Лабораторная работа №4
Устойчивость электропередачи, оборудованной поперечной компенсацией

Цель работы:
Исследование характеристик поперечно компенсированной линии электропередачи

Теоретическая часть

Power system stability may be broadly defined as that property of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance.

Instability in a power system may be manifested in many different ways depending on the system configuration and operating mode. Traditionally, the stability problem has been one of maintaining synchronous operation. Since power systems rely on synchronous machines for generation of electrical power, a necessary condition for satisfactory system operation is that all synchronous machines remain in synchronism or, colloquially, “in step.” This aspect of stability is influenced by the dynamics of generator rotor angles and power-angle relationships.

Instability may also be encountered without loss of synchronism. For example, a system consisting of a synchronous generator feeding an induction motor load through a transmission line can become unstable because of the collapse of load voltage. Maintenance of synchronism is not an issue in this instance; instead, the concern is stability and control of voltage. This form of instability can also occur in loads covering an extensive area supplied by a large system.

In the evaluation of stability the concern is the behaviour of the power system when subjected to a transient disturbance. The disturbance may be small or large. Small disturbances in the form of load changes take place continually, and the system adjusts itself to the changing conditions. The system must be able to operate satisfactorily under these conditions and successfully supply the maximum amount of load. It must also be capable of surviving numerous disturbances of a severe nature, such as a short-circuit on a transmission line, loss of a large generator or load, or loss of a tie between two subsystems. The system response to a disturbance involves much of the equipment. For example, a short-circuit on a critical element followed by its isolation by protective relays will cause variations in power transfers, machine rotor speeds, and bus voltages; the voltage variations will actuate both generator and transmission system voltage regulators; the speed variations will actuate prime mover governors; the change in tie line loadings may actuate generation controls; the changes in voltage and frequency will affect loads on the system in varying degrees depending on their individual characteristics. In addition, devices used to protect individual equipment may respond to variations in system variables and thus affect the system performance. In any given situation, however, the responses of only a limited amount of equipment may be significant. Therefore, many assumptions are usually made to simplify the problem and to focus on factors influencing the specific type of stability problem. The understanding of stability problems is greatly facilitated by the classification of stability into various categories.

The following sections will explore different forms of power system instability and associated concepts by considering, where appropriate, simple power system configurations. Analysis of such systems using idealized models will help identify fundamental properties of each form of stability problem.

1.1 Rotor Angle Stability

Rotor angle stability is the ability of interconnected synchronous machines of a power system to remain in synchronism. The stability problem involves the study of the electromechanical oscillations inherent in power systems. A fundamental factor in this problem is the manner in which the power outputs of synchronous machines vary as their rotors oscillate. A brief discussion of synchronous machine characteristics is helpful as a first step in developing the related basic concepts.

Synchronous machine characteristic

A synchronous machine has two essential elements: the field and the armature. Normally, the field is on the rotor and the armature is on the stator. The field winding is excited by direct current. When the rotor is driven by a prime mover (turbine), the rotating magnetic field of the field winding induces alternating voltages in the three-phase armature windings of the stator. The frequency of the induced alternating voltages and of the resulting currents that flow in the stator windings when a load is connected depends on the speed of the rotor. The frequency of the stator electrical quantities is thus synchronized with the rotor mechanical speed: hence the designation “synchronous machine.”

When two or more synchronous machines are interconnected, the stator voltages and currents of all the machines must have the same frequency and the rotor mechanical speed of each is synchronized to this frequency. Therefore, the rotors of all interconnected synchronous machines must be in synchronism.

The physical arrangement (spatial distribution) of the stator armature windings is such that the time-varying alternating currents flowing in the three-phase windings produce a rotating magnetic field that, under steady-state operation, rotates at the same speed as the rotor. The stator and rotor fields react with each other and an electromagnetic torque results from the tendency of the two fields to align themselves. In a generator, this electromagnetic torque opposes rotation of the rotor, so that mechanical torque must be applied by the prime mover to sustain rotation. The electrical torque (or power) output of the generator is changed only by changing the mechanical torque input by the prime mover. The effect of increasing the mechanical torque input is to advance the rotor to a new position relative to the revolving magnetic field of the stator. Conversely, a reduction of mechanical torque or power input will retard the rotor position. Under steady-state operating conditions, the rotor field and the revolving field of the stator have the same speed. However, there is an angular separation between them depending on the electrical torque (or power) output of the generator.

In a synchronous motor, the roles of electrical and mechanical torques are reversed compared to those in a generator. The electromagnetic torque sustains rotation while mechanical load opposes rotation. The effect of increasing the mechanical load is to retard the rotor position with respect to the revolving field of the stator.

