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SUMMARY OF DISSERTATION

Dynamic model of two synchronous generators connected via long transmission line

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Doctoral Study Programme: Mechanical Engineering

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Supervisor: Prof. Ing. Ivan Uhlíř, DrSc.

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Title in Czech language: *Dynamický model dvou synchronních generátorů propojených dlouhou přenosovou linkou.*

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Název práce: *Dynamický model dvou synchronních generátorů propojených dlouhou přenosovou linkou.*

Anotace:

V posledníc DYNAMICKÝh letech významně vzrostly nároky na pružnost výměny elektrické energie což klade zvýšené nároky na dynamickou analyzu energetických systémů. Zatím co dynamika a stabilita sítí je dlouhodobě studována při dlouhodobém plánování, je nyní zapotřebí k zamezení nežádoucích výpadků přenosu energie tuto analyze provádět daleko rychleji on-line s okamžitými on-line naměřenými daty.

Dynamicky stabilní výkon přenášený v energetických systémech je důležitý jak z organizačních důvodů, tak z ekonomického hlediska spolu s hlediskem spolehlivosti. Analýzou dynamiky a stability energetických systémů se s současnosti zabývá velké množství aktuální odborné literatury. Literární studie se liší podle detailnosti popisu systému a jeho velikosti. Dynamické jevy byly diskutovány podle základní funkce, podle vlastností, podle časového měřítka atd.

V reálném systému se elektrická energetická soustava skládá z propojení velkého počtu synchronních generátorů pracujících paralelně. Tyto generátory jsou propojeny přenosovými linkami. Při provozním procesu se úhly rotorů generátorů v průběhu přechodových otáček relativně otáčejí jiným. Při poruchách dochází k synchronizaci strojů v systému při zachování rovnováhy mezi elektromagnetickými a mechanickými momenty. Jinými slovy, systém je nestabilní, pokud úhlový rozdíl mezi dvěma propojenými generátory není dostatečně tlumen. Nestabilita se zpravidla vede ke ztrátě synchronizace s ostatními generátory a k rozpadu okrsku sítě výpnutím proudových, napěťových a výkonových ochran.

Jedním z omezení stability přináší pro dálková přenos dlouhým vedením. Dlouhé metalické vedení zvyšuje fázový úhlový rozdíl, který je nutný k přenosu daného výkonu střídavým proudem. Proto se za účelem získání popisu dynamického chování systému při poruchách soustředí tato práce na modelování dvou synchronních generátorů propojených dlouhým AC přenosovým vedením.

V rámci této práce je pro analýzu systémových režimů systém vypočítán na základě podrobného modelu synchronních strojů, transformátorů, zátěží a dlouhé přenosové linky včetně dynamiky napětí a frekvenční odezvy.

Rovnice rovnovážné síly systému jsou odvozeny a linearizovány pro malou poruchovou stabilitu a některé přechodné poruchy. Tyto výsledky mohou sloužit ke stanovení rozpětí stability energetického systému. Tento limit stability by měl významnou roli při zlepšování návrhů různých podmínek připojení k systému.

Title: *Dynamic model of two synchronous generators connected via long transmission line*

Abstract:

Due to the large desire to utilize transmission networks for more flexible power interchange transactions, the high requirement for power system dynamic analysis has grown significantly in recent years. While dynamics and stability have been studied for years in a long term planning and design environment, there is a recognized need to perform this analysis online.

The dynamic performance of power systems is important to both the system organizations, from an economic viewpoint, and society in general, from a reliability viewpoint. The analysis of power system dynamics and stability is increasing daily in terms of number and frequency of studies, as well as in complexity and size. Dynamic phenomena have been discussed according to basic function, time-scale properties, and problem size.

In a realistic system, electric power system consist of the interconnection of large numbers of synchronous generators operating in parallel. These generators are connected together by transmission lines. In the operation process, the rotor angles of generators swing relatively to another one during transients. Under disturbances the synchronism of machines in system is achieved when maintaining equilibrium between electromagnetic and mechanical torques. In other words, a system is unstable if the angle difference between two interconnected generators is not sufficiently damped in the evaluation time. The instability typically occurs as increasingly swings angle generators leading to some loss of synchronism with other generators.

One of the constraints for long distance AC transmission is the large phase angular difference which is required to transmit a given amount of power. Therefore, in order to gain dynamic behavior characteristics of system when subject to disturbances, this work will focus on modeling two synchronous generators linked by long AC transmission line.

Within the content of this work, for the analysis of system modes, the system is computed based on a detailed model of synchronous machines, transformers, loads and the long transmission line including voltage dynamics and frequency response.

The system power equilibrium equations are derived and linearized for the small disturbance stability analysis and some transient disturbances. These results can serve to define stability margin of a power system. This stability limit would play important role in improving designs of the different system connection conditions.

Keywords: synchronous generators, stability, transient model, long transmission line, synchronization.

Contents

Chapter **1**

Introduction

In the recent years, modern electrical power systems have grown to a large complexity due to increasing interconnections, installation of large generating units and high voltage tie-lines, etc. Therefore, it is very challenging and uneconomical to make the system be stable for all disturbances.

In the last decade, several major blackouts were reported separately in many research papers. The first massive power failure properly reported was the Northeast power failure on 9th November 1965 in the United States [1]. The main cause was the weak transmission line between northeast and southwest. The second power failure was on 13th July 1977, which was a collapse of the Con Edison system [2]. A power failure in Tokyo, Japan occurred on 23rd July 1987 affecting 2.8 million customers with the outage of 3.4 GW power out of the maximum power demand of 38.5 GW [3]. A cascaded power interruption was reported [4] on 2nd July 1996, leading to a failure of the Western North American power system.

In Europe, the Swedish/Danish system had a blackout on 23rd September 2003 [5]. This made a total of 6550 MW load lost in Sweden and Denmark affecting 4 million people. The other major blackout occurred in Italy on 28th September 2003 [6]. After several minutes, the entire Italian system collapsed as the nationwide blackout. The frequency decay was not controlled sufficiently to stop generation from tripping.

Two severe power blackouts affected most of northern and eastern India on 30 and 31 July 2012 due to relay problems [13]. The outage affected more than 620 million people, about 9% of the world population, or half of India's population, spread across 22 states in Northern, Eastern, and Northeast India. An estimated 32 GW of generating capacity was taken offline

These above mentioned failures and blackouts in different parts of the power network have forced power systems researchers to look beyond the traditional approach of analyzing power system functionalities in steady-state, pay serious attention to their dynamic characteristics.

Recent articles have proposed various dynamical models of power sources. However, these models have not been sufficiently developed for multi-generator power system in the presence of the new energy sources. These sources developments are related to frequency dynamics and power system operation. Since frequency dynamics are faster in power systems with low rotational inertia, this can lead to large transient frequency and power oscillations in multi-area power systems [7]. And the system stability can be lost due to these unexpected oscillations.

In addition, with the expansion of modern interconnected power system, inter-area low-frequency oscillations are becoming a phenomenon of concern in power system operations. The oscillation energy distribution in generators and branches will reflect the properties of power system oscillation and it can be used to identify the oscillation mode and to determine the strongly correlated generators associated with the inter-area oscillation mode.

Above mentioned disadvantages lead to the wide discussion about power system stability. Ensuring stability, reliability and security in power systems is importance to system operators and the end users [8]. In recent studies, some main areas of interest were given broadly as modelling of power system leading to better understanding and control of the power system [9][10], and the electromechanical behavior of the power system. Those studies are based on the particular studies which are analyzing the influence of generator rotational inertia and long transfer distances among power plants on the power system fluctuations e.g. frequency, voltage, etc. [11].

Synchronous machines, specifically synchronous generators, are extremely important components in power generation systems worldwide. Many large synchronous generators connected to the power grid are usually found in recent power system, which is common in several countries around the world. Synchronous machines are used in many industrial applications due to their high power ratings and constant speed operation. The electrical and electromechanical behavior of most synchronous machines can be predicted from the equations that describe the three phase salient pole synchronous machine [12].

Based on such two generator model behavior, this work shows how the electromechanical dynamic of one generator in system may swing against each other when a disturbance sets in. The modes of study in this work represent prototypes of two transfer systems linked by long transmission line. First of all, the model must to be identified, and then derive analytical results showing how the voltage, phase angle, and frequency oscillations at two ending buses on the transfer path, follow a small-signal oscillations or transient disturbances. The focus in this dissertation is to present the simulation dynamic model of two synchronous generators connected via the long AC transmission line, and shows behavior characteristics of system through stability of voltage and frequency responses.

Chapter **2**

Literary Research

The stability of power systems has been and continues to be of major concern in system operation. The grow of modern electrical power systems are a large complexity such as increasing interconnections, installation of large generating units and extra-high voltage tie-lines.

Synchronous machines are used in many industrial applications due to their high power ratings and constant speed operation. Simulation of the synchronous machine is well documented in the literature researches.

It is important to develop mathematical models for studying of synchronous machines, which adequately describe their behavior. Incorrect mathematical modeling leads to instability zone in corresponding models, which is lacking in real electrical machines. Hence, it is necessary to develop analytical methods for stability analysis of mathematical models.

The electrical machines and their controls are developing rapidly in the recent years. To get their operating characteristics under normal/fault condition needs implementation of modeling process. Simulation model of Permanent Magnet Synchronous Machine (PMSM) was presented mathematically in [16]. The Permanent Magnet Synchronous motor is a rotating electric machine where stator is a classic three-phase Induction Motor and rotor has permanent magnets. Mathematical modelling of Permanent Magnet Synchronous Motor is carried out and simulated using MATLAB [14].

