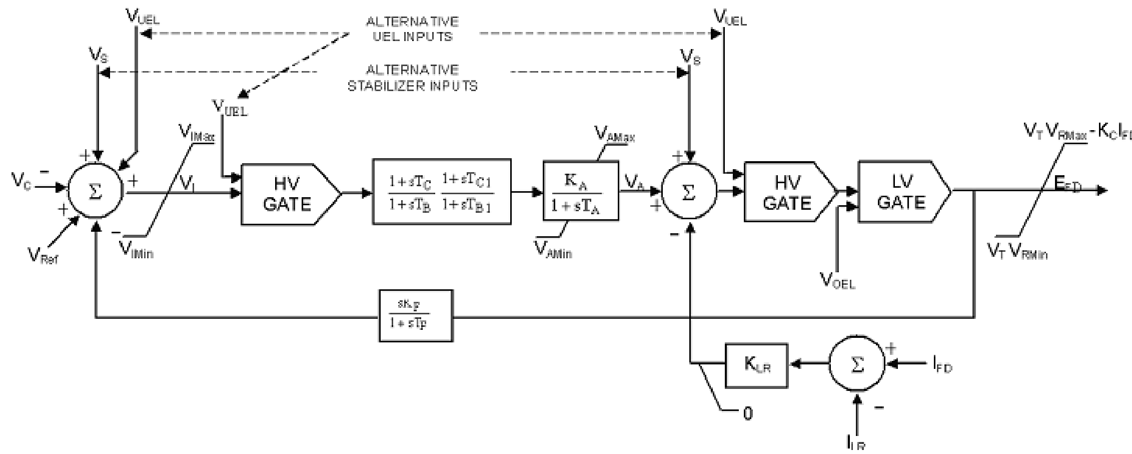

Figure 2.4-3: Type ST1A—Potential-source, controlled-rectifier exciter [16]

Figure 2.4-3 shows the block diagram of a typical ST1A excitation system. The inherent exciter time constants of such type of exciter system are very small and hence exciter stabilization may not be required. On the other hand, it may be desirable to reduce the transient gain of these systems for other reasons. The model shown is sufficiently versatile to represent transient gain reduction implemented either in the forward path via time constants, T_B and T_C (in which case K_F would normally be set to zero), or in the feedback path by suitable choice of rate feedback parameters, K_F and T_F. Voltage regulator gain and any inherent excitation system time constant are represented by K_A and T_A, respectively.

While for the majority of these excitation systems, a fully controlled bridge is employed, the model is also applicable to systems in which only half of the bridge is controlled, in which case the negative field voltage limit is set to zero ($V_{RMIN} = 0$).

2.5. **High Voltage Direct Current (HVDC) Transmission**

High voltage direct transmission is a highly efficient alternative for long-distance bulk-power delivery and for special purpose applications. It is a high power electronics technology used in electric power systems. The first commercial application of HVDC transmission was between the Swedish mainland and island of Gotland in 1954. HVDC is considered advantageous to AC in applications such as long underground/submarine cables, long distance overhead bulk power transmission, stable AC interconnection, low short circuit levels and asynchronous interconnection. [13]

There are two types of HVDC transmission system based upon types of converters used. The HVDC transmission based on line commutated current source converters (CSCs) called classical HVDC system and HVDC transmission based on self-commutated voltage source converters (VSCs) called VSC HVDC system.

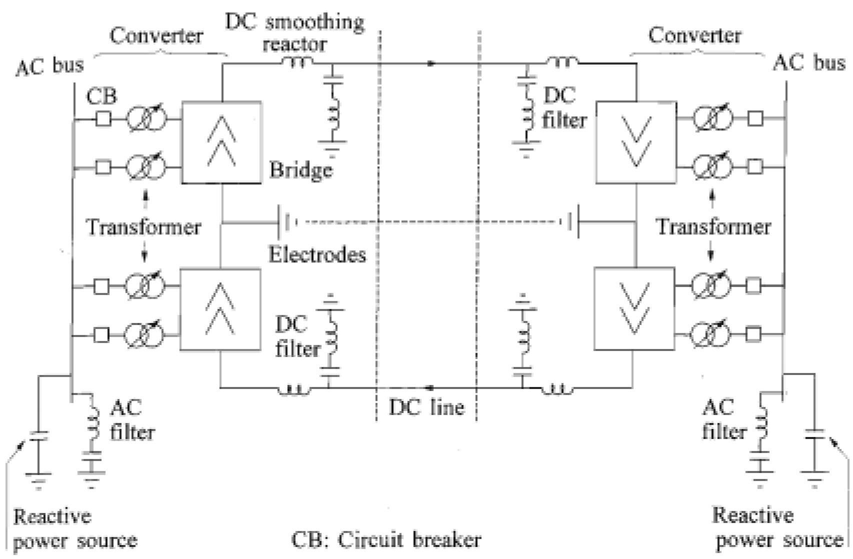

Figure 2.5-1: Schematic diagram of Bipolar HVDC system. [13]

2.5.1. Classical HVDC Systems

Figure 2.5-1 above shows a typical classical HVDC transmission system with line-commutated CSCs. the main components associated with HVDC system are given below.

a. Converters

Each converter consists of a positive, negative pole and transformers with tap changers which performs AC/DC and DC/AC conversion. Each pole consists of two six pulse bridge connected through converter transformers with winding structures Y-Y and Δ-Y, forming a 12-pulse converter bridge. The six-pulsed bridge is equipped with thyristors valves comprising of number of thyristors connected in series to achieve desired voltage rating.

b. Smoothing Reactors

These are large reactors connected in series with each pole of converter station. Their purpose is to reduce the current and voltage harmonic in the DC line. In addition, they prevent commutation failure in inverters, prevent current from being discontinuous at light load and limit crest current in the rectifier during short circuit.

c. Harmonics AC filters

The AC and DC filters prevents current harmonic generated by converters from entering into the connected AC sides and DC sides respectively. Current harmonics may cause overheating of capacitors and nearby generators and interference with telecommunication systems.

d. Reactive power supplies

Line commutated CSCs can only operate with the AC current lagging the voltage. Due to this the converters demands reactive power during the conversion process. During steady state conditions, the reactive power consumed is about 50% of active power transferred. Whereas under transient conditions, the consumption of reactive power is much higher. The reactive power is provided partly by synchronous condensers of static VAR compensators and partly by filter banks.

e. Electrodes

In many AC links the earth is used as a neutral conductor. The connection to the earth requires a large-surface-area conductor to minimize current densities and surface voltage gradients. This conductor is referred to as an electrode.

f. DC lines

They may be overhead lines or cables that connect the converters in the sending and receiving ends.

g. AC circuit breakers

AC circuit breakers are there to clear faults in the transformer and for taking DC link out of service. Converter control clears the faults on the DC side and hence AC circuit breakers are not used for this purpose.

2.5.2. VSC type HVDC system

The HVDC system using VSCs are composed of six-pulse bridge, which uses new generation devices like GTOs and IGBTs. The VSC being self-commutated can perform conversion at very high frequencies, using a method called pulse-width modulation. Because of this, VSC can control both active and reactive power independent of one another together with the control of harmonic generation as well. Figure below shows a basic configuration of VSC type HVDC system.

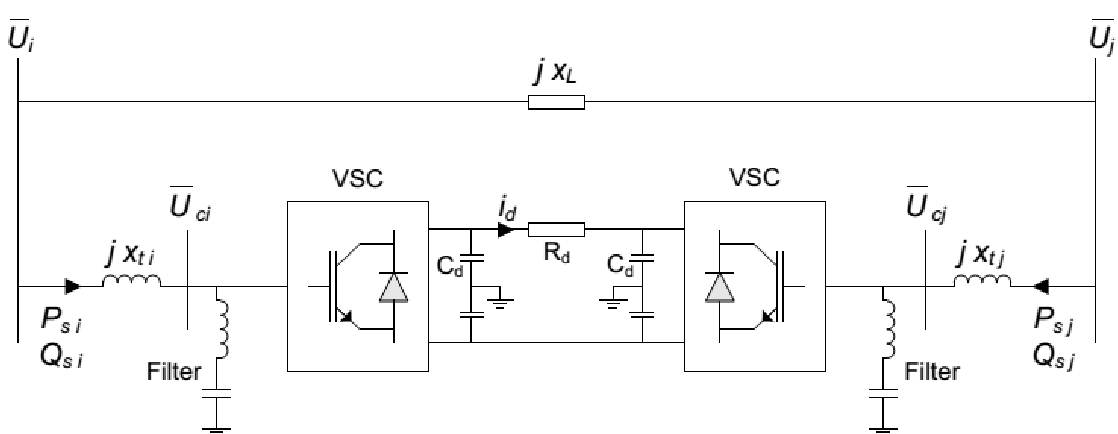

Figure 2.5-2: Basic structure of a VSC-HVDC transmission [27]

a. Phase Reactors:

The phase reactors provides both active and reactive power control. The phase reactor together with the transformer impedance limit the short-circuit current through the valves.

b. High-Frequency Filters:

The switching of switches generates high-frequency noises. These high-frequency filters prevents these harmonics from entering the AC system.

c. DC Capacitors

The DC capacitors gets charged and discharged during switching of the valves, hence acting as energy storage. It also provides a low inductive path for the turn-off current. The main objective of the DC capacitors is to provide a stiff voltage source. The disturbances in the system causes voltage variation in the DC side. The size of the DC capacitor determines its ability to limit the voltage variation.

Because of the possibility of very high frequency switching of valves, pulse width modulation with switching frequency of 1-2 kHz is used to recreate the AC voltage. Control of active power can be done by changing the phase angle of converter AC voltage with respect to the filter bus voltage. Control of active power can be done by changing the phase angle of converter AC voltage with respect to the filter bus voltage. Similarly, the control of reactive power can be done by changing the magnitude of the fundamental component of the converter AC voltage with respect to the filter bus voltage. The change in the phase angle and voltage amplitude can be done almost instantaneously with the change in the PWM pattern. Due to these reasons the separate instantaneous control of active and reactive power is possible. This separate control allows the use of separate active and reactive power control loops. The active power control loop can be set to control either the active power of the DC-side voltage. In a DC line, one station will then be selected to control the active power while the other must be set to control the DC-side voltage. The reactive power control loop can be set to control either the reactive power or the AC-side voltage. [17]

VSC-HVDC improves the reliability and transfer capability of the power systems. It also helps in reducing system instability by preventing voltage collapse caused by progressive voltage depression. The instant power reversal capability can improve the reliability of power system and instant power reversal can greatly reduce the inter-area low frequency oscillation. [18] When operating HVDC in parallel with AC line, the AC system can be better utilized by modulating the power factor of the HVDC transmission line. The system can be made to transfer more active power over the combination of both. [19]

2.5.3. Advantages of HVDC over HVAC

AC interconnection has been preferred globally for electric power transmission for past 100 years. AC usually provides the greatest interconnection benefits, except in certain cases for which DC is the preferred option. However, synchronous interconnection of different systems is technically more demanding. The major issues of transmission include thermal limits, stability limits and voltage regulation, which are the main constraints on transmission line operation.

HVDC transmission has both technical and economic advantages in comparison to HVAC transmission.