In the above discussion, the terms torque and power have been used interchangeably. This is common practice in the power system stability literature, since the average rotational velocity of the machines is constant even though there may be small momentary excursions above and below synchronous speed. The per unit values of torque and power are, in fact, very nearly equal.

Power versus angle relationship

An important characteristic that has a bearing on power system stability is the relationship between interchange power and angular positions of the rotors of synchronous machines. This relationship is highly nonlinear. To illustrate this let us consider the simple system shown in Figure 1(a). It consists of two synchronous machines connected by a transmission line having an inductive reactance XL but negligible resistance and capacitance. Let us assume that machine 1 represents a generator feeding power to a synchronous motor represented by machine 2.

The power transferred from the generator to the motor is a function of angular separation (6) between the rotors of the two machines. This angular separation is due to three components: generator internal angle δ_G (angle by which the generator rotor leads the revolving field of the stator); angular difference between the terminal voltages of the generator and motor (angle by which the stator field of the generator leads that of the motor); and the internal angle of the motor (angle by which the rotor lags the revolving stator field). Figure 2.1(b) shows a model of the system that can be used to determine the power versus angle relationship. A simple model comprising an internal voltage behind an effective reactance is used to represent each synchronous machine. The value of the machine reactance used depends on the purpose of the study. For analysis of steady-state performance, it is appropriate to use the synchronous reactance with the internal voltage equal to the excitation voltage. The basis for such a model and the approximations associated with it are presented in Chapter 3.

A phasor diagram identifying the relationships between generator and motor voltages is shown in Figure 2.1(c). The power transferred from the generator to the motor is given by

$$P = \frac{E_G E_M}{X_T}\sin\delta \quad , \qquad \text{were} \qquad X_T = X_G + X_L + X_M \qquad (1)$$

The corresponding power versus angle relationship is plotted in Figure 1(d). With the somewhat idealized models used for representing the synchronous machines, the power varies as a sine of the angle: a highly nonlinear relationship. With more accurate machine models including the effects of automatic voltage regulators, the variation in power with angle would deviate significantly from the sinusoidal relationship; however, the general form would be similar. When the angle is zero, no power is transferred. As the angle is increased, the power transfer increases up to a maximum. After a certain angle, nominally 90°, a further increase in angle results in a decrease in power transferred. There is thus a maximum steady-state power that can be transmitted between the two machines. The magnitude of the maximum power is directly proportional to the machine internal voltages and inversely proportional to the reactance between the voltages, which includes reactance of the transmission line connecting the machines and the reactances of the machines.

When there are more than two machines, their relative angular displacements affect the interchange of power in a similar manner. However, limiting values of power transfers and angular separation are a complex function of generation and load distribution. An angular separation of 90° between any two machines (the nominal limiting value for a two-machine system) in itself has no particular significance.