Besides synchronous motor, synchronous generator is also the main part of the power system. It has a complex dynamic behavior. This behavior influences on the entire power system. Hence, in order to analyze different problems of the power system, one must build the mathematical model of the synchronous generator. The model of the synchronous generator with damper windings is described by the system of six differential equations [17].

Due to the development of modern computer technology, the numerical methods and several software solutions for simulations, control and scientific visualization have been reported such as Authorware, Hypertext, Labtech, Visual C, Visual Basic, LabVIEW and Matlab/Simulink. A new information about the behavior of trajectories can be obtained. Simulations of the same synchronous generator in Matlab/Simulink and LabVIEW verify the accuracy of the model in LabVIEW [19]. Modeling the synchronous generator with an excitation system in Matlab/Simulink and Sim-Power Systems allows full analysis in both static and dynamic states [22].

The main objectives of electricity networks operation is to ensure the functioning of a system in good condition and keep it in a stable state when it faces to a sudden disturbance, as in the cases of line faults or electric generator separations. In transient stability studies, generator model with AVR and PSS will constitute the worst-case scenario with respect to system stability following a disturbance [21].

Many different techniques have been proposed for transient stability analysis in power systems, especially for a multi-machine system. Simulation of multi-machine power system was described [27]. Rotor angle stability denotes the ability of synchronous machines in the grid to remain in synchronism following large or small disturbance, and sustaining or re-establishing the equilibrium between electromagnetic torque and mechanical torque at each synchronous machine in the system.

Modelling and simulation studies are an integral part of power system analysis. They are used in the electricity related industry from the early days of digital computers and the operation, stability of the system, controllers design and testing, operator training. A dynamic simulation program for a single machine infinite bus test system was developed by using MATLAB/Simulink software [28].

With the expansion of modern interconnected power system as penetration of renewable energy sources which is represented as a multi-machine interconnected system, inter-area low-frequency oscillations are becoming a phenomenon of concern in power system operations. Currently, researchers have come up with many effective methods to analyze the low-frequency oscillation problems and loss of synchronism between generators. From any small or large disturbance in the power system electromechanical oscillations could result and could be damped and consequently the system can return to a stable operating state.

The main reasons of loss of synchronism, which led to accidents, were the increasing of load torque and voltage collapse such as the accident happened due to the multiple additional variable loads on a hydraulic aggregate connected with transition through non-recommended operation domain of a turbine. The loss of synchronism can occur between one machine and the rest of the system or between groups of machines. Because of these reasons the qualitative analysis of transient processes in synchronous machines under sudden change of load is required. Stability is a condition of equilibrium between opposing forces. Under steady-state conditions, there is equilibrium between the input mechanical torque and the output electrical torque of each machine, and the speed remains constant. If one generator temporarily runs faster than another, the angular position of its rotor relative to that of the slower machine will advance. The resulting angular difference transfers part of the load from the slow machine to fast machine, depending on power-angle relationship. This tends to reduce the speed difference and hence the angular separation. Beyond a certain limit, an increase the angular separation is accompanied by a decrease in power transfer; this increase the angular separation further and leads to instability. For any given situation, the stability of the system depends on whether or not the deviations in angular positions of the rotors result in sufficient restoring torques.

It is known that, an initial generator rotor angle swing which does not exceed 160° is considered stable (practical limit). A rotor angle swing exceeding 160° only has a small margin before pole slipping (180°), and an initial rotor swing angle higher than 160° may result in a pole slip or repeated pole slipping, which is considered unstable [30]. The characteristics of inter-area oscillation are studied by analyzing the distribution of the oscillation energy [18]. A modal kinetic energy participation factor is proposed for evaluating the participation of each generator in the oscillation. The distribution characteristics of voltage angle oscillation and branch potential energy in inter-area oscillation is developed.

The dynamic stability of synchronous machines can be increased by implementing a controller. The controller may influence either on stator and rotor currents or directly on the torque of the rotor. A variable frequency drive is frequently used as a controller, which allows one to change amplitude and frequency of current. Stability of a multi-generator representation of the power system is achieved by employing novel controllers. When a fault or a disturbance occurs in the power system, the generator angles and speeds deviate from their normal operating range. Unless there is a controller to mitigate the oscillations, which bounce back and forth among multiple generators, the power system will not return to its normal operating state after the fault is removed. Since the disturbance is a function of the power network voltages and angles as well as generator states, it is generally hard to design a centralized damping controller for the complex interconnected power network. A damping controllers are developed with the application of conventional multi-machine stabilizing techniques such as Power System Stabilizer (PSS) and Automatic Voltage Regulator (AVR) [29]. The end result is a feedback controller that makes possible for power systems with penetration of renewable energy sources. This thesis is based on the major publications [9] [11] [12] [16] [18] [20] [22] [23] [24] [25][26].

Taking motivation from above discussion, this dissertation is modeling two synchronous generators connected via long transmission line to see how the system behaves when subject to disturbances. The major objectives of this work are dynamic model of the synchronous generators and behavior characteristics of system through voltage and frequency stability index.

Chapter **3**

Aim of dissertation

According to the discussion and analysis in chapter 2, the main aims of my dissertation are:

To implement the complete system model for electromechanical oscillation of connected generators including mechanical components under steady state and disturbances condition.

To analysis the influence of the length of line for oscillation of power system using the complete system model.

Based on analyzing oscillation problems in chapter 2, almost authors in the articles tended to cut mechanical part and electrical part separately. In fact, two these parts have a tight connection through electromechanical oscillation. This oscillation limits to power transfer capacity. New modes of oscillation, involving the interaction between the dynamics of the different machines which are not modeled in the single machine models. It is necessary to have comprehensive modelling and analysis techniques of all the components that may interact to produce oscillations. Each component of the power system i.e. prime mover, generator rotor, generator stator, transformers, transmission lines, load, controlling devices and protection systems should be mathematically represented to assess the rotor angle, voltage and frequency stability through appropriate analysis tools. For the correct representation of a generating unit, both the electrical and the associated mechanical phenomena must be modeled

Power transfer capability in power system has been limited by stability considerations under the long transmission distance between load centers and power sources. This dissertation work will give dynamic model of system and respect length of long lines as influent index to oscillations. It is due to the big blackouts in history was mostly in large countries with long lines. My country Vietnam with long transmission distance from Northern to Southern is facing to some dangerous blackouts for long lines. Therefore, the length of line needs to be considered as one of the most influent factors to system oscillation

Chapter **4**

Methods

4.1 Synchronous Generator Modelling

4.1.1 Introduction

This project presents important aspects regarding dynamic characteristic of a direct phase synchronous machine model **[PV].** It briefs the synchronous machine model in both abc frame and qd0 frame, a mathematical expression is used to relate the current and inductance, then the inductance may be directly found with the fluxes, which are used as the state variables in the simulation model. The model of synchronous machine has been implemented in MATLAB/SIMULINK. Simulation studies are performed under various conditions of system.

Fig 4.1 shows an internal block diagram representation of a synchronous machine model. It consists of three blocks, namely torque-angle loop, rotor electrical block, and excitation system block **[PVII]** [31].

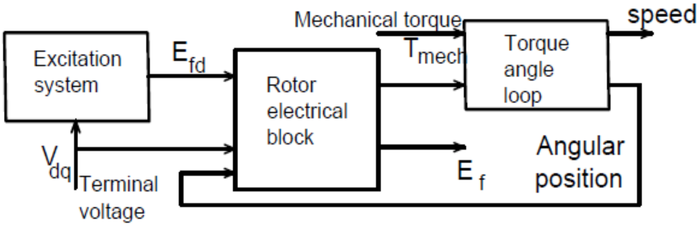

Fig. 4.1. Block diagram representation of synchronous machine model

The torque angle loop represents turbine and generator mechanical system. Input to this block are mechanical and electrical torques, and outputs are rotating speed and rotor position. If mechanical torque and electrical torque are balanced, the rotor will rotate at a constant speed called synchronous speed. A change one of the torques will cause the speed to change. Another output of the block is the rotor position which considers any fixed point in the rotor.

The mathematical description and model developed in this section is based on the concept of an ideal synchronous machine with two basic poles. Fig. 4.2 shows a circuit representation of an idealized machine model of the synchronous machine commonly used in analysis **[PVII].**

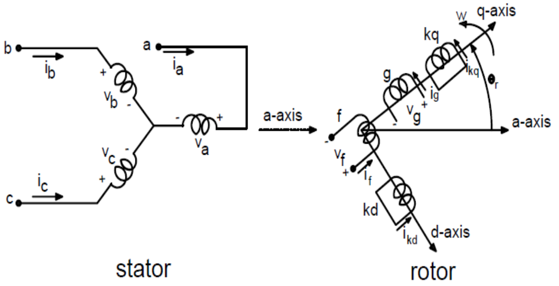

Fig. 4.2. Diagram of idealized synchronous machine

4.1.2 Steady state model

4.1.2.1 Mathematical model

The circuit of an idealized synchronous machine, three phase windings a-b-c, field winding f and two equivalent damper coils kd-kq are shown in Fig. 4.2.