2.5.4. Technical Advantages:

The production and consumption of reactive power by the line constitutes a serious problem in long overhead lines. In DC transmission no reactive power is transmitted over the line. The converters at the ends only draw reactive power which varies with transmitted power but is independent of line length. For lines greater than 100 km length, a DC line requires less reactive power than an AC line. For underground ac cables, the reactive power generated by cables always exceeds the reactive power absorbed by series inductance. In a cable of about 50 km, the charging current itself equals the load current. Hence, the practical length of ac cables is only 40 km or so. [20]

a. To maintain the stability of an ac system under transient condition, the length of a 50 Hz uncompensated ac line must be less than about 500 km. If series compensation is used, the length can be somewhat longer than this value. The dc transmission line has no such limitations and no stability problem. Two separate ac systems interconnected by a dc link do not operate in synchronism and may even operate at different frequencies. For instance, in Japan where the half country is a 60 Hz and the other a 50 HZ, HVDC can be used to interconnect the two sides. [21]
b. The interconnection of two ac systems by an AC line increases the short circuit current in the system. Whereas, the contribution of a dc line to the short circuit is only up to the rated current of the dc line.
c. The ac system interconnected by a dc line can be controlled independently. They can be completely independent as regards frequency, system control, short circuit rating, future extension etc.
d. A fast change in the direction of energy flow is possible which allows a more flexible coordination of system control at the two ends, a more economical use of cheap power generation in either of the two ac systems and regulation of system reserve and standby capacity. [20]
e. For the same conductor diameter and voltage, the corona loss and radio interference are lower for dc line as compared to ac line. Another environmental advantages is that the DC transmission line have lower environmental impact than AC line. [21]

2.5.5. Economic advantage

a. The dc line terminal equipment is considerably more expensive than ac line terminal equipment because of the high cost of converters. The main equipment of DC station is converter, which costs 50% of HVDC transmission system. But dc lines and cables are cheaper than ac lines and cable. Also, DC lines needs smaller right of way (ROW) as comparison to AC lines. The towers of AC lines are simpler, cheaper and narrower as comparison to AC lines. Therefore, after a certain breakeven distance, the total cost of dc transmission is lesser than the total cost of ac transmission. Figure below shows comparative costs of AC and DC transmission system for Nelson River Bipole 1 which lies in Manitoba, Canada. [10]

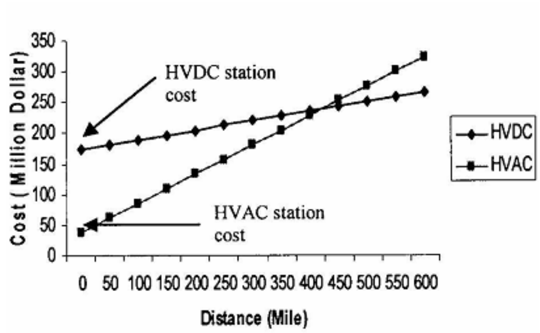

Figure 2.5-3: HVDC and HVAC transmission cost. [10]

Chapter 3. Modelling

3.1. Indian grid

The Indian side of the power system grid was represented by a three phase source. The three phase source consists of a RL branch in series with an ideal voltage generator. The short circuit ratio (SCR) is defined as the ratio of system short circuit level to the DC power. The short circuit ratio is used as an indicator to characterize the strength of a power system. The impedances of generators, transformers, transmission lines and loads constitutes the impedance of the system. The high system impedance is an indication of weak system. An electric power system with SCR less than 3 is considered weak system [22]. The weaker systems are more vulnerable to voltage variations. SCR is also an indicative measure of the amount of power that can be accepted by the power system without affecting the power quantity at the point of connection. For a weak grid, 20% change in reactive power changes the grid voltage by 20%, whereas on strong grids, 20% change in reactive power only changes grid voltage by 7%. [23]

The SCR varies with location in a power system. Even in a large interconnected power system, there may be loads connected only with one or two lines to the rest of the network. The SCR on their point of connection is low [23]. The common concept of "infinite bus" (equivalent to infinite strong) is a special case of SCR = ∞. This bus is able to maintain constant voltage for all fault location outside itself. With the same rational, busses with finite strength may be classified in the range of, $0<SCR<<\infty$.

The Indian grid has been represented by an ideal voltage source with the grid impedance in series. The SCR of the Indian grid side has been taken as 3 and X/R ratio as 3 considering a weak grid. The installed capacity of Bihar state of India is 2,283 MW. Due to this the base capacity has been considered as 3000 MVA. Even though the cross border transmission line is designed for 400 kV, it is planned to be charged with 220 kV in the beginning and hence the base voltage has been considered as 220 kV. With this parameters the base impedance obtained is 53.33 ohms and the grid resistance and reactance are 5.62 ohms and 16.86 ohms. This gives the grid impedance as 17.77 ohms.

3.2. Transmission lines

The voltage level above 66 kV is considered transmission voltage level in Nepal [8] Currently 66 kV and 132 kV are the only transmission voltage being used in Nepal. Higher voltage levels of 220 KV and 400 kV are under construction, which are going to be charged in coming years. In the thesis, only the 132kV, 220 kV and 400 kV transmission lines are modelled. The Upper Tamakoshi- Khimti and Khimti-Dhalkebar, 400 kV, transmission yet to be completed has been considered in the modelling. The 456 MW Upper Tamakoshi Hydro Power Plant which is scheduled to be completed on 2016 has been considered. All the conductors used are Aluminum Conductor Steel Reinforced (ACSR), which are concentrically stranded conductor with one or more layers of hard drawn aluminum wire on galvanized steel wire core. All the transmission lines are the transposed.

3.2.1. Single circuit 132 kV transmission line

At present, 132 kV is the largest transmission line voltage being used in Nepal. Different types of 132 kV transmission line conductors are being used. 132 kV transmission lines are of either single or double circuit types.

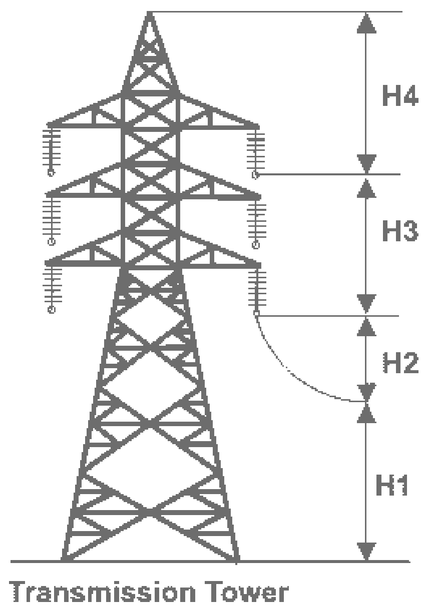

Figure 3.2-1: Double Circuit Vertical Line configuration

All of the 132 kV transmission lines have the configuration as shown above in Figure 3.2-1. The single circuit is kept in vertical configuration in one side. When upgrading of transmission line is required, another circuit is stringed on the other side of the tower making it a double circuit 132 kV transmission line. A typical sketch of a double circuit transmission line conductors are shown below. One circuit phase conductors are a-b-c and the other a’-b’-c’ are the other phase conductors.

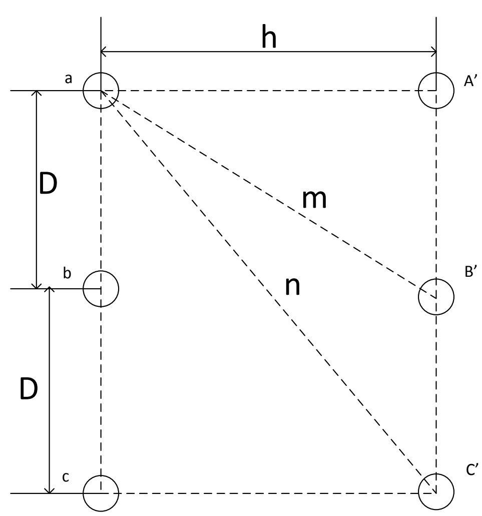

Figure 3.2-2: Distance between phase conductors

For different voltage levels, the conductor spacing and ground clearance are given below.

Table 3.2-1: Clearance between conductors for different voltage levels.

S. No	Voltage Level	Vertical Spacing, D (m)	Horizontal Clearance, h	Ground Clearance	m	n
1	132	3.00	9.00	6.10	9.49	10.82
2	220	4.50	10.00	7.00	10.97	13.45
3	400	5.40	12.60	8.84	13.71	16.60

The inductance and capacitance have been calculated for both single and double circuit transmission lines.

3.2.2. Sample calculation

a. Inductance Calculation

Conductor: Bear

Equivalent cross-sectional area of the conductor = $0.25\ sq\ inch = 1.6129 * 10^{-4}\ m^2$ [8]

Actual radius of the conductor, $r = 7.16 * 10^{-3}\ m$

Radius of a fictious conductor which has no internal flux, $r' = 0.7788 * r = 5.58 * 10^{-3}\ m$

Equivalent Spacing, $D_{eq} = \sqrt[3]{3 * 3 * 6}\text{m} = 3.78\text{ m}$

Therefore, inductance per phase of the transposed conductors

$L_a = 2 * 10^{-7} \ln\left(D_{eq}/r'\right) H/m$ [24]

$$= 1.304\ mH/km$$

b. Capacitance Calculation

Equivalent Spacing, $D_{eq} = \sqrt[3]{3 * 3 * 6}\text{m} = 3.78\text{ m}$

Radius of conductor = $r = 7.16 * 10^{-3}\ m$

Positive/negative sequence capacitance, $C_1 = C_2 = 2\pi\varepsilon_0/\ln\left(D_{eq}/r\right) = 8.87\ pF/m = 8.87\ nF/km$

$$D_{3c} = (D_{aa} * D_{bb} * D_{cc} * D_{ab'}^2 * D_{bc'}^2 * D_{ca'}^2)^{1/9} = 17.594\ m$$

$$d_{3c} = \left(r'^3 * D_{ab} * D_{bc} * D_{ac}\right)^{1/9} = 0.2763\ m$$

Zero sequence capacitance, $C_0 = 2\pi\varepsilon_0/3\ ln(D_{3C}/d_{3C}) = 4.45\ pF/m = 4.45\ nF/km$

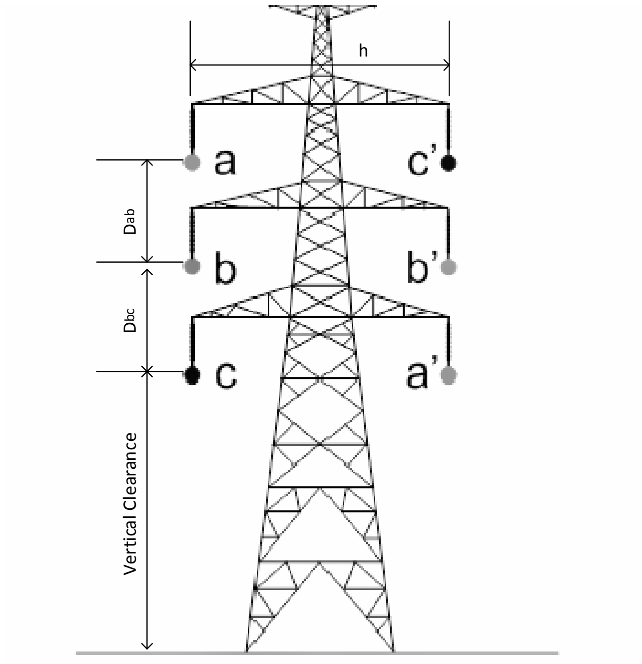

Figure 3.2-3: Spacing of conductors

3.2.3. Double Circuit 132 kV transmission line

a. Inductance Calculation

Most of the 132 kV transmission lines are double circuit types. Double circuit helps us to achieve greater reliability and a higher transmission capacity. As the separation between the two transmission lines are not considerably large, the inductance of the double circuit lines is not half to that of the single transmission line. The configuration of the conductors are done in such a way through which minimum inductance is achieved. The conductors of two phases (conductors a, a' and c, c' as in Figure 3.2-3 are placed diametrically opposite and the third phase (conductors b,b' as in Figure 3.2-3) are placed horizontally opposite to each other.

For the calculation of capacitance, radius of conductor (r) is used instead of r'.