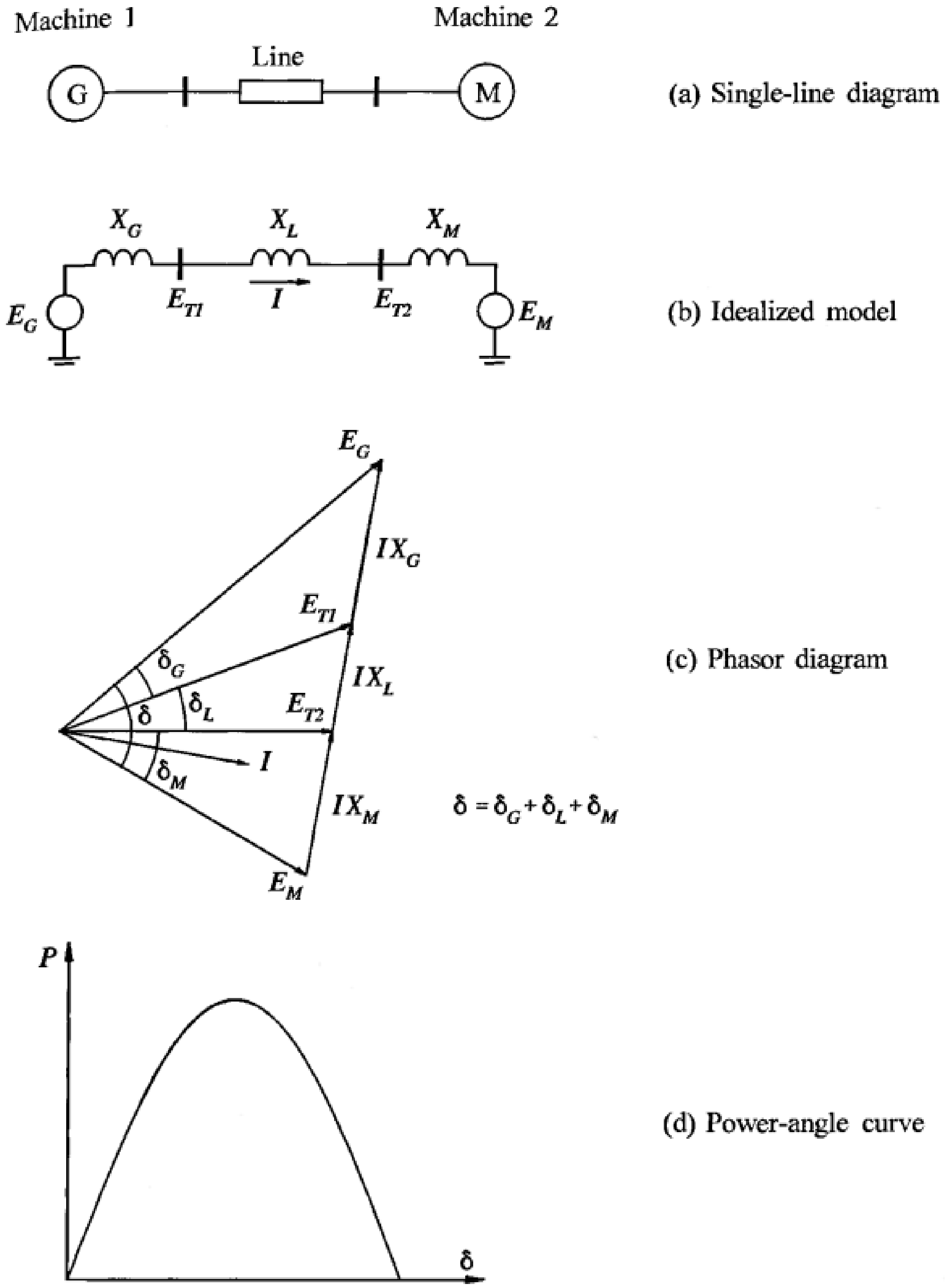


Figure 1 – Power transfer characteristic of a two-machine system

The power stability phenomena

Stability is a condition of equilibrium between opposing forces. The mechanism by which interconnected synchronous machines maintain synchronism with one another is through restoring forces, which act whenever there are forces tending to accelerate or decelerate one or more machines with respect to other machines. 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 the system is perturbed this equilibrium is upset, resulting in acceleration or deceleration of the rotors of the machines according to the laws of motion of a rotating body. 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 the fast machine, depending on the power-angle relationship. This tends to reduce the speed difference and hence the angular separation. The power-angle relationship, as discussed above, is highly nonlinear. Beyond a certain limit, an increase in angular separation is accompanied by a decrease in power transfer; this increases 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.

When a synchronous machine loses synchronism or “falls out of step” with the rest of the system, its rotor runs at a higher or lower speed than that required to generate voltages at system frequency. The “slip” between rotating stator field (corresponding to system frequency) and the rotor field results in large fluctuations in the machine power output, current, and voltage; this causes the protection system to isolate the unstable machine from the system.

Loss of synchronism can occur between one machine and the rest of the system or between groups of machines. In the latter case synchronism may be maintained within each group after its separation from the others.

The synchronous operation of interconnected synchronous machines is in some ways analogous to several cars speeding around a circular track while joined to each other by elastic links or rubber bands. The cars represent the synchronous machine rotors and the rubber bands are analogous to transmission lines. When all the cars run side by side, the rubber bands remain intact. If force applied to one of the cars causes it to speed up temporarily, the rubber bands connecting it to the other cars will stretch; this tends to slow down the faster car and speed up the other cars. A chain reaction results until all the cars run at the same speed once again. If the pull on one of the rubber bands exceeds its strength, it will break and one or more cars will pull away from the other cars.

With electric power systems, the change in electrical torque of a synchronous machine following a perturbation can be resolved into two components:

$$\Delta T_e = T_S \Delta\delta + T_D \Delta\omega \qquad \textbf{(2)}$$

where

T_S Δω is the component of torque change in phase with the rotor angle perturbation Д6 and is referred to as the synchronizing torque component; **T_S** is the synchronizing torque coefficient.

$\mathbf{T_D \Delta\omega}$ is the component of torque in phase with the speed deviation $\mathbf{\Delta\omega}$ and is referred to as the damping torque component; $\mathbf{T_D}$ is the damping torque coefficient.

System stability depends on the existence of both components of torque for each of the synchronous machines. Lack of sufficient synchronizing torque results in instability through an aperiodic drift in rotor angle. On the other hand, lack of sufficient damping torque results in oscillatory instability.

For convenience in analysis and for gaining useful insight into the nature of stability problems, it is usual to characterize the rotor angle stability phenomena in terms of the following two categories:

- Small-signal (or small-disturbance) stability is the ability of the power system to maintain synchronism under small disturbances;
- Transient stability is the ability of the power system to maintain synchronism when subjected