In terms of flux linkage, the voltage equations of the stator and rotor windings in the circuit can be expressed in phase frame as [20]:

$$\begin{bmatrix} v_s \\ v_r \end{bmatrix} = \begin{bmatrix} r_s & 0 \\ 0 & r_r \end{bmatrix} \begin{bmatrix} i_s \\ i_r \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \Psi_s \\ \Psi_r \end{bmatrix} \tag{4.1}$$

4.1.2.2 Voltage and currents equations

The main inputs to the machine simulation are the stator a-b-c phase voltages, the excitation voltage applied to the field windings, and the applied mechanical torque to the rotor **[PI].**

Performing the transformation to qd0 reference frame of voltages yields:

$$\begin{aligned} v_q = \frac{2}{3}\Big\{ & v_a \cos(\theta_r(t)) + v_b \cos\left(\theta_r(t) - \frac{2\pi}{3}\right) \\ & + v_c \cos\left(\theta_r(t) + \frac{2\pi}{3}\right)\Big\} \end{aligned} \tag{4.2}$$

$$\begin{aligned} v_d = \frac{2}{3}\Big\{ & v_a \sin(\theta_r(t)) + v_b \sin\left(\theta_r(t) - \frac{2\pi}{3}\right) \\ & + v_c \sin\left(\theta_r(t) + \frac{2\pi}{3}\right)\Big\} \end{aligned} \tag{4.3}$$

$$v_0 = \frac{1}{3}(v_a + v_b + v_c) \tag{4.4}$$

The stator winding qd currents can be transformed back to abc winding currents using the following rotor to stationary qd, and stationary qd0 to abc transformations:

$$i_q^s = i_q \cos(\theta_r(t)) + i_d \sin(\theta_r(t)) \tag{4.5}$$

$$i_d^s = -i_q \sin(\theta_r(t)) + i_d \cos(\theta_r(t)) \tag{4.6}$$

$$i_a = i_q^s + i_0 \tag{4.7}$$

$$i_b = -\frac{1}{2}\, i_q^s - \frac{1}{\sqrt{3}} i_d^s + i_0 \tag{4.8}$$

$$i_c = -\frac{1}{2} i_q^s + \frac{1}{\sqrt{3}} i_d^s + i_0 \tag{4.9}$$

4.1.2.3 Power and torque equations

The expression for the electromagnetic torque developed by the machine can be obtained from the component of the input power that is transferred across the air-gap **[PI].** The generator power and the electromechanical torque are given in per unit by:

$$T_{em}(pu) = \Psi_d(pu) i_q(pu) - \Psi_q(pu) i_d(pu) \tag{4.10}$$

$$\begin{aligned} T_{mech}(pu) + T_{em}(pu) - T_{damp}(pu) &= 2H \frac{d\left(\frac{\omega_r - \omega_e}{\omega_b}\right)}{dt} \\ &= 2H \frac{d(\Delta\omega(pu))}{dt} \end{aligned} \tag{4.11}$$

$$\frac{d\delta_e}{dt} = \omega_r - \omega_e \tag{4.12}$$

$$\omega(pu) = \Delta\omega(pu) + 1 \tag{4.13}$$

$$T_{damp}(pu) = D\left(\frac{\omega_r - \omega_e}{\omega_b}\right) \tag{4.14}$$

$$P_g(pu) = Re\{(v_q - jv_d)(i_q - ji_d)^*\} = v_q i_q + v_d i_d \tag{4.15}$$

4.1.3 Transient model

The electromechanical oscillation frequency between synchronous generators in a power system typical lies between 0.5 to 3 Hz **[PV] [PVI].**

The stator winding equations are:

$$v_q = -r_s i_q - x'_d i_d + E'_q \tag{4.16}$$

$$v_d = -r_s i_d - x'_q i_q + E'_d \tag{4.17}$$

Rotor winding equations are:

$$T'_{do}\frac{dE'_q}{dt} = -E'_q - (x_d - x'_d)i_d + E_f \tag{4.18}$$

$$T'_{qo}\frac{dE'_d}{dt} = -E'_d - (x_q - x'_q)i_q \tag{4.19}$$

The torque and motion equation are:

$$T_{em} = E'_d i_d + E'_q i_q + (x'_q - x'_d)i_d i_q \tag{4.20}$$

$$2H\frac{d\left(\frac{\omega_r - \omega_e}{\omega_b}\right)}{dt} = T_{mech} - T_{em} - T_{damp} \tag{4.21}$$

4.2 Excitation system modelling

4.2.1 Introduction

The generator excitation system consists of an exciter and an Automatic Voltage Regulator (AVR) [28]. Fig 4.3 shows block diagram of simplified excitation system with Automatic Voltage Regulator AVR and Power System Stabilizer PSS [PVII] [33].

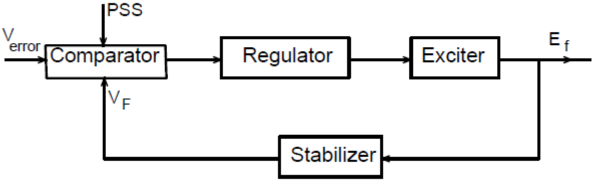

Fig 4.3 Block diagram of the Excitation System with AVR and PSS

4.2.2 Automatic voltage regulator AVR

The AVR regulates the generator terminal voltage by controlling the amount of current supplied to the generator field winding by the exciter. AVR consists of an error amplifier with limiter with whose function is to protect the AVR, exciter and generator from excessive voltages and currents [15] [22]. A power system stabilizer (PSS) is added to the AVR subsystem to help damp power swings in the system.

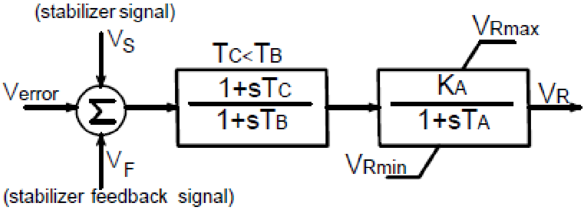

Fig 4.4 Regulator amplifier

4.2.3 Exciter system

Voltage of the field winding and armature winding in exciter are [33]:

$$v_f = i_f r_f + \frac{d\Psi_f(i_f)}{dt}, \quad v_x = f(i_f, i_x) \tag{4.22}$$

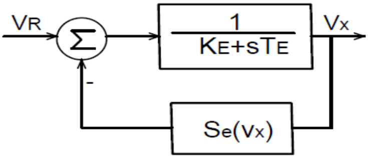

Fig 4.5 Exciter loop

4.2.4 Stabilizer

Stabilizer provides more phase margin in the open-loop frequency response of regulator/exciter loop. The transient gain reduction to counter negative damping can be achieved by adding a zero-pole compensator with a proper value of T_E or T_C and T_B [32].

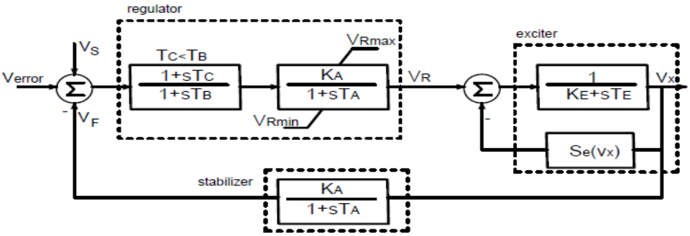

Fig 4.6 Stabilizer for the regulator/exciter loop

4.2.5 Power system stabilizer PSS

Power System Stabilizers (PSS) are used for many years to add damping to the electromechanical oscillations. The basic structure, modelling and performance of speed based stabilizers are illustrated in Fig. 4.7 [32].

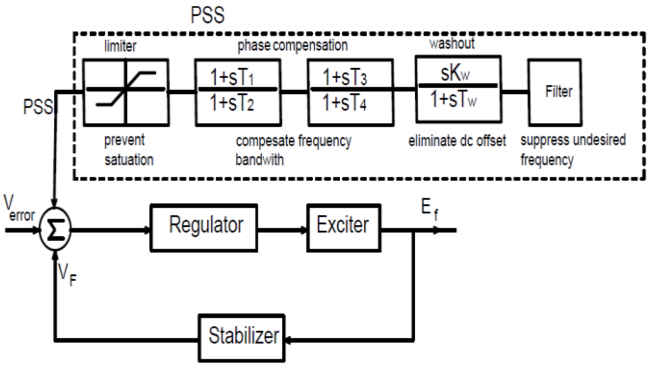

Fig 4.7 Power System Stabilizer

4.3 Network modelling

4.3.1 Transmission lines

The long line model involves partial differential equations which in some sense represent an infinite number of ordinary differential equations. For the line over 250km, the equivalent circuit of a transmission line must be considered in Fig.4.8 **[PVI].**

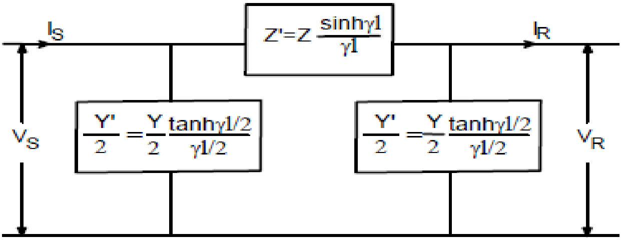

Fig. 4.8 Equivalent π-network of a long transmission line

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} (1+\frac{1}{2}Y'Z') & Z' \\ Y'(1+\frac{1}{4}Y'Z') & (1+\frac{1}{2}Y'Z') \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix} \tag{4.23}$$

4.3.2 Transformers

Transformers are generally used as inter-connecting and generator transformers. These transformers are usually with off-nominal-turns-ratio and are modelled as equivalent π circuit [31] as shown in Fig 4.9.