GMR of conductors of phase a, $D_{sa} = \sqrt{r' * n} = \sqrt{5.58 * 10^{-3} * 10.82} = 0.2457\ m$

GMR of conductors of phase b, $D_{sb} = \sqrt{r' * h} = \sqrt{5.58 * 10^{-3} * 9} = 0.2241\ m$

GMR of conductors of phase a, $D_{sc} = \sqrt{r' * n} = \sqrt{5.58 * 10^{-3} * 10.82} = 0.2457\ m$

Equivalent GMR, $D_{sL} = \sqrt[3]{D_{sa}D_{sb}D_{sc}} = 0.2383\ m$

Geometric Mean Distance between phases a and b = $D_{ab} = \sqrt{D * m} = \sqrt{3 * 9.49} = 5.336\ m$

Geometric Mean Distance between phases b and c = $D_{bc} = \sqrt{D * m} = \sqrt{3 * 9.49} = 5.336\ m$

Geometric Mean Distance between phases c and a = $D_{ca} = \sqrt{2D * h} = \sqrt{2 * 3 * 9} = 7.348\ m$

Therefore, the Equivalent GMD, $D_{eq} = \sqrt[3]{D_{ab} * D_{bc} * D_{ca}} = 5.94\, m$

Inductance per phase per meter, $L = 2 * 10^{-7} * ln(Equivalent\ GMD/Equivalent\ GMR)$

$$= 2 * 10^{-7} * ln\left[2^{1/6}(D/r')^{1/2}\ (m/n)^{1/3}\right] H/m$$

$$= 6.43 * 10^{-7}\ H/m$$

$$= 0.643\ mH/km$$

b. Capacitance Calculation

For the calculation of capacitance, radius of conductor (r) is used instead of r'.

GMR of conductors of phase a, $D_{sa} = \sqrt{r * n} = \sqrt{7.16 * 10^{-3} * 10.82} = 0.2783\, m$

GMR of conductors of phase b, $D_{sb} = \sqrt{r * h} = \sqrt{7.16 * 10^{-3} * 9} = 0.2538\, m$

GMR of conductors of phase a, $D_{sc} = \sqrt{r * n} = \sqrt{7.16 * 10^{-3} * 10.82} = 0.2783\, m$

Equivalent GMR, $D_{sc} = \sqrt[3]{D_{sa} D_{sb} D_{sc}} = 0.2699\, m$

Capacitance per phase per meter, $C = 2\pi\varepsilon_0/ln(Equivalent\ GMD/Equivalent\ GMR)$

$$= 2\pi\varepsilon_0/ln(5.94/0.2699)$$

$$= 17.99\ pF/m$$

Similarly for other conductors and voltage levels the inductances and capacitances has been calculated as follows.

Inductance and Capacitance of Single Circuit Transmission line

Table 3.2-2: Inductance and Capacitance Calculation of Single Circuit Transmission line

Conductor	Voltage Level	Area (sq. inch)	Area ($*10^{-4}$ sq. m)	r (m)	r' (m)	D_{eq}(m)	L_a (mH/km)	X_a (Ω/km)	C_a (nF/km)
Panther	132	0.3	1.9355	0.00785	0.00611	3.78	1.285	0.4038	9.0021
Bear	132	0.25	1.6129	0.00717	0.00558	3.78	1.303	0.4095	8.8712
Duck	132	0.2	1.2903	0.00641	0.00499	3.78	1.325	0.4166	8.7160
Wolf	132	0.15	0.9677	0.00555	0.00432	3.78	1.354	0.4256	8.5239

Inductance and Capacitance of Double Circuit Transmission line

Table 3.2-3: Inductance and Capacitance Calculation of Double Circuit Transmission line

Conductor	Voltage Level	Area (sq. inch)	Area ($*10^{-4}$ sq. m)	r (m)	r' (m)	H (m)	m (m)	n (m)	D (m)	La (mH/km)	GMD	GMR_C	C_n(nF/km)
Panther	132	0.3	1.9355	0.00785	0.0061	9	9.49	10.82	3	0.6340	5.94	0.2826	18.26
Bear	132	0.25	1.6129	0.00717	0.0056	9	9.49	10.82	3	0.6431	5.94	0.2700	17.99
Duck	132	0.2	1.2903	0.00641	0.0050	9	9.49	10.82	3	0.6542	5.94	0.2553	17.67
Wolf	132	0.15	0.9677	0.00555	0.0043	9	9.49	10.82	3	0.6686	5.94	0.2376	17.28
Bison	220	0.35	2.2581	0.00848	0.0066	10	10.97	13.45	4.5	0.6619	7.76	0.2937	16.98
Moose	400	0.4	5.0000	0.01262	0.0098	12.6	13.71	16.60	5.4	0.6412	9.52	0.3583	16.95

Table 3.2-4: 132 kV Transmission lines parameters values.

S. N.	From	To	Condutor Type	Voltage Level (kV)	Single/Double	Length(km)	Parameters	
							R(Ω)	X(Ω)
1	Anarmani	Duhabi	Bear	132	Single	75.76	8.23	30.10
2	Kusha	katiya	Bear	132	Single	15	1.63	5.96
3	Duhabi	Hetuda	Bear	132	Double	598	16.24	58.90
4	Hetuda	KL2 P/S	Bear	132	Single	8	0.87	3.18
5	Bharatpur	Marsyangdi P/S	Bear	132	Single	25	2.72	9.93
6	Hetuda	Bharatpur	Duck	132	Single	70	6.64	28.36
7	Marsyangdi	Suichatar	Panther	132	Single	84	11.39	34.69
8	Suichater	KL2 P/S	Duck	132	Single	36	3.42	14.59
9	Suichater	New Bhaktapur	Bear	132	Single	26.9	2.92	10.69
10	New Bhaktapur	Lamosangu	Bear	132	Double	96	2.61	9.46
11	Lamosangu	khimti P/S	Bear	132	Single	46	5.00	18.28
12	Lamosangu	Bhotekoshi P/S	Bear	132	Single	31	3.37	12.32
13	Bharatpur	Damauli	Wolf	132	Single	39	7.07	16.45
14	Bharatpur	Bardghat	Panther	132	Single	70	9.49	28.91
15	Bardghat	Gandak P/S	Panther	132	Double	28	0.95	2.72
16	Bardghat	Butwal	Bear	132	Double	86	4.67	8.47
17	Butwal	KGA P/S	Duck	132	Double	116	5.51	11.65
18	KGA P/S	Lekhnath	Duck	132	Double	96	4.56	9.64
19	Lekhnath	Damauli	Panther	132	Single	45	6.10	18.58
20	Lekhnath	Pokhara	Wolf	132	Single	7	1.27	2.95
21	Pokhara	Modikhola P/S	Bear	132	Single	37	4.02	14.70
22	Butwal	Lamahi	Bear	132	Single	112	12.17	44.51
23	Lamahi	Jhimruk P/S	Dog	132	Single	50	5.43	19.87
24	Lamahi	Attariya	Bear	132	Single	243	26.39	96.56
25	Attariya	Gaddachauki	Bear	132	Single	49	5.32	19.47
26	Marsyangdi	M. Marsyangdi	Bear	132	Single	40	4.34	15.89
27	Khimti	Dhalkebar	Bison	220	Double	150	5.68	15.60

* KL2 P/S: Kulekhani 2 Power Station

* KGA P/S : Kaligandaki A Power Station

3.3. **HVDC Modelling**

The HVDC model used in the simulation has been provided by the SINTEF. The model contained the .slx file, which contained the electrical circuit model of the grid connected voltage source converter and the control system that regulates the power flow and the DC voltage level. The folder containing the .slx file also consists of an initialization file, which was named "Init_SINTEF_converter.m". The simulation time step and the ratio between the simulation time step and the control time step can be set in the .m file. The setting of the converter is loaded by invoking the Matlab file Converter_settings.m, whereas the parameter setting for the electrical part of the simulation is done by invoking the matlab file Model_electrical_simulation_setting.m. A brief introduction of main files are done below. [25]

Converter_Settings.m file

The structure containing the ratings of the converts A, B, C and D and their base values are created by executing this file. With this, the per unit values and the circuit parameter are calculated and strored. To change the value of a parameter, the correct structure must be invoked. The file path should be added to the current Matlab path. [25]

Model_electrical_simulation_settings.m file

The electrical grid parameters like, RMS amplitude of the grid voltage, short circuit ratio and frequency can be defined with this file. Moreover, the resistance, inductance, capacitance, length and number of pi-section are defined here. [25]

The simulation model of HVDC transmission line with its controller block is shown in Figure 3.3-1. The Indian and Nepalese power system has been represented by an ideal three phase voltage source.

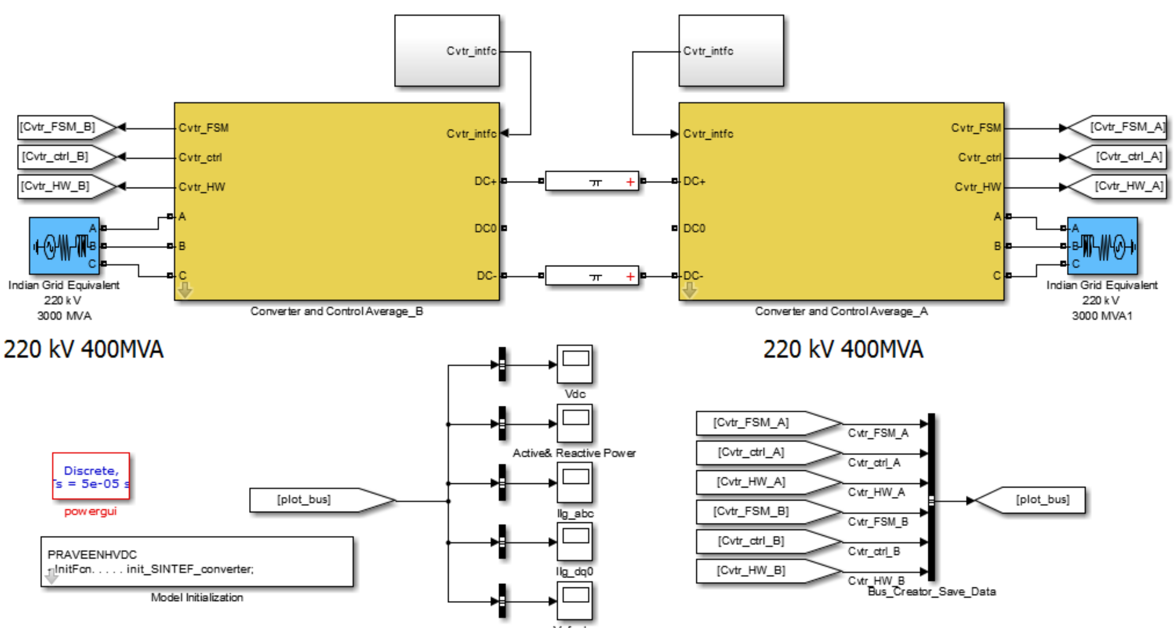

Figure 3.3-1: Simulation model of HVDC transmission link and its control

3.4. **Plant Modelling**

For the modelling of different generation plant, a single representation of generators, excitation system, governor system has been used. A resistive load has been connected before the power transformer to represent the station supply.

3.4.1. Generator Modelling

A model from Simpowerspace library has been used for the representation of the synchronous generator. The model of the synchronous generator is shown in figure below.

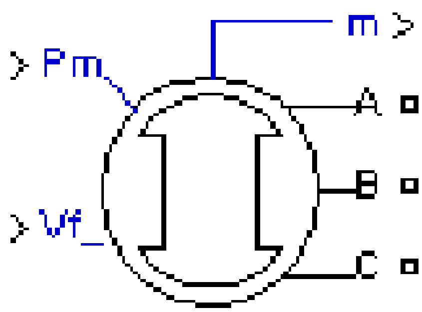

Figure 3.4-1: Pictoral representation of synchronous generator model in Simulink

This model can be used as a generator or motor depending upon the direction of the mechanical power. When used as a generator, ports P_m and V_f are used as Simulink interface blocks, port m as output for Simulink interface blocks and three ports A, B and C as interface for modeled power system. The preset model available in the Simulink hasn't been used and the parameter of the generator has been taken from Table 3.4-1. The parameters of the generators has been taken equal to the parameters of the generator close to its rated capacity from the Table 3.4-1. The rotor type has been selected as salient pole. It is because the hydro-generators are low speed type. The mechanical input has been provided from hydro-turbine governor block.

All the generators of the plant has been represented by a single generator. The equivalent impedances has been obtained by dividing the impedances of the single generator by the numbers of generators. The d and q-axis parameters with leakage reactances, stator resistances and time constants are kept as shown in the table below.