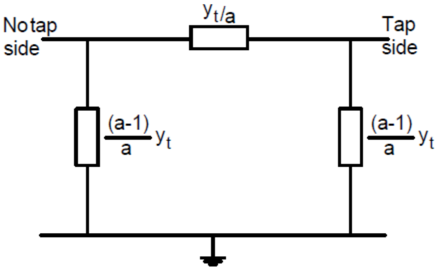

Fig. 4.9 Transformer model

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4.3.3 Loads

The load at bus is represent by an equivalent circuit as shown in Fig 4.10 **[PVII].**

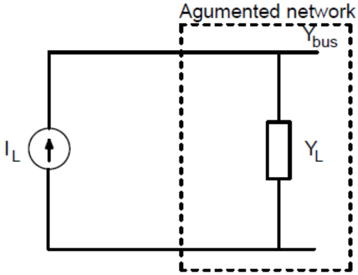

Fig. 4.10 Equivalent circuit of load

In the content of this work, the test network model includes two synchronous generators connected via two step-up transformers, long transmission line. Fig.4.11 shows the equivalent circuit of two-bus system with generators, transformer and loads at each bus.

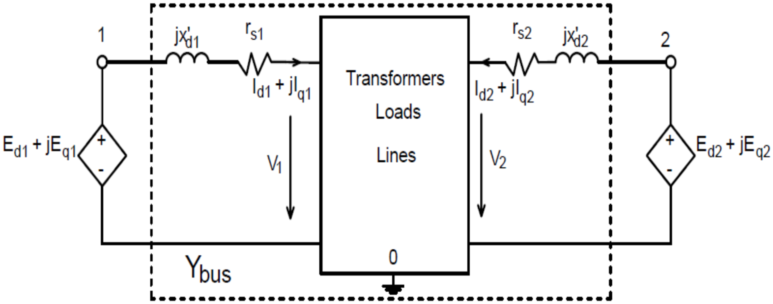

Fig.4.11 Equivalent circuit of system model

Chapter **5**

Results

5.1 Three Phase Synchronous Generator Steady-State Model

In this case the operation conditions are similar to conditions in which the generator is connected directly to infinite network given in Fig.5.1. The parameters of simulink model are given in appendix Tab.1.

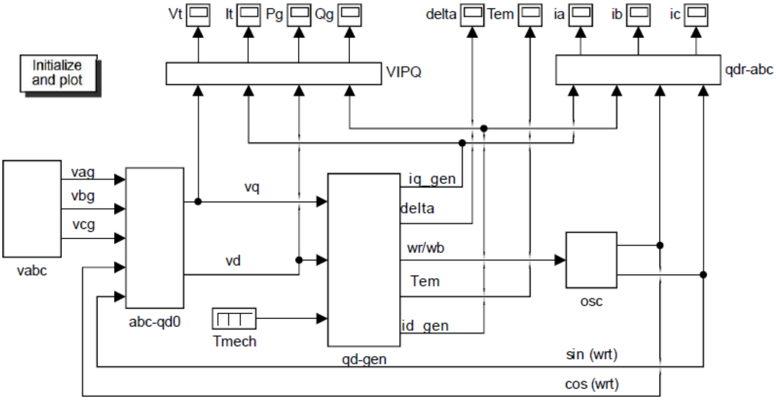

Fig.5.1 Three phase synchronous generator model

The simulation 1 is implemented when the mechanical torque of generator at 1 pu in the beginning of simulation, then decreasing in 0.8pu at time 0.2 seconds and finally 1pu at time 0.5 seconds until simulation end. The figure 5.2 and 5.3 show results of the electromechanical torque, speed, field current, active and reactive generating power, and phase a current in simulation 1 when changing the mechanical torque.

The field voltage implemented during simulation is constant at 1pu.

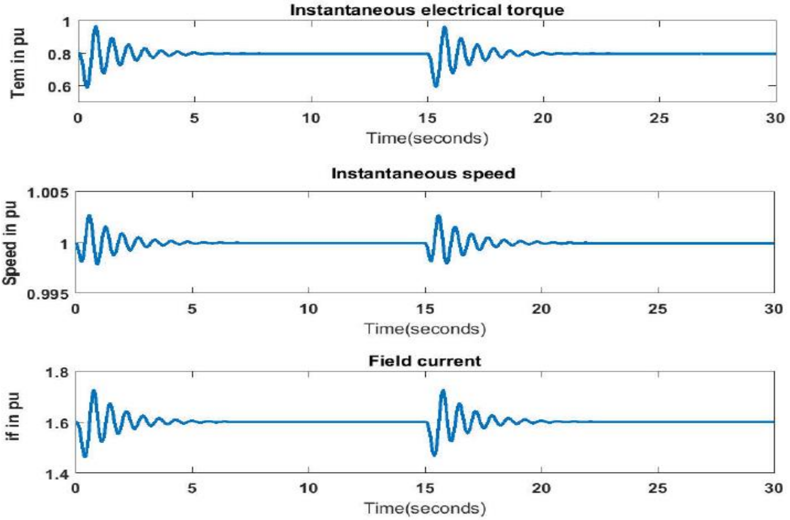

Fig. 5.2 Torque, speed and field current results of simulation 1 in pu

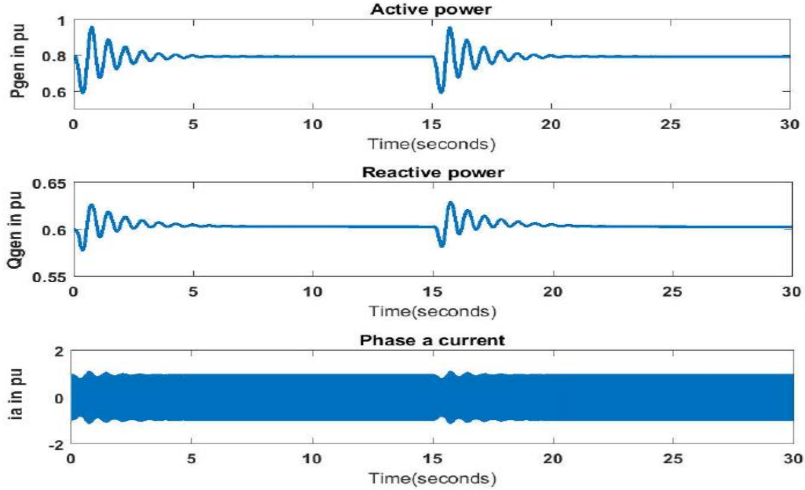

Fig. 5.3 Active power, reactive power and phase a current results of simulation 1 in pu

Figure 5.4 and 5.5 show results of the electromechanical torque, speed, field current, active and reactive generating power, and phase a current in simulation 2 when changing the field voltage implemented to field winding by 20% steps, that means implementing field voltage of 1 pu in the beginning of simulation, 1.2 pu at time 0.2 seconds and 1 pu at 2 seconds until simulation end.

The mechanical torque implemented during simulation is constants at 0.8 pu.

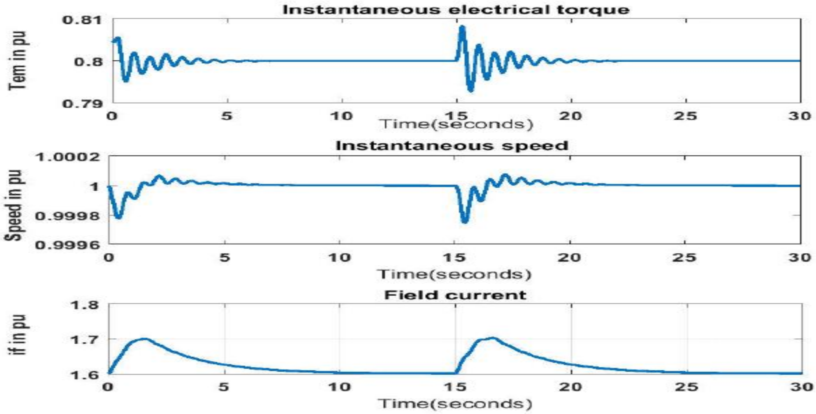

Fig. 5.4 Torque, speed and field current results of simulation 2 in pu

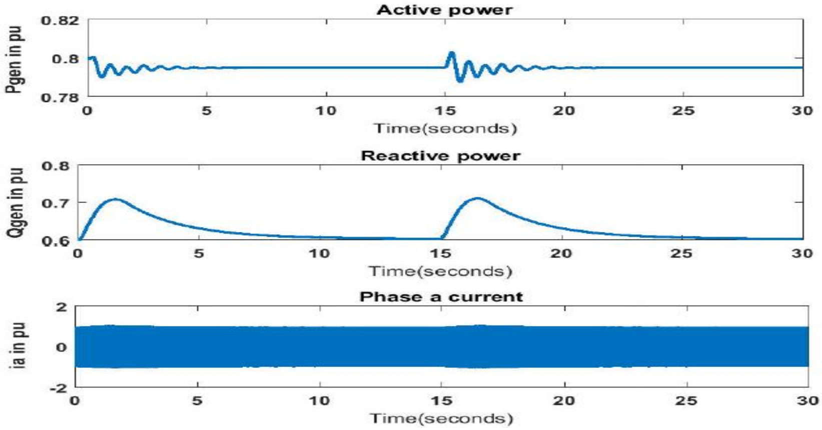

Fig. 5.5 Active power, reactive power and phase a current results of simulation 2 in pu

The results in simulation 1 and 2 showed that when changing the mechanical torque and the field voltage in small amount in steady state operation, the generating power and speed of generator do not oscillate so much and about 4 seconds they would be getting original stable state **[PVII].**