Table 3.4-1: Typical Data for Hydro (H) Units

GENERATOR										
Unit no.		$H1$	$H2$	$H3$	$H4$	$H5$	$H6$	$H7$	$H8$	$H9$
Rated MVA		9.00	17.50	25.00	35.00	40.00	54.00	65.79	75.00	86.00
Rated kV		6.90	7.33	13.20	13.80	13.80	13.80	13.80	13.80	13.80
Rated PF		0.90	0.80	0.95	0.90	0.90	0.90	0.95	0.95	0.90
SCR	(1)	1.250	...	2.280	1.167	1.180	1.18	1.175	2.36	1.18
x''_d	pu	0.329	0.330	0.310	0.235	0.288	0.340	0.240	0.140	0.258
x'_d	pu	0.408	...	...	0.260	0.318	0.380	0.260	0.174	0.320
x_d	pu	0.911	1.070	1.020	1.000	0.990	1.130	0.900	0.495	1.050
x''_q	pu	...	...	...	0.264	0.306	0.340	...	0.135	0.306
x'_q	pu	0.580	0.660	0.650	0.620	0.615	0.680	0.540	...	0.670
x_q	pu	0.580	0.660	0.650	0.620	0.615	0.680	0.540	0.331	0.670
r_a	pu	...	0.003	0.0032	0.004	0.0029	0.0049	0.0022	0.0041	0.0062
x_ℓ or x_p	pu	...	0.310	0.924	0.170	0.224	0.2100	...	0.120	0.140
r_2	pu	...	0.030	0.030	0.040	...	...	0.014	...	0.060
x_2	pu	...	0.490	0.460	0.270	0.297	0.340	0.260	0.130	0.312
x_0	pu	...	0.200	0.150	0.090	0.125	0.180	0.130	0.074	0.130
τ''_d	s	...	0.035	0.035	0.035	...	...	...	...	0.044
τ'_d	s	...	1.670	2.190	2.300	1.700	3.000	1.600	1.850	2.020
τ''_{d0}	s	...	...	...	...	...	...	...	...	0.051
τ'_{d0}	s	4.200	5.400	7.200	7.100	5.300	8.500	5.500	8.400	4.000
τ''_q	s	...	0.035	0.035	0.035	...	...	...	...	0.017
τ'_q	s	...	0.835	1.100	1.150	...	...	...	...	...
τ''_{q0}	s	...	...	...	...	...	...	...	...	0.033
τ'_{q0}	s	...	...	...	...	...	...	...	...	...
τ_a	s	0.1800	...	...	...	...	...	...	...	0.286
W_R	MW·s	23.50	117.00	183.00	254.00	107.90	168.00	176.00	524.00	233.00
r_F	Ω	...	...	...	...	0.269	0.301	0.199	0.155	0.332
$S_{G1.0}$	(2)	0.160	0.064	0.064	0.064	0.194	0.3127	0.1827	0.170	0.245
$S_{G1.2}$	(2)	0.446	1.018	1.018	1.018	0.685	0.7375	0.507	0.440	0.770
E_{FDFL}	(2)	2.080	2.130	2.130	2.130	2.030	2.320	1.904	1.460	2.320
D	(3)	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000

Table 3.4-2: Parameters of the hydro-generators

Generation Station	Rated Apparent Power (MVA)	Rated Voltage (kV)	Rated Current	Rated frequency (Hz)	Rated Power factor	Unsaturated Reactances: Direct axis synchronous reactance (Xd)	Unsaturated Reactances: Direct axis transient reactance (X'd)	Unsaturated Reactances: Direct axis subtransient reactance (X"d)	Unsaturated Reactances: q-axis synchronous reactance (Xq)	Unsaturated Reactances: q-axis subtransient reactance (X"q)	Leakage Reactance (Xl)	Time Constants (Short Circuit): Direct axis Transient (T'd)	Time Constants (Short Circuit): Direct axis Subtransient (T"d)	Time Constants (Short Circuit): q-axis Subtransient (Ta)	Time Constants (Short Circuit): Tq"	Time Constants (Short Circuit): Stator Resistance Rs (pu)
Kaligandaki	169.5	13.8	7092	50	0.85	0.3767	0.1267	0.1133	0.2267	0.1133	0.0700	3.0000	0.0400	0.2000	0.0350	0.0016
Middle Marshangdi	78	11	6141	50	0.9	0.4950	0.1590	0.1440	0.3075	0.1530	0.1120	1.7000	0.0350	0.2000	0.0350	0.0015
Lower Marshyangdi	90	11	4725	50	0.85	0.5000	0.2600	0.2350	0.6200	0.2640	0.1700	2.3000	0.0350	0.2000	0.0350	0.0040
Kulekhani I	70	11	3674	50	0.85	0.5000	0.1300	0.1175	0.3100	0.1320	0.0850	2.3000	0.0350	0.2000	0.0350	0.0020
Kulekhani II	37.6	6.6	3289	50	0.85	0.5350	0.1300	0.1650	0.3300	0.1320	0.1550	1.6700	0.0350	0.2000	0.0350	0.0015
Khimti	71	10.5	3904	50	0.85	0.2140	0.0520	0.0660	0.1320	0.0528	0.0620	1.6700	0.0350	0.2000	0.0350	0.0006
Bhotekoshi	50	11	2624	50	0.85	0.5100	0.1300	0.1550	0.3250	0.1320	0.4620	2.1900	0.0350	0.2000	0.0350	0.0016
Upper Tamakoshi	540	13.8	22592	50	0.85	0.1750	0.0533	0.0430	0.1117	0.0510	0.0233	2.0200	0.0440	0.2860	0.0170	0.0010

3.5. **Loads:**

The major load centers has been represented by three phase parallel RLC loads block. The loads are parallel combination of RLC elements. The loads are balanced and exhibits a constant impedance at a specified frequency level. The loads are assumed to be inductive and have power factor of 0.8, which are not compensated. The loads are directly connected to the transmission lines. The pictorial representation of the load is as shown in Figure 3.5-1.

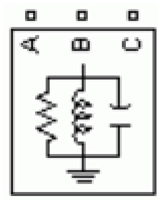

Figure 3.5-1: Three phase parallel RLC load

The load considered has been centralized at different substations in the power system. Due to lack of actual rating of loadings, the loading has been considered equivalent to the rating of the substation. Only the major loads are considered. The major industries lie either in the southern plains or in Kathmandu valley. Due to large residential area in Kathmandu, the electric consumption is very high in comparison to other parts of the country. The major loads that has been considered has been shown in Table 3.5-1

Table 3.5-1: Major load centers of Nepal with their ratings

Load	Ratings (MVA)
Kathmandu	150.00
Bhaktapur	94.50
Bharatpur	67.50
Damauli	26.00
Pokhara	30.00
Kamane	30.00
Parwanipur	135.00
Pathalya	22.50
Chandranigapur	68.00
Lahan	74.00
Damak	75
Total	772.5

3.6. INPS Modelling

A model of Integrated Nepal Power System (INPS) is shown in the Figure 3.6-1. The reference for the interconnection of the hydropower plants and loads with transmission lines has been taken from Annual Report 2014, NEA [3]. In the model the generation plant has been represented by green boxes. The power has been evacuated by connecting an equivalent power transformer which steps up the voltage to transmission voltage. The generation voltages were of 6.6 kV, 10 kV, 11 kV and 13.8 kV. The transmission voltage considered were 132 kV and 220 kV. In reality, Kulekhani I steps up at 66 kV but for the simplicity, here in the simulation 132 kV transmission voltage has been considered. Except Upper Tamakoshi plant, all other plants steps up at 132 kV. Only the large load centers has been considered, which has been represented by red color. Many of the hydropower plants are at the northern parts of the country, whereas major loads are in the southern parts of the country. In the north, hydropower plants are in the central and western development region whereas in the south, the loads are mostly in the central and eastern development region [2]. Due to lack of timely construction of transmission lines, the available transmission lines are insufficient to transfer the power from power plants to the loads. There is power congestion in Bardaghat-Bharatpur, Marsyangdi-Siuchatar, Khimti-Bhaktapur, and Marsyangdi-Kathmandu transmission system [26]. The 220 kV, Khimti-Dhalkebar, Hetauda-Bharatpur and Bharatpur-Bardghat and many other 132 kV transmission lines which are under construction will help to elevate the congestion problem in near future [26].

The generation plants, load centers and transmission lines considered with their parameters are given in Table 3.4-2, Table 4.1-2 and Table 3.2-4 respectively.

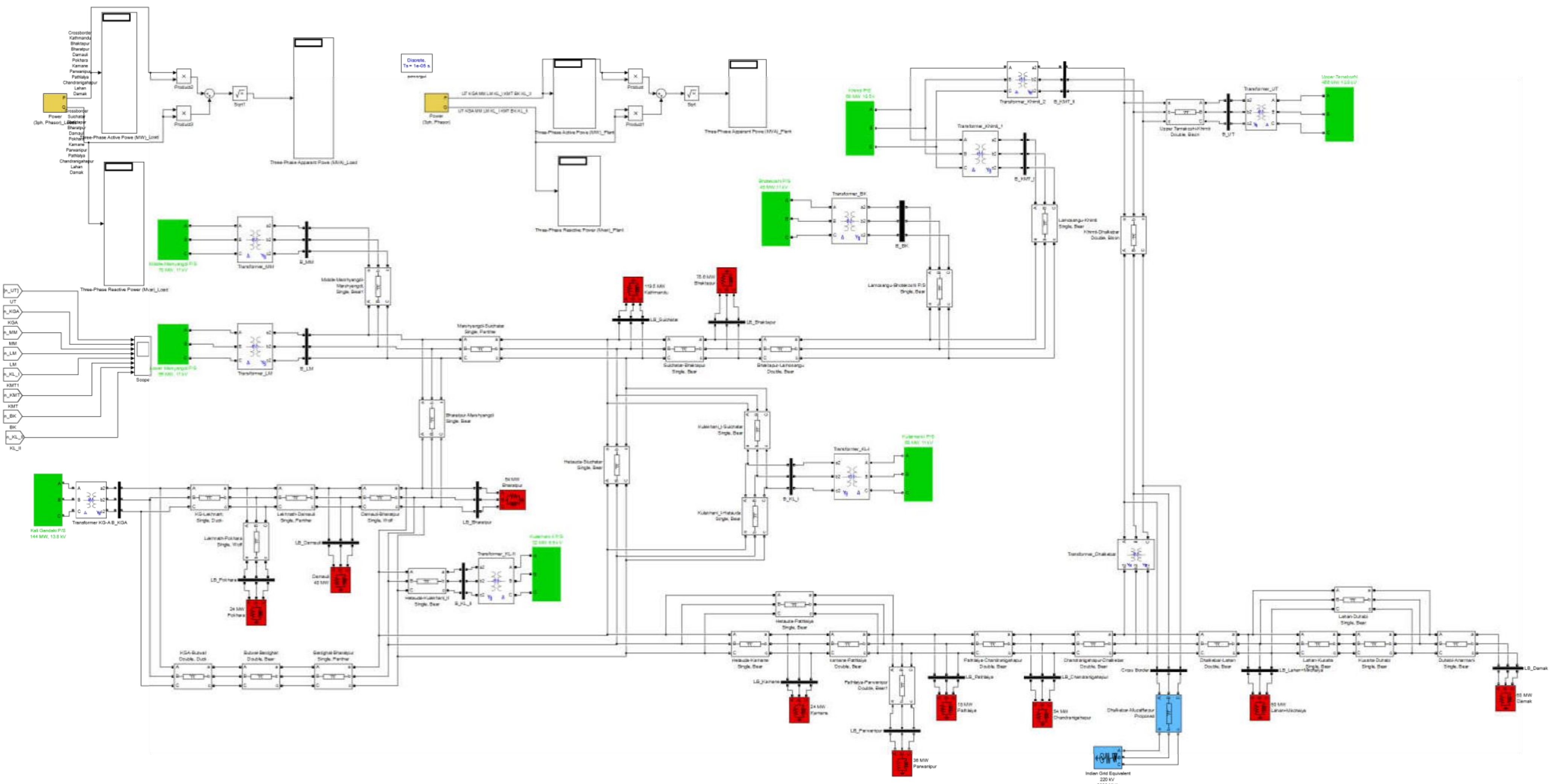

Figure 3.6-1: Integrated Nepal power system containing major power plants and load centers

Chapter 4. Simulation Results

This section presents the simulation results from the different models considered in the thesis. The HVAC was connected as cross border transmission link in the beginning and then followed by HVDC in parallel. The power through the HVAC depends upon the generation of the plants and the connected loads. Finally, only HVDC is connected and the power through the HVDC was regulated.

The Nepalese grid was made part by part by connecting the hydroelectric plants and loads with transmission lines. After connecting each plant and loads, simulation was executed to check the stability of the system. It was found that the system starts to become unstable when the rated capacity of Upper Tamakoshi hydroelectric plant is increased more than 100 MVA. Different changes were made in the governor, excitation system of the plant including the loads of the system but no solution was found to make the system stable when the capacity of Upper Tamakoshi is made larger than 100 MVA. There is an oscillation in the power flow of the plants and loads. The oscillation can also be seen in the amplitude of the plant current.

4.1. INPS without Indian grid

In the beginning, simulation was executed keeping the rated capacity of Upper Tamakoshi at its real value, ie. 540 MVA). The simulation was unstable and the scope didn’t show any stator current waveform. Load of the system was balanced with the generation but still the system was unstable. Also, the power measurement was not available during the execution of the model.

Several changes were made and finally, the system was stable when the rating of the Upper Tamakoshi Hydropower Plant was kept at or below 100 MVA. Therefore, in all the simulation performed, the rating of Upper Tamakoshi HPP was kept at 100 MVA. Figure 4.1-1 and Figure 4.1-2 show the instantaneous stator current of one of the generator in the system. All the phase currents are balanced and there is no oscillation in the stator currents. The pu speed of Khimti power plant is shown in the Figure 4.1-3, which shows that speed comes close to 1 pu after an overshoot, and then finally becomes stable.

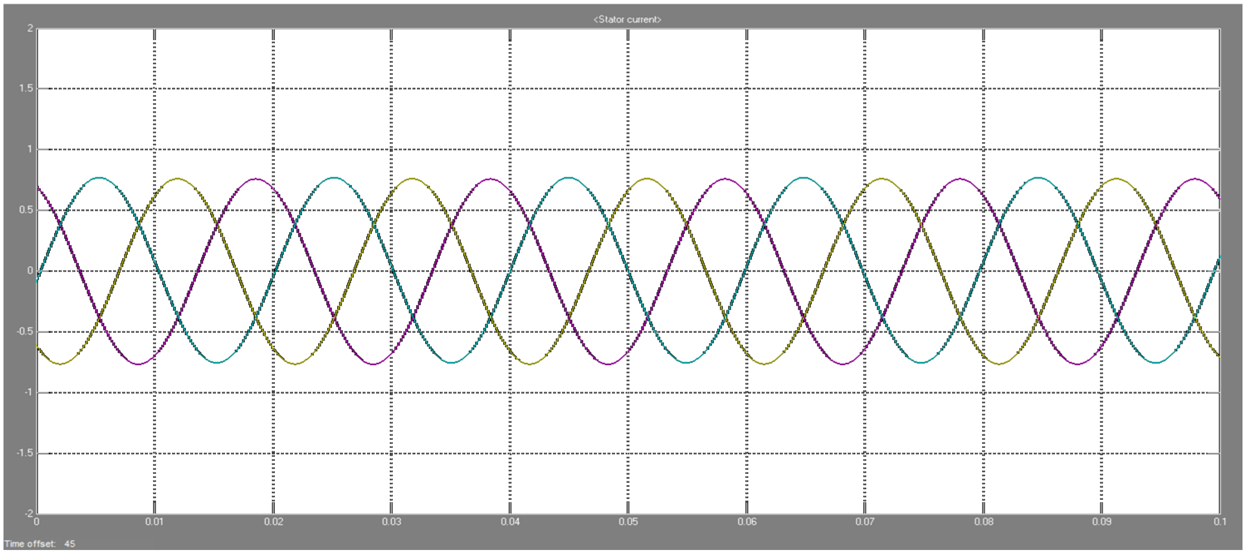

Figure 4.1-1: Instantaneous stator current of Khimti Power plant in pu.(1 second, INPS only)

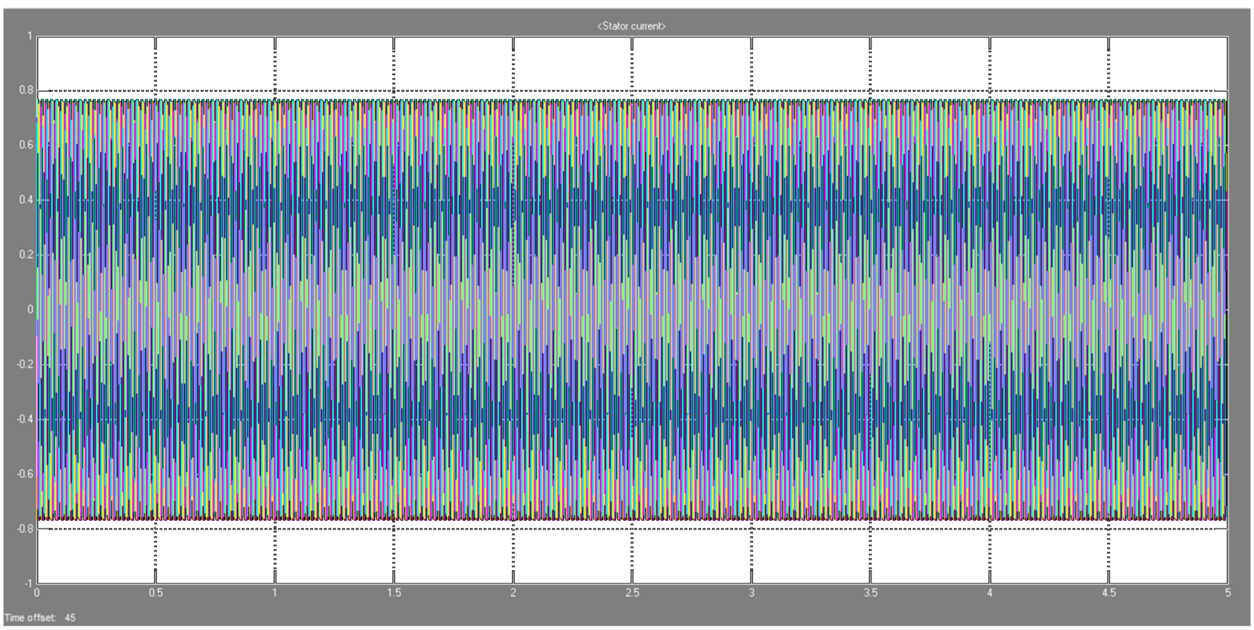

Figure 4.1-2: Stator current of Khimti Power plant in pu (5 sec, INPS only)

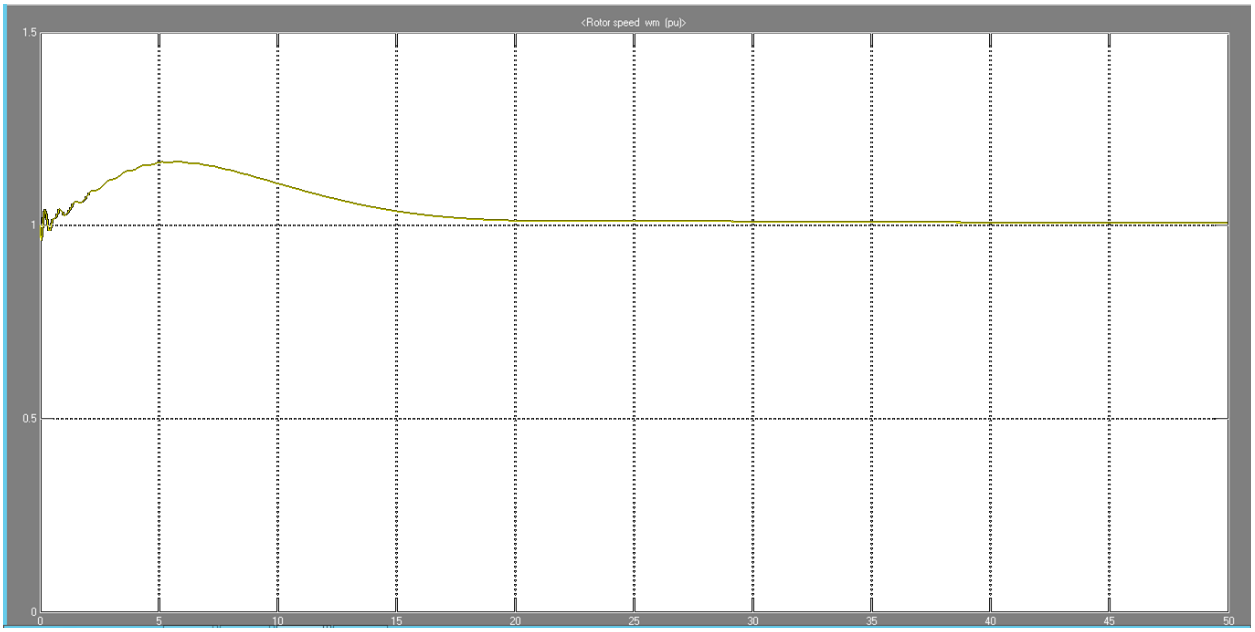

Figure 4.1-3: Speed of generator at Khimti Hydropower plant in pu (INPS only)

The power generated and consumed by different plants and major loads during the execution of the simulation are given in the Table 4.1-1 and Table 4.1-2 below.

Table 4.1-1: Power generation of power plants

Generation Station	Active Power (MW)	Reactive Power (MVAr)	Apparent Power (MVA)
Upper Tamakoshi	58.23	2.95	58.31
Kaligandaki	93.66	45.34	104.1
Middle Marshangdi	44.41	25.98	51.45
Lower Marshyangdi	47.08	57.21	74.1
Kulekhani I	35.02	86.31	93.14
Khimti	35.15	29.74	46.04
Bhotekoshi	30.91	30.66	43.54
Khlekhani II	21.97	42.13	47.52
Total	366.43	320.32	518.2

Table 4.1-2: Power consumption of major loads

Load	Ratings (MVA)	Active Power (MW)	Reactive Power (MVAr)	Apparent Power (MVA)
Kathmandu	150.00	95.27	70.77	118.70
Bhaktapur	94.50	60.32	44.83	75.15
Bharatpur	67.50	44.08	32.64	54.88
Damauli	26.00	32.19	23.94	40.11
Pokhara	30.00	20.45	15.22	25.49
Kamane	30.00	18.95	14.09	23.62
Parwanipur	135.00	26.21	19.49	32.66
Pathalya	22.50	13.45	10.01	16.77
Chandranigapur	68.00	9.13	6.70	11.33
Lahan	74.00	8.80	6.55	10.96
Damak	75.00	6.70	4.99	8.37
Total	772.50	335.55	249.23	418.05

The total power consumption of the loads was 335.55 MW and 249.23 MVAr. The apparent power consumption was less than the ratings of the loads. The loads' consumption exactly equals their nominal ratings when the terminal voltage of the load is 132 kV and at rated frequency. Though the frequency was nearly equal to 50 Hz, the terminal voltage is not equal everywhere. Most of the loads are at the southern parts, which are away from the power plants. Also, due to congestion in the transmission line the voltage drop was significant. Because of this, the power consumption drop was more for the loads which were far from the generation plants. For e.g. Chandranigapur, Lahan and Damak were farthest at the north east and hence have the lowest power consumption of 11.33, 10.96, 8.37 MVA respectively.

4.2. **INPS connected to the Indian Grid**

4.2.1. With HVAC only

The Indian grid was represented by a three phase voltage source. The HVAC was a 400 kV double circuit transmission line which was 145 km in length. Although, the transmission line was designed as 400 kV transmission line, it was charged at 220 kV in the simulation. In the actual system also, the line is to be charged at 220 kV in the beginning. When charged at 400 kV, 1200 MW of power can be transmitted and with 220 kV, 500 MW can be transferred, which is sufficient in the beginning years. The Indian grid is represented by a 3000 MVA three phase voltage source. The Indian grid is considered a weak one and hence the X/R ratio of the grid is considered 3. The base voltage is considered 220 kV, which is the same used for transmitting the power. The simulation model is shown in Figure 3.6-1.