5.2 Synchronization of two three Phase Synchronous Generators in a small disturbance.

This section implements modelling the synchronization of two synchronous generator connected via parallel long lines in a small disturbance condition. The Fig.5.6 shows connected network model. Fig. 5.7 illustrates overall model of the two synchronous generators connected via transmission line. The parameters of simulink model are given in appendix Tab.1-Tab.4

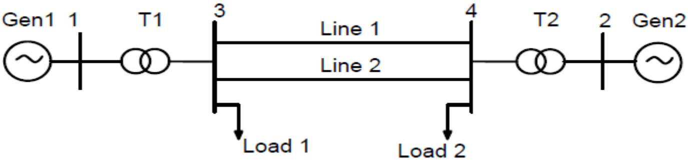

Fig. 5.6. Simulation network

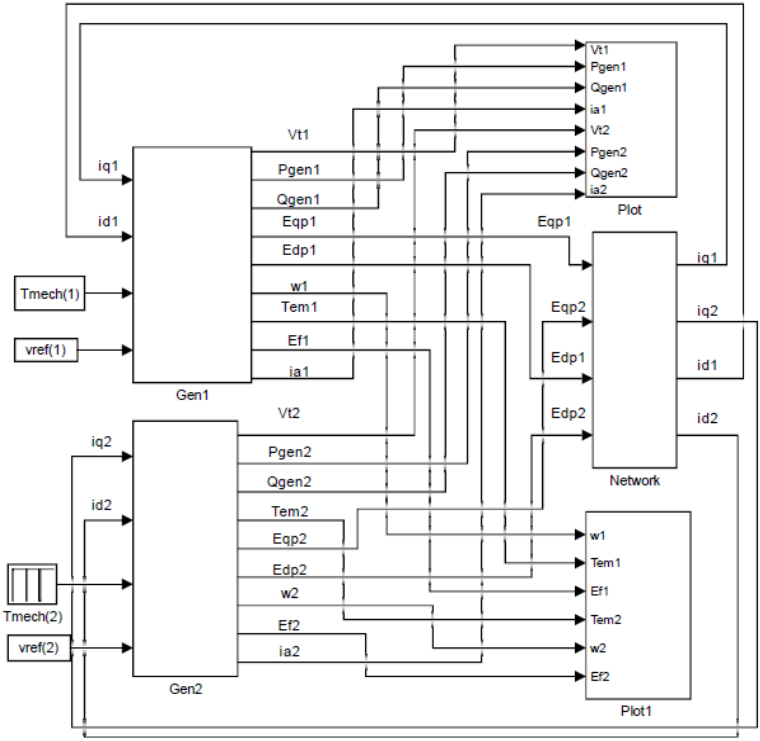

Fig. 5.7 The model of two synchronous generators via transmission line

The simulation is implemented when the mechanical torque of generator 2 at 1 pu in the beginning of simulation, then decreasing in 0 pu at time 0.2 seconds and finally 1pu at time 0.5 seconds until simulation end at time 15 seconds. The simulated results of the electromechanical torque, speed, field voltage, active and reactive generating power, phase a current and generator terminal voltage obtained in Fig.5.8-Fig.5.13 by changing transmission distances from 50 km to 1000 km.

-Case 1: L=50km

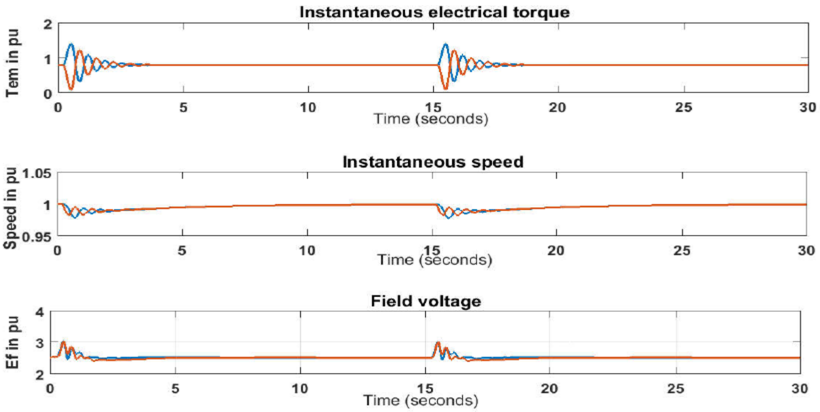

Fig. 5.8 Torque, speed and field voltage in pu

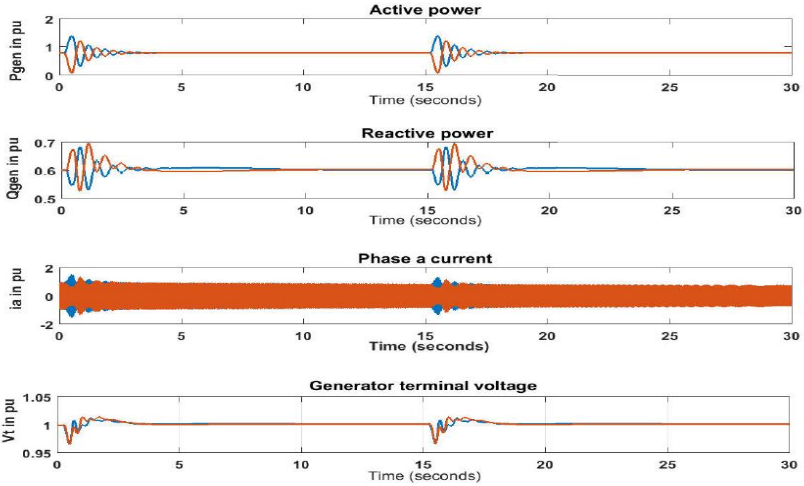

Fig.5.9 Active power, reactive power, phase a current and generator terminal voltage in pu

-Case 2: L=500km

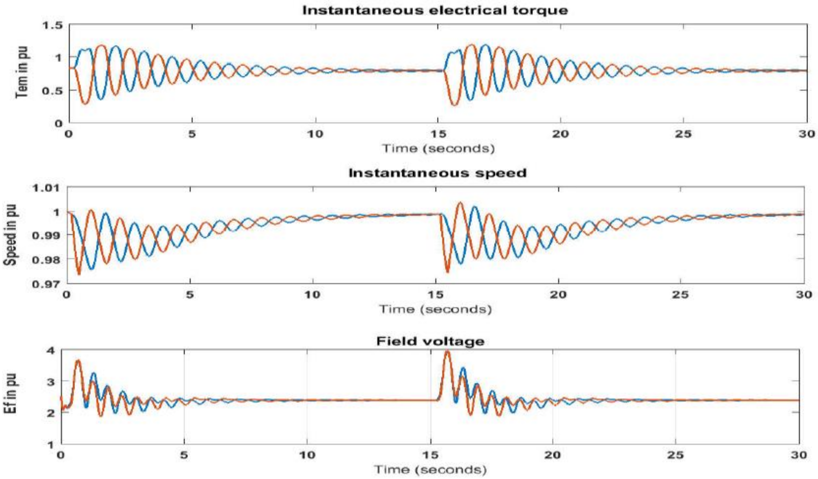

Fig.5.10 Torque, speed and field voltage in pu

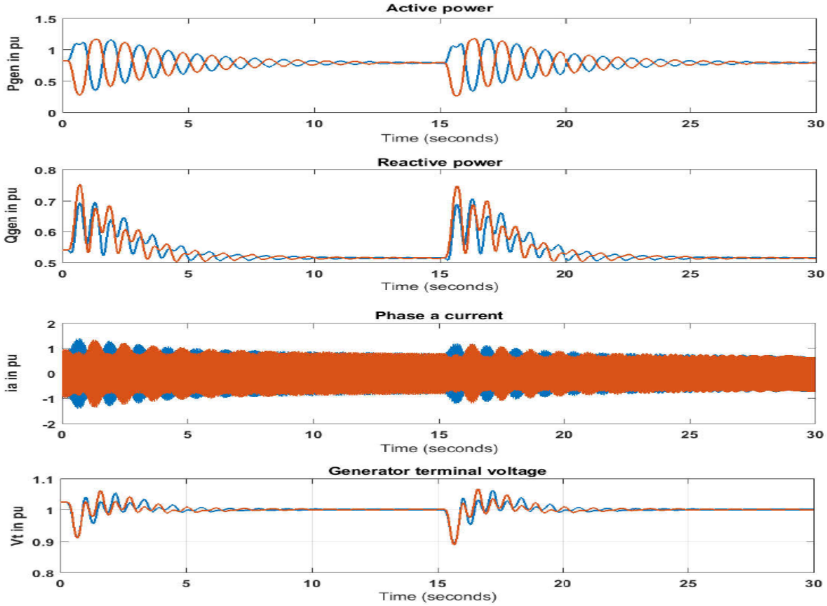

Fig. 5.11 Active power, reactive power, phase a current and generator terminal voltage in pu