The stable Nepalese grid when connected with the Indian grid equivalent showed some oscillation. In the Figure 4.2-1 below, the amplitude of the stator current continuously increases. After a while the amplitude decreases and follows a pattern as shown in Figure 4.1-2. The pattern repeats after each 0.75 seconds. Even though, the loads conditions, generator parameters, three phase short circuit level, X/R ratio were changed and different combinations were tried, the oscillations persisted. The oscillation decreased with the decrease in the length of the HVAC cross border transmission line but didn't disappear completely. The pu speed of Khimti power plant is shown in Figure 4.2-2, which shows that the speed is fluctuating with time and isn't stabilizing at a fixed point. The power generated and consumed also fluctuated. Similar to the Khimti power plant, the speed and power generated by other power plants fluctuated in the similar manner.

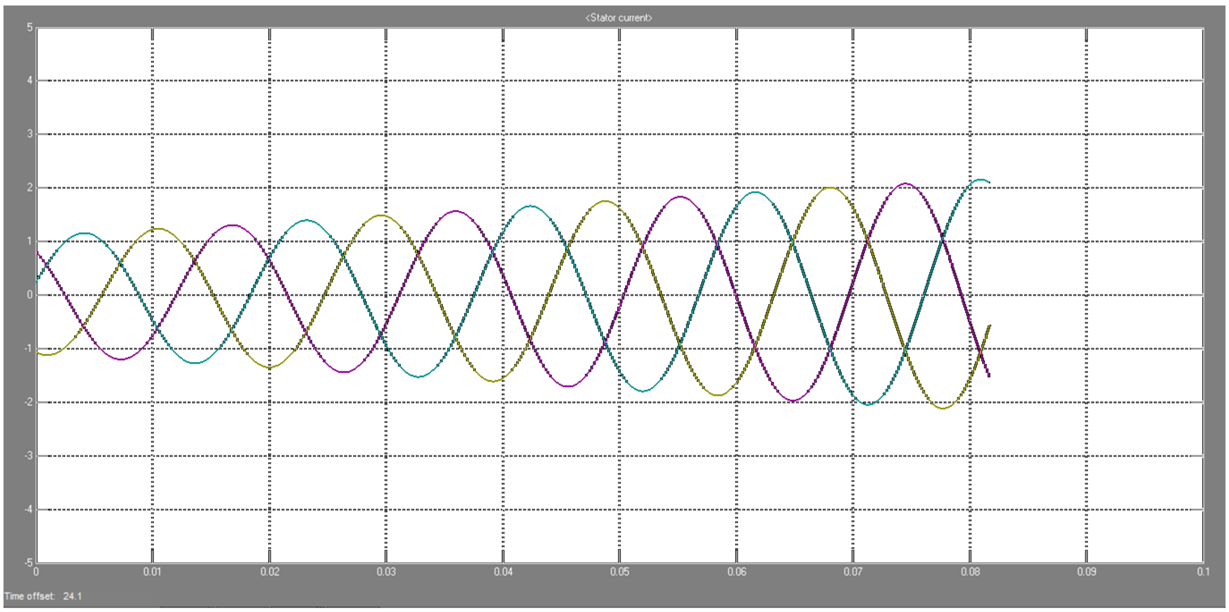

Figure 4.2-1: Stator current of Khimti power plant in pu (0.1 sec, HVAC only)

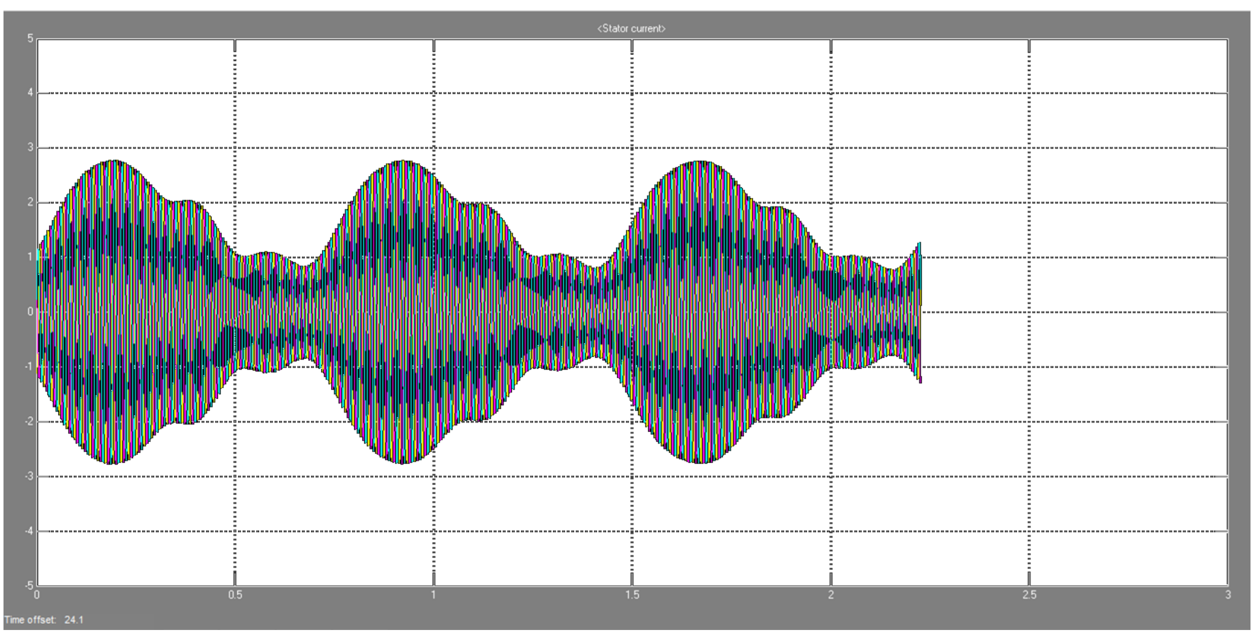

Figure 4.2-2: Stator current of Khimti Power plant in pu (5 sec, HVAC only)

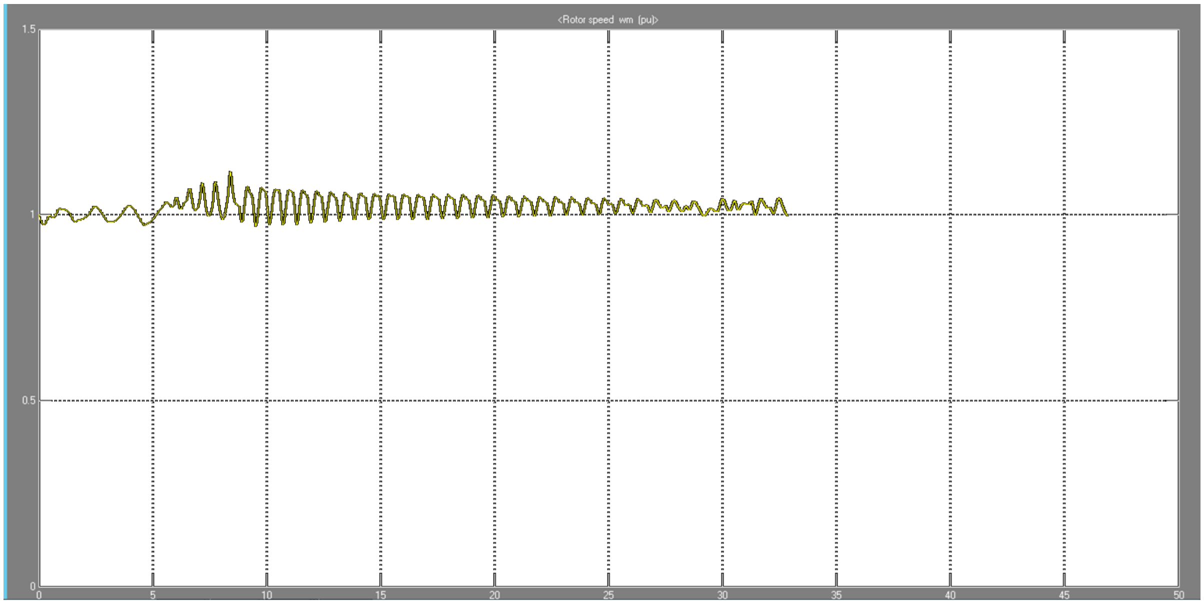

Figure 4.2-3: Speed of generator at Khimti power plant in pu (HVAC only)

4.2.2. With HVDC in parallel with HVAC

In the next step, the HVDC was connected in parallel with the HVAC. The simulation model is shown in Appendix B. The HVDC can change the direction of power flow in either direction without changing the DC polarity. Also, the independent control of active and reactive power flow is possible. The controller of converter B, at the Nepalese side is set to control active and reactive power only whereas the control of converter A, at the Indian side was set to control the DC voltage level. The DC voltage level was set at 500 kV and the active and reactive powers were varied.

After connecting HVDC, the oscillation didn’t stop. Both the active and reactive power flow through the HVDC was regulated but no stable state was obtained. The power flow through the HVDC can be controlled by setting the active and reactive power in the HVDC controller block. Figure 4.2-4 shows the per unit instantaneous current of Khimti hydropower plant where the amplitude of the current fluctuates. The power generated and consumed also fluctuated. As with the case with only HVAC, the oscillation in the stator amplitude decreased with the decrease in the HVAC transmission line length but didn’t disappear completely. Due to this no further simulation was performed.

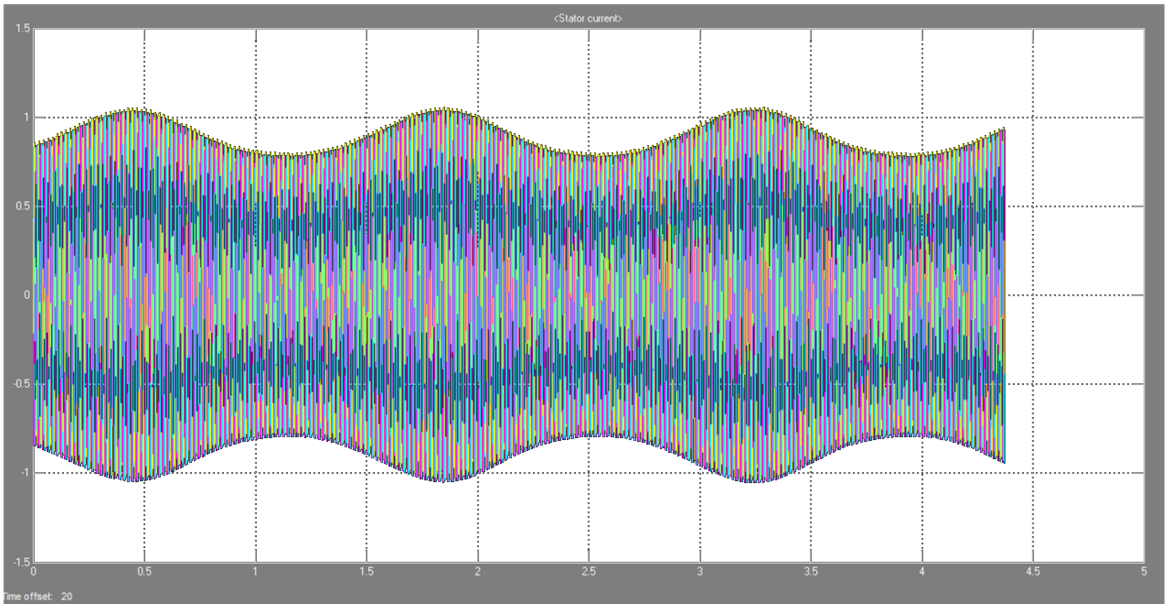

Figure 4.2-4: Per unit instantaneous stator current of Khimti hydropower plant (HVAC length = 145 km, HVDC in parallel to HVAC)

Figure 4.2-4 shows per unit instantaneous current of Khimti hydropower plant with the HVAC cross border transmission line length of 145 km. By changing the length of the HVAC line to 1 km, the oscillation as shown in Figure 4.2-5 is obtained. By comparing Figure 4.2-4 and Figure 4.2-45, it can be found that the amplitude of the oscillation decreases with the decrease in the HVAC line length. The inductance and capacitance of transmission line is directly proportional to its length. Because of this, it can be inferred that the amplitude of oscillation has direct relation with the inductance and capacitance of the transmission line.

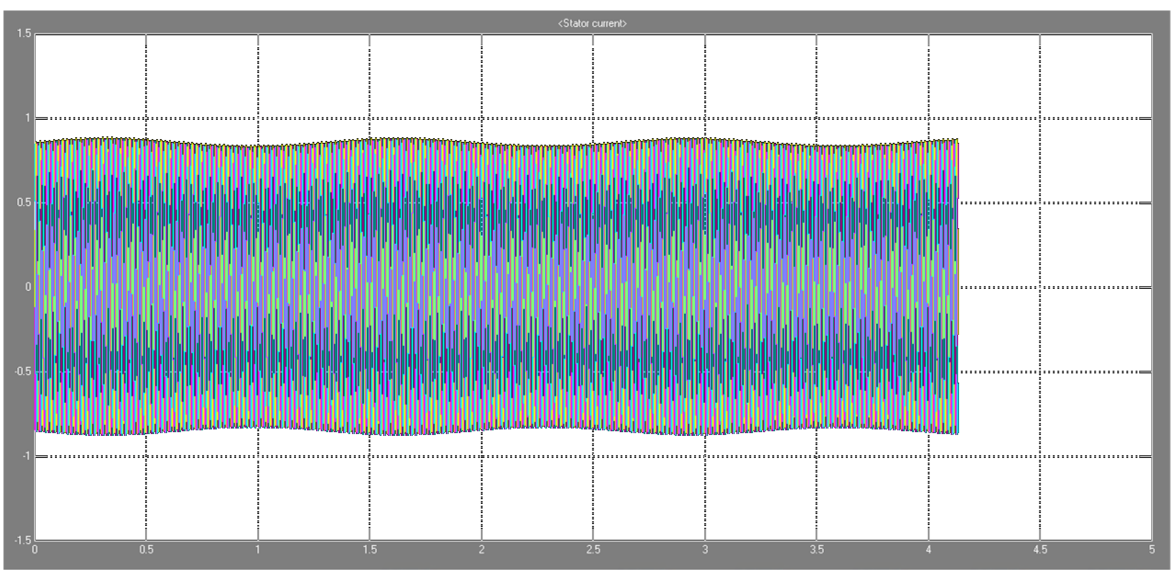

Figure 4.2-5: Per unit instantaneous stator current of Khimti hydropower plant (HVAC length = 1 km, HVDC in parallel to HVAC)

4.2.3. With HVDC only

The simulation was executed with only HVDC. The power transfer was varied from +200 MW to -200 MW with different reactive powers. The power transfer was set on the converter located at the Nepalese side. The power setting kept as positive in the converter B, connected at the Nepalese side, is considered as import for Nepal. In this case, the power flows from Indian grid to Nepalese grid. The power setting of the converter B on the Nepalese side was set at 200 MW and 0 MVAr, while the DC voltage level on the converter A, on the Indian side was set to 500 kV. The rated capacity and voltage level of the converters are set to 400 MVA and 220 kV respectively in the "Converter_settings.m" file. In the "create_base_value.m" file, the base MVA and DC voltage level for DC side has been calculated to be 800 MVA and 359.26 kV.

In all cases, the oscillations in the stator current, generator speed and the power fluctuation in both generators and loads didn't appear and the system was stable. Figure 4.2-6 and Figure 4.2-7 below show the stator current of Khimti Hydropower Plant. In both the figures, the amplitudes of the stator current is constant. Similar is the case with other generators. Figure 4.2-8 shows the generator speed of Khimti Power Plant in pu, which shows that the speed of the generator stabilizes at around 1 pu.

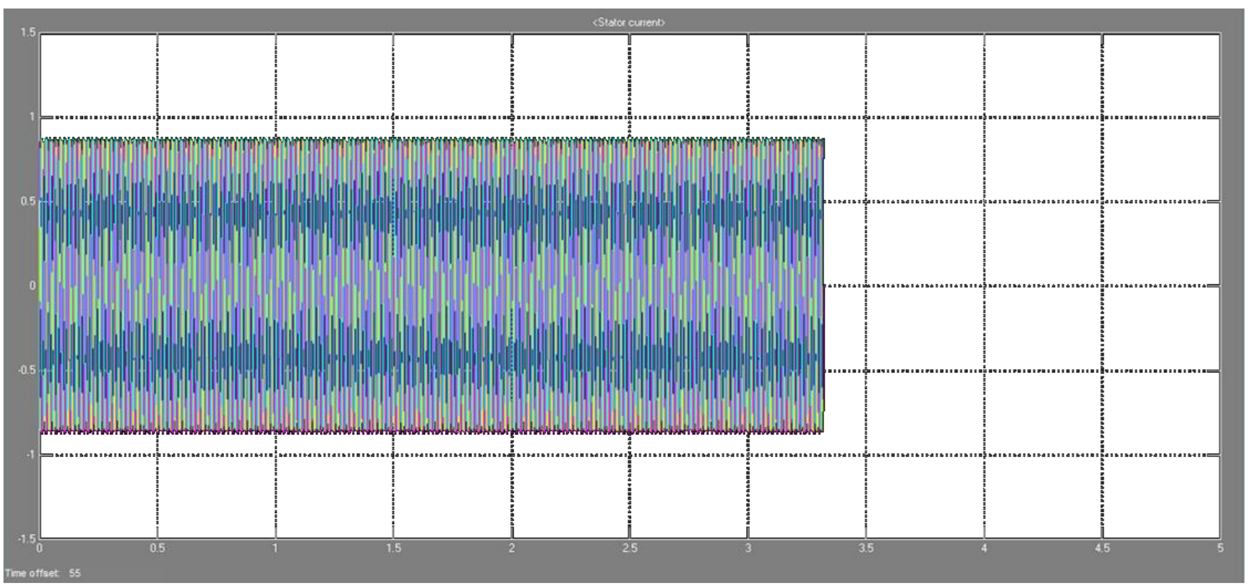

Figure 4.2-6: Stator current of Khimti Power plant in pu (5 sec, with HVDC only)

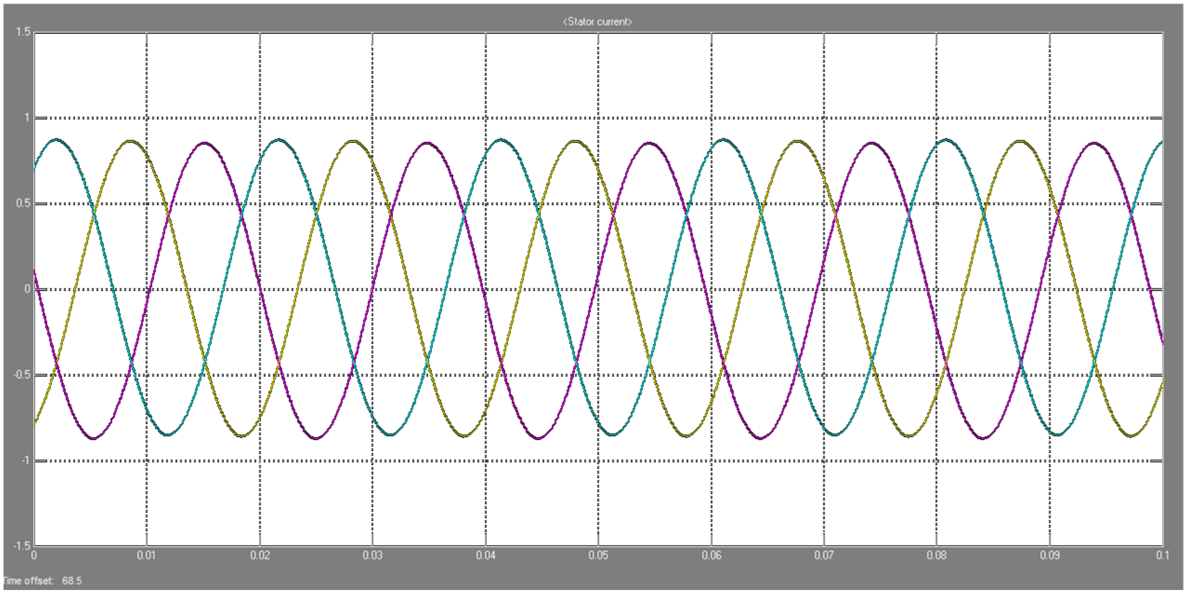

Figure 4.2-7: Instantaneous stator current of Khimti Power plant in pu.(1 second, with HVDC only)

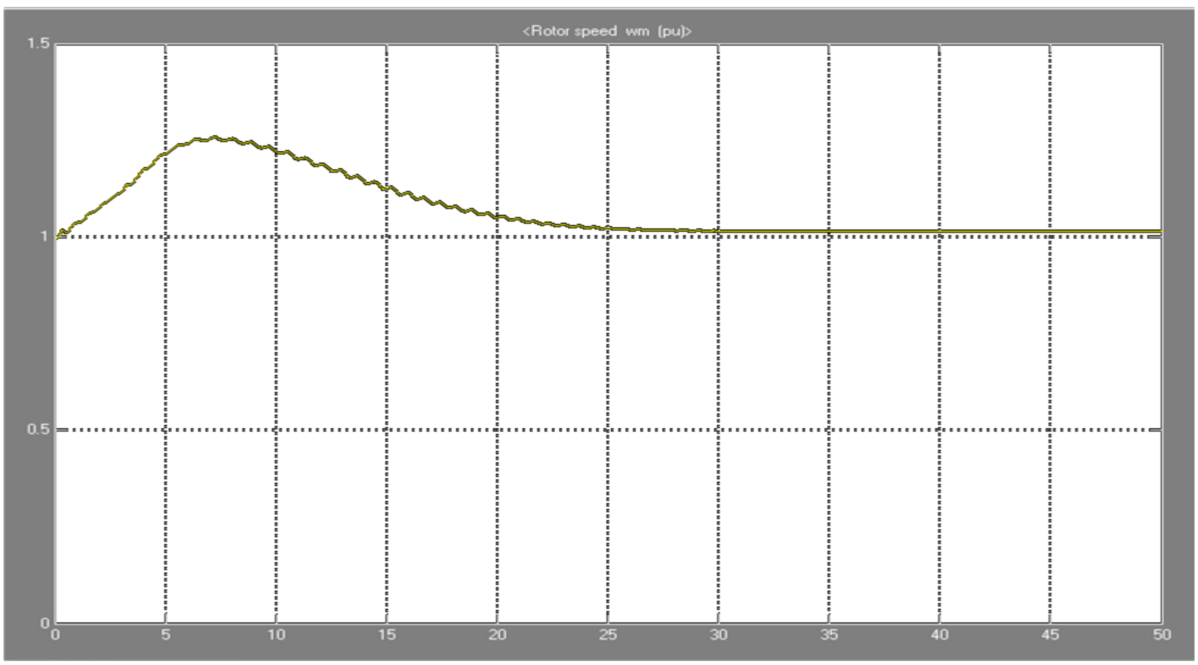

Figure 4.2-8: Speed of generator at Khimti Hydropower plant in pu (with HVDC only)

The active power and reactive power is set at +200 MW (0.25 pu) and 0 (0 pu) MVAr and the DC voltage at 500 kV (1.39 pu) from zero values at 3 seconds onwards. Figure 4.2-9 above shows the power transfer through the HVDC transmission line. The cyan and red line shows the active and reactive power flow. From the Figure 4.2-9, it can be seen that the active power rises from zero and becomes 0.25 pu (200 MW) after few seconds, whereas the reactive power remains at zero.