-Case 3: L=1000km

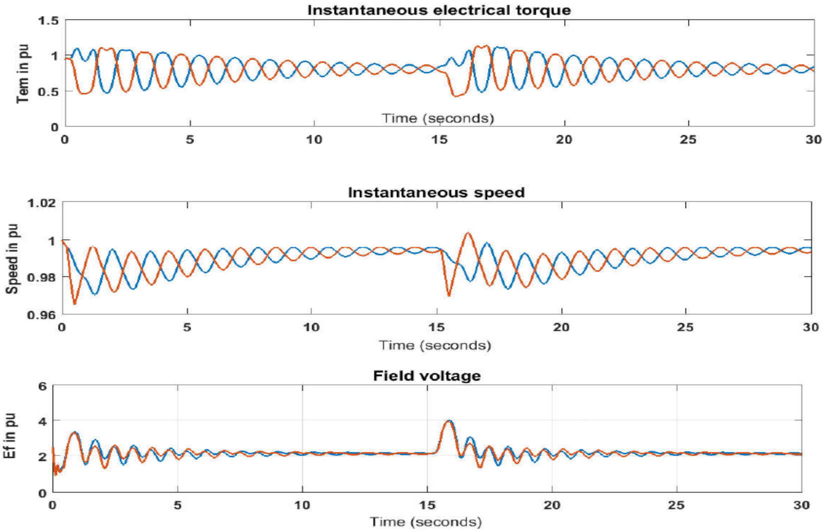

Fig. 5.12 Torque, speed and field voltage in pu

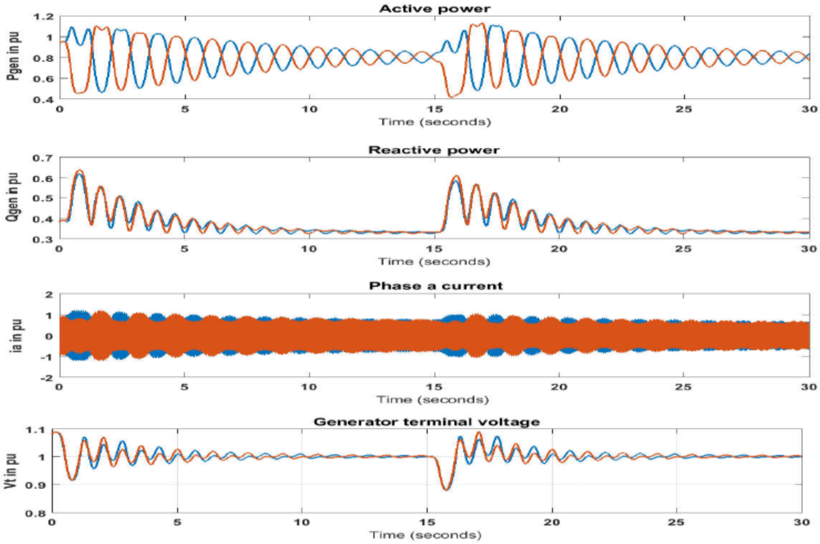

Fig. 5.13 Active power, reactive power, phase a current and generator terminal voltage in pu

Obviously, the longer transmission lines are, the more oscillate the speed and power transmission capacity of generators do. When the length of lines reach to 1000 km, there will exist a loss of synchronism between two generators through power and speed index **[PIII].**

5.3 Synchronization of two three Phase Synchronous Generators in a large disturbance

Three phase short circuit in the second line near bus 3 in system given in Fig. 5.14. The parameters of simulink model are given in appendix Tab.1-Tab.4

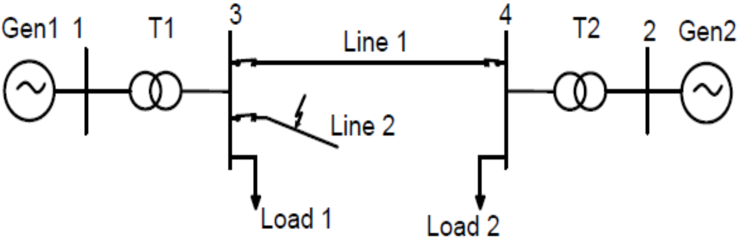

Figure 5.14 Short circuit in Line 2 near bus 3 in system

The implementation of system simulation is a combination of the change of mechanical torque T_{mech} in generator 1 and three phase short circuit in Line 2. In this case, the system operates with only Line 1 and all transferred powers between two generators make stress to Line 1.

The mechanical torque of generator 1 at 1 pu in the beginning of simulation, then increasing in 1.01 pu at time 0.2 seconds and finally 1pu at time 0.4 seconds until simulation end at time 30 seconds. Similarly, simulation in section 5.2, the synchronism analyses of two generators and transmission capacity of power line under large disturbance are investigated through changing of power line distance from 50 km to 500 km.

-Case 1: L=50 km

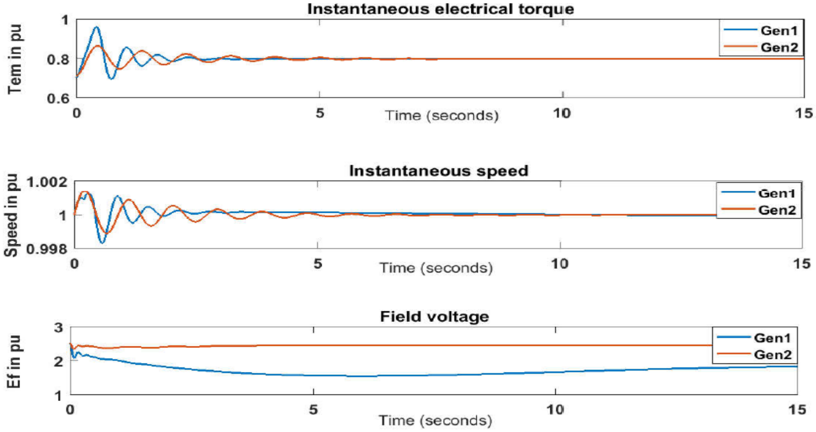

Fig. 5.15 Torque, speed and field voltage in pu

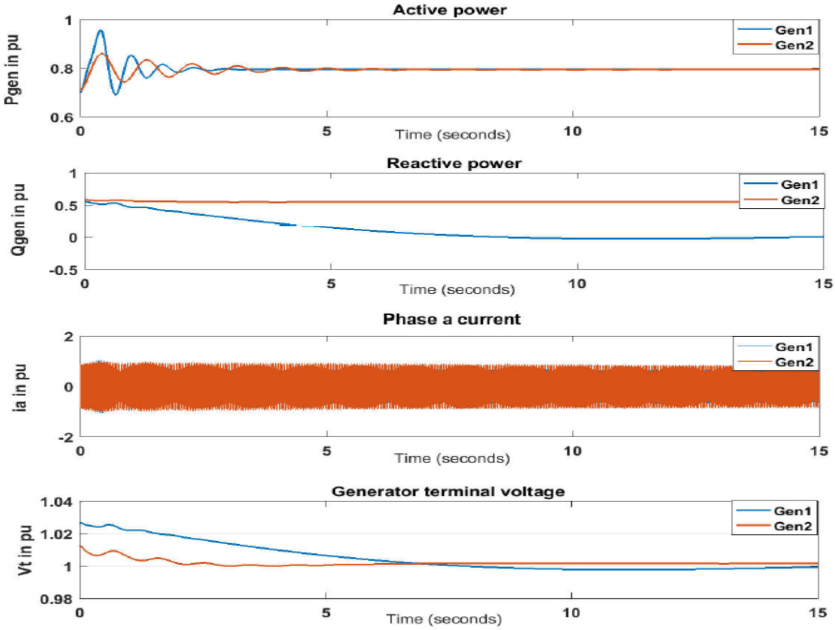

Fig. 5.16 Active power, reactive power, phase a current and generator terminal voltage in pu

-Case 2: L=500 km

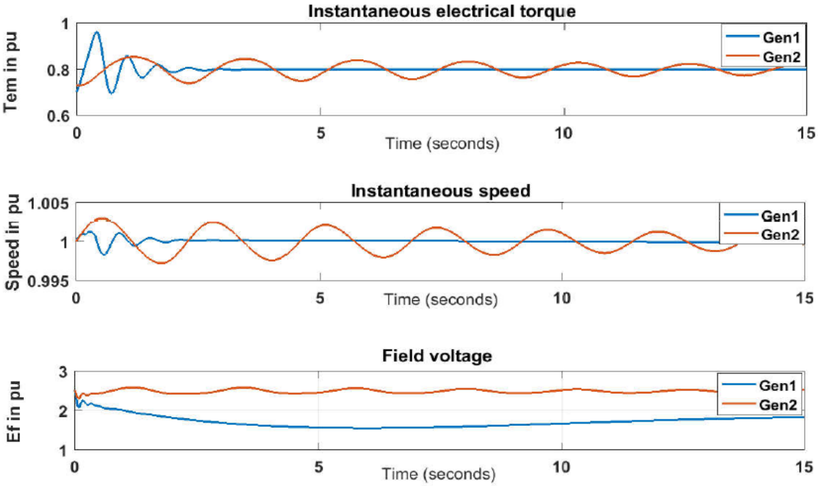

Fig. 5.17 Torque, speed and field voltage in pu

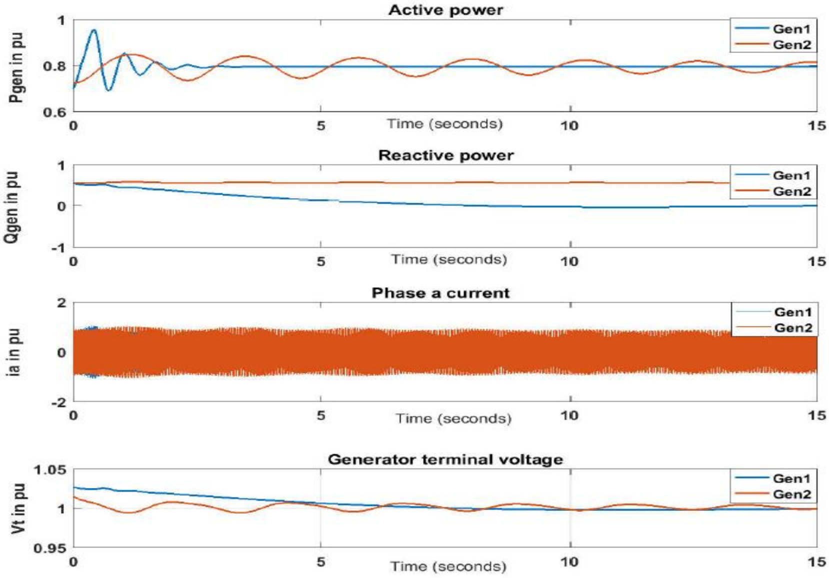

Fig. 5.18 Active power, reactive power, phase a current and generator terminal voltage in pu

The presented results in above show that when three phase fault at one of parallel operation lines, the change of mechanical torque in generator 1 and the length of line reached to more than 200 km, there is a loss of synchronism between two generators **[PII] [PIV].** It is necessary to find out some how to improve this un-synchronization in system.

Chapter **6**

Practical Design

In the content of this work a proposed improved method for increasing transfer capacity of lines is change of connected network model. The one-line diagram of a sixteen-bus system shown in Fig.6.1 is a meshed network which consists of a number of internally well-mesh sub-systems connected by the same relatively weak tie-lines. This situation is typical of an interconnected system. The weakness of connections may lead to asynchronous rotations in tie-lies following a disturbance. Therefore, the interconnected system is important role in improving reliability and stability of power system compared to previous test system **[PII][PIII][PIV].**

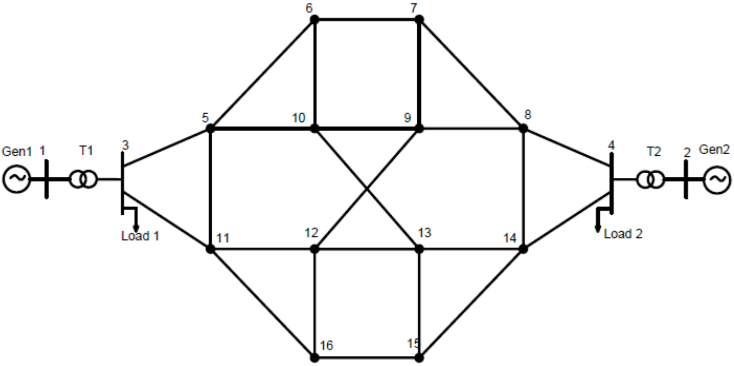

Figure 6.1 Two generators connected via the mesh network

6.1 Steady state operation

The Fig.6.2 shows the network model of the sample power system prepared on the above lines after lumping the shunt admittances Y/2 at the buses. The equivalent power source at each bus is represented by a shaded circle. The equivalent power source at the i^{th} bus injects current I_i into the bus. It may be observed that the structure of power system is such that all the sources are always connected to a common ground node. Besides the ground node, there are two other nodes (buses) at which the current from the sources is injected into the network. The line admittance between nodes i and k is depicted by $y_{ik}=y_{ki}=1/z_{ik}$. Further, the mutual admittance between lines is assumed to be zero.

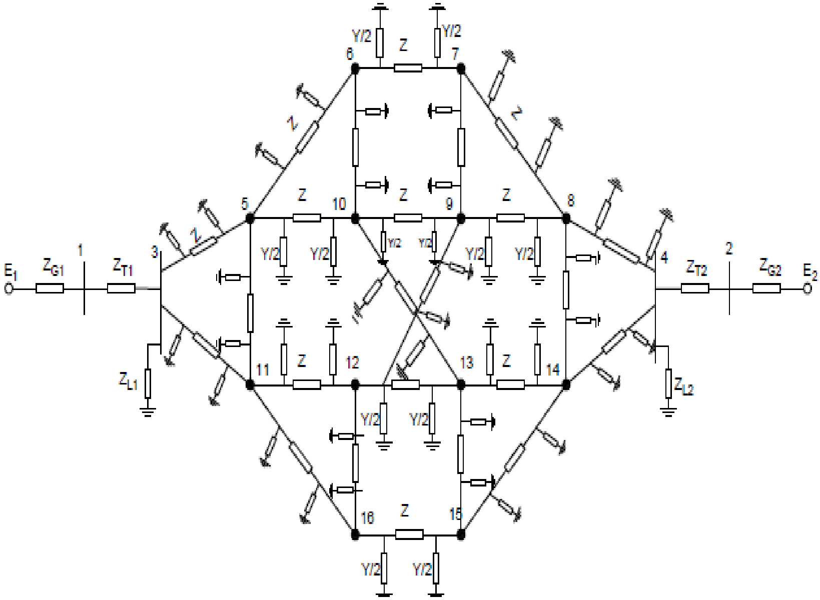

Fig. 6.2 Equivalent diagram of two generators connected via the mesh network

The results of the electromechanical torque, speed, field voltage, active and reactive generating power, phase a current and generator terminal voltage are given in Fig.6.3 and Fig.6.4. Compared with results of system model with two power lines L1 and L2 in previous chapter, the proposed mesh network with 16 buses decreases the oscillation of output significantly and improves stability of system.

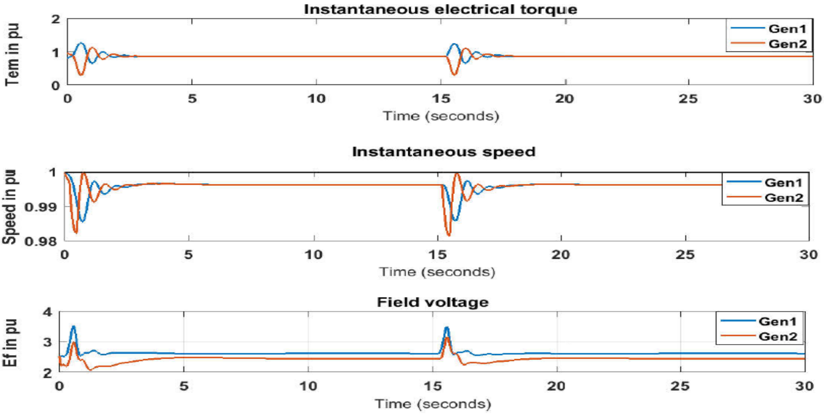

Fig. 6.3 Torque, speed and field voltage in pu

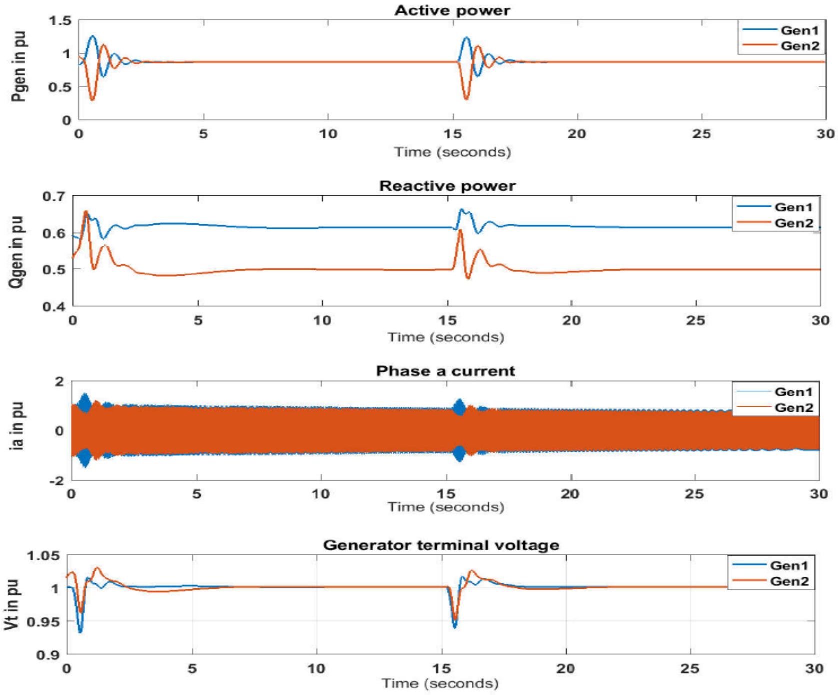

Fig.6.4 Active power, reactive power, phase a current and generator terminal voltage in pu

6.2 Three phase short circuit at line 3-11

Assume that there is a three phase short circuit in only line 3-11 near bus 3 given in Fig.6.5. The calculation of parameters of system is implemented similarly in (6.1). The results of the electromechanical torque, speed, field voltage, active and reactive generating power, phase a current and generator terminal voltage are given in Fig.6.6 and Fig.6.7. Compared with results of system model operating in only power lines L1 and short circuit in line L2 in previous chapter, the proposed mesh network with 16 buses improves stability and reliability of system with a short time response under disturbance condition.