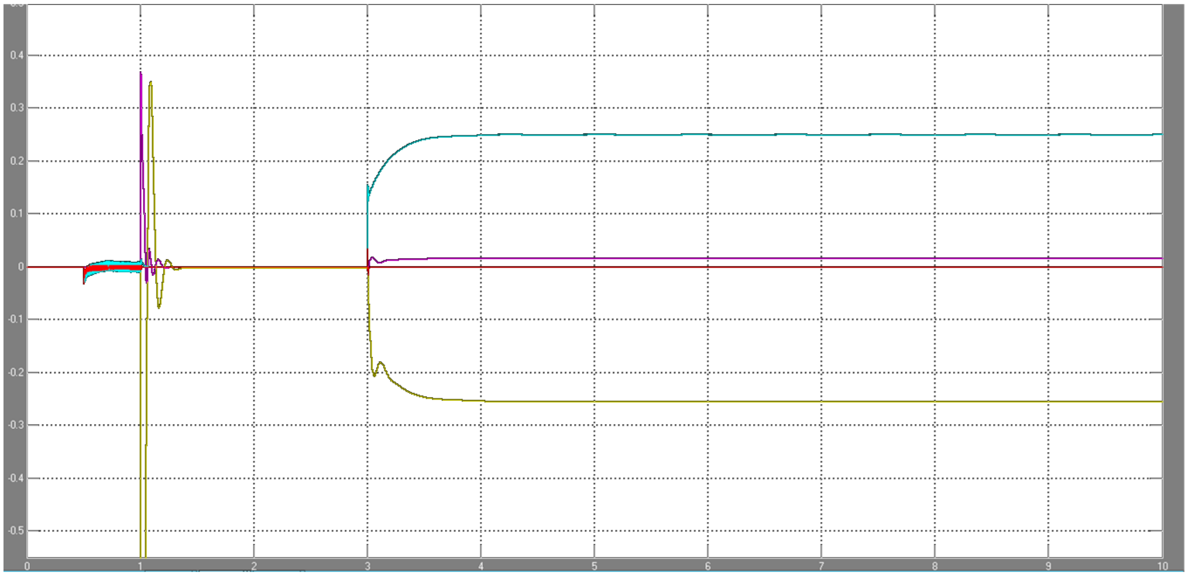

Figure 4.2-9: Per unit power transfer through the HVDC.

Similarly, as shown in Figure 4.2-10 at 3 seconds, the voltage level changes from zero to 1.39 pu. After a overshoot and few oscillations, the DC voltage remains constant.

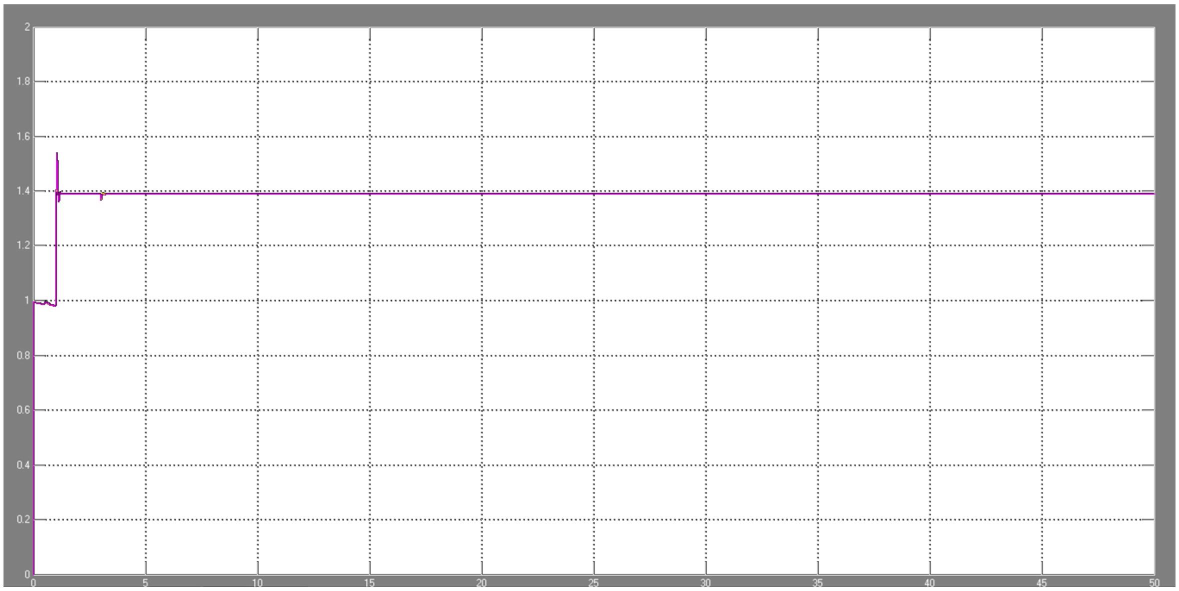

Figure 4.2-10: Per unit DC voltage level of HVDC

Chapter 5. Conclusions and Future works

5.1. Conclusions

A model of Nepalese power system in presented in the thesis. MATLAB Simulink has been used for the simulation. The Indian side gird has been represented by a three phase voltage source. The HVDC model was provided by SINTEF [25]. Since the grid is a hydro dominated system, all the power plant considered are hydro power plants. All the hydropower plants above 30 MW have been considered in the simulation.

Lots of efforts were made in finding the actual generator, governor, exciter, transformer and transmission line real parameters. Because of difficulty in finding the real parameters, the standard parameters were used from different mentioned sources. In the considered Dhalkebar-Muzaffarpur link, HVAC, HVAC in parallel with HVDC and HVDC only were kept and different conditions were applied.

With only HVAC as cross border transmission line, the control of power flow through it was not possible. The power flow couldn’t be controlled by changing the phase angle and voltage level of the Indian grid equivalent. By changing the phase angle, the reference of the whole system got changed. All the phase angles of the system changed in reference to the change in the phase angle of Indian grid equivalent and hence there was no change in the power flow of the system. The system itself was unstable too.

With HVDC in parallel with HVAC, the power flow through the HVDC could be controlled with the controller of the converters. Also, by controlling the power flow through HVDC, the power flow thorough the HVAC could be controlled indirectly. However, the system was still not stable. The oscillation decreased with the decrease in the length of the transmission line. The problem could be because of the inductance and capacitance involved in the transmission line.

Next, only the HVDC transmission line was used with which there were no oscillations. The power transfer could be controlled smoothly between both sides. During the simulation, up to 200 MW of power was imported and exported from Nepal. There were no changes in the power consumption of loads, but the power generation of hydropower plants changed. As the power transfer to the Indian side increased, the power generation of the power plant also increased automatically. The increase in power generation were shared more or less equally by all the generators.

From the above simulations, it can be concluded that the HVDC could be a better option than an HVAC. With HVDC, a precise control of power transfer is possible. This also helps in stabilizing the system.

5.2. **Future Work**

A model of Nepalese power system, Indian grid equivalent, HVAC and HVDC was made and the control of power transfer through the cross border link was done. The power transfer was made through HVAC and HVDC in parallel and individually. The following work is recommended as future work.

- Use of the real parameters for the generators, turbines, excitation systems, governors, power transformers and transmission lines involved instead of standard parameters.
- Use of separate units in each power plants.
- Control of individual generators according to the amount of loads connected and the power transfer through the cross border transmission line.
- Representation of Indian grid in more detail.
- Use of Eigen value method to find the cause of instability of the system when connected with the Indian grid via HVAC and when the rated capacity of Upper Tamakoshi is exceeded above 100 MVA.

References

[1] D. Adhikari, "Hydropower Development in Nepal, Economic Review," Nepal Rastra Bank, Kathamandu, Nepal.

[2] "A Year in Review - Fiscal Year 2014/2015," Nepal Electricity Authority, Durbarg Marg, Kathmandu, Nepal, 2015.

[3] "A YEAR IN REVIEW- FISCAL YEAR-2013/2014," Nepal Electricity Authority, Durbar Marg, Kathmandu, Nepal.

[4] Nepal Electricity Authority, [Online]. Available: http://www.nea.org.np. [Accessed 29 January 2016].

[5] "Nepal India Cooperation on Hydropower (NICOH)," Independent Power Producers' Association Nepal, Confederation of Indian Industry, January 2006.

[6] S. K. Mishra, "Nepal-India Power Exchange: A Critical Review," *HYDRO NEPAL,* no. 5, 2009.

[7] D. 2. U. International Resources Group Ltd.Washington and K. N. IRG/Nepal, "Nepal-India Transmission Line Link to Facilitate Power Trade," December 2006.

[8] "Nepal Electricity Authority Annual Report 2014," NEPAL ELECTRICITY AUTHORITY, Kathmandu, Nepal, 2014.

[9] M. H. Brown and R. P. Sedano, Electricity Transmission, A Primer, National Council on Electric Policy, June 2004.

[10] K. Meah and S. Ula, "Comparative Evaluation of HVDC and HVAC Transmission Systems," Vols. 1-5, 24-28 June 2007.

[11] J. J. Grainger and J. William D. Stevenson, Power System Analysis, Singapore: McGraw-Hill, Inc., 1994.

[12] J. Machowski, J. W. Bialek and J. R. Bumby, Power System Dynamics: Stability and Control, Wiltshire, Great Britain: John Wiley & Sons, Ltd, 2008.

[13] P. Kundur, Power System Stability and Control, McGraw-Hill, Inc., 1994.

[14] "Dynamic Models for Steam and Hydro Turbines in Power System Studies.," *Power Apparatus and Systems, IEEE Transactions,* p. 1904-1915, 1973.

[15] L. A. L. Tenorio, "Hydro Turbine and Governor Modelling, Electric - Hydraulic Interaction," Norwegian University of Science and Technology, Trondheim, June 2010.

[16] "IEEE Recommended Practice for Excitation System Models for Power System Stability Studies," IEEE Power Engineering Society, New York, NY 1 001 6-5997, USA, 21 April 2006.

[17] M. P. Bahrman and B. K. Johnson, "The ABCs of HVDC Transmission Technologies," *IEEE Power & Energy Magazine,* Vols. 5, No. 2, pp. 32-44, Mar./Apr. 2007.

[18] L. Zhang, L. Harnefors and P. Rey, "Power System Reliability and Transfer Capability Improvement by VSC-HVDC (HVDC Light©)," in *SECURITY AND RELIABILITY OF ELECTRIC POWER SYSTEMS, CIGRÉ Regional Meeting*, Tallinn, Estonia, June 18-20, 2007.

[19] S. G. Johansson, G. Asplund, E. Jansson and R. Rudervall, "POWER SYSTEM STABILITY BENEFITS WITH VSC DC-TRANSMISSION SYSTEMS," in *Cigré Conference*, Paris, France, August 2004.

[20] B. R. Gupta, Power System Analysis and Design, Gurgaon: S. Chand and Company Ltd., 2005.

[21] D. A. Woodford, "HVDC Transmission," Manitoba HVDC Research Centre, 400-1619 Pembina Highway, Winnipeg, Manitoba, R3T 3Y6 Canada, 18 March 1998.

[22] N. P. W. Strachan and D. Jovcic, "Stability of a Variable-Speed Permanent Magnet Wind Generator With Weak AC Grids," *IEEE TRANSACTIONS ON POWER DELIVERY,* Vols. 25, NO. 4, p. 2779–2788, OCTOBER 2010.

[23] S. Grunau and F. W. Fuchs, "Effect of Wind-Energy Power Injection into Weak Grids," Institute for Power Electronics and Electrical Drives, Christian-Albrechts-University of Kiel, D-24143 Kiel, Germany.

[24] B. Gupta, Power System Analysis and Design, New Delhi: S. Chand & Company Ltd., 2007.

[25] G. Bergna-Diaz, "User Guide for ProOfGrids Models in Matlab/Simulink," SINTEF Energi AS, Trondheim, Norway, 29 Dec. 2014.

[26] "http://samriddhi.org/," Samriddhi, The Prosperity Foundation, 18 March 2014. [Online]. Available: http://www.nepalenergyforum.com/wired-in-problems/. [Accessed 12 February 2016].

[27] "STANDARDS/MANUALS/ GUIDELINES FOR SMALL HYDRO DEVELOPMENT," Alternate Hydro Energy Center, Indian Institute of Technology, Roorkee, May 2011.

[28] H. LATORRE, "Modeling and Control of VSC-HVDC Transmissions," KTH Royal Institute of Technology, Stockholm, Sweden, 2011.

Appendix A HVDC in parallel with HVAC