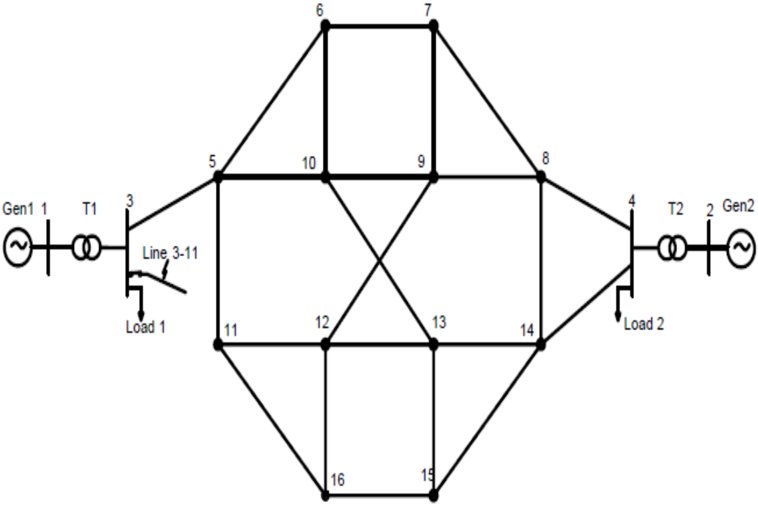

Fig. 6.5 Two generators connected via the mesh network when short circuit on line 3-11

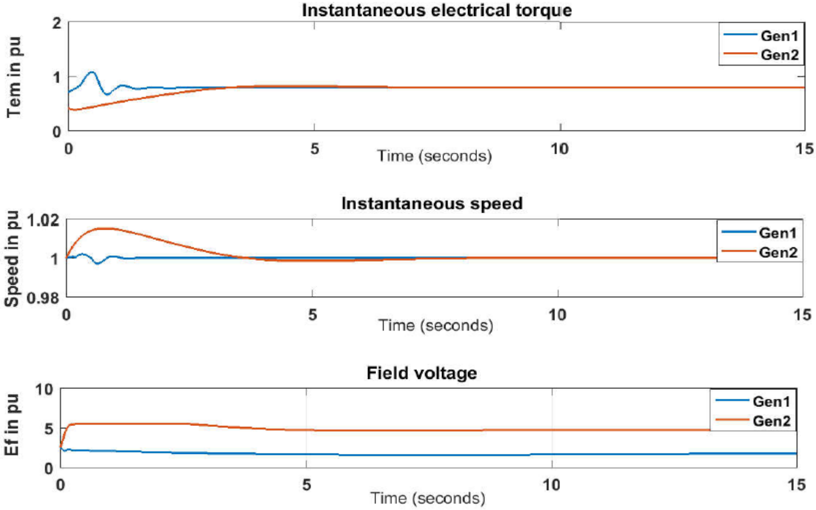

Fig. 6.6 Torque, speed and field voltage in pu

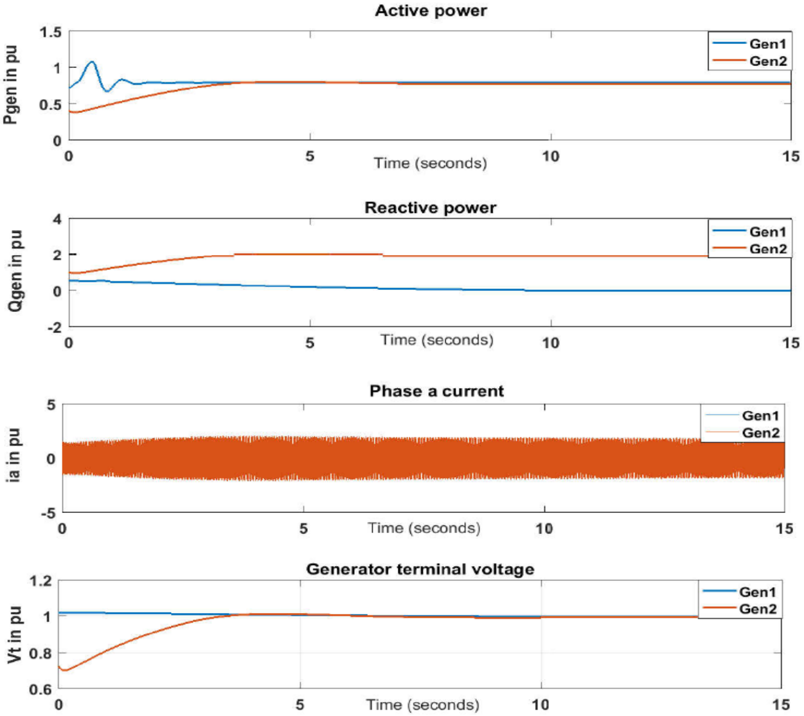

Fig. 6.7 Active power, reactive power, phase a current and generator terminal voltage in pu

Chapter **7**

Conclusion

The following conclusions are made:

- The synchronous machine models have been documented and explained in detail in this technical thesis, including the steady-state operation and transient operation.
- The two synchronous machine fundamental frequency models, connected via the long transmission lines, have been analyzed in synchronization in term of transient stability.
- Influence of length of line to the system oscillation is analyzed and determined as the important index of stability.

In this work, the modeled system consists of synchronous generator with excitation system and connected network model with transformer, transmission line and loads.

Two synchronous generator models, steady state model and transient model, were simulated using qd rotating reference frame. The modeled generator is connected to transmission line, Thevenin’s equivalent circuit was considered to represent the generator connection. A transient stability study during three phase fault at power line was performed, and the effect of using power system stabilizer on the system stability was discussed. The MATLAB library was used to simulate the network and to build up a data acquisition of system.

In this work, the method of change of connected network was investigated to get more stable and reliable system operation **[PVII].**

To optimize a very long distance transmission line, a more fundamental and open approach is given in this work. Instead of reactive compensation with high cost and technique requirements, the idea to restructure the network by a mesh network topology was shown. Each node in mesh network cooperates in the relaying of data or information in the network. The advantage of this mesh network followed as: A broken node won’t distract the transmission of data in a mesh network. Each node is connected to several other nodes which make it easier to relay data. A broken device will be ignored by the signals and will then find a new one that is connected with the node. Additional devices in a mesh topology will not affect its network connection. Hence it will improve the traffic in the network. Mesh topology makes a large data center that simulates useful information to its nodes. A mesh topology can also handle high amount of network traffic since every additional device into the network is considered a node. Interconnected devices can simultaneously transfer data smoothly and will not complicate the network connection. Based on all above discussion, the mesh network topology should be considered as the first criteria for decreasing the loss of synchronism and improving stability of network.

This thesis studied the system behavior when connecting two synchronous generators through long transmission line under steady state and transient operation. The chosen part of the power system to apply was synchronous generator, transformer, transmission line and load.

The electric transmission system plays a critical role in the stability of power system. It is an ever-changing system both in physical terms and how it is operated and regulated. These changes must be recognized and actions developed accordingly. The transmission components continue to get older and investment is not keeping up with needs when looking over a future horizon. Technology development and application undoubtedly will create a new look and advance methods to combat the congestion issues and increased electrical demand and new overhead or restructure of transmission lines will be only one of the solutions considered. In the other hand, DC (direct) transmission system is also optimal solution for improving transmission capacity and stability of power system.

In terms of measurement technique, extensive and powerful tools to facilitate the gathering of information on all aspects regarding system stability is possible through implementation of Phasor Measurement Unit (PMU) **[PIII] [PIV] [PVI].** Relay functions of PMU installed in two ends of transmission line. PMU measurements at both ends will provide voltages (magnitude and angle) and currents (magnitude and angle) in real time. They help for collecting data in global and overcoming disturbances occurred in system in limited time. Hence the behavior or characteristics of the power line is an excellent candidate for representation of system/network synchronism or stability.

In future work, the following paragraphs could be considered: that would be important for further refinement in the restructure to widen networks, in the improvement control system **[PVII]** and in application of DC transmission system. Having a reliable, regional, uncongested transmission system will enable to ensure stability of system.

APPENDIX– SIMULATED SYSTEM PARAMETERS

Tab. 1: Synchronous generator parameters used in simulation

Parameter	**Value in SI unit**	**Value in per unit**
S	889 x 10^6 VA	0.889
cosφ	0.9	0.9
V	18 x 10^3 V	1
f	50Hz	1
Poles	2	2
r_s	0.0015 Ω	0.0048
x_{ls}	0.066 Ω	0.215
x_d	0.555 Ω	1.79
x_q	0.514 Ω	1.66
x'_d	0.11 Ω	0.355
x'_q	0.177 Ω	0.57
T'_{d0}	5.032 s	7.9
T'_{q0}	0.261 s	0.41
H	4.5 sW/VA	4
D	2	2

Tab. 2: Excitation system parameters

Parameter	**Value in SI unit**	**Value in per unit**
T_A	0.06 s	0.06
K_A	50	50
T_E	0.052 s	0.052
K_E	-0.0465	-0.0465
K_F	0.0832	0.0832
T_F	1 s	1.0
V_{Rmax}	18 x 10^3 V	1
V_{Rmin}	-18 x 10^3 V	-1
A_{ex}	0.0012	0.0012
B_{ex}	1.264	1.264

Tab. 3: Voltage stabilizer parameters

Parameter	**Value in SI unit**	**Value in per unit**
T_A	0.06 s	0.06
K_A	50	50
T_E	0.052 s	0.052
K_E	-0.0465	-0.0465
K_F	0.0832	0.0832
T_F	1 s	1.0
V_{Rmax}	18 x 10^3 V	1

Tab. 4: Transformer, load and line parameters

Parameter	**Value in SI unit**	**Value in per unit**
Transformer	450×10^{6} VA/10%	0.45
Transformer voltage	$18/230 \times 10^{3}$ V	1
Load	$(750+j580) \times 10^{6}$ VA	0.75+j0.58
Line impedance	$(0.045+j0.44) \times 10^{-3}$ Ω/m	0.004+j0.0042
Line susceptance	3.6×10^{-9} S/m	3.8×10^{-4}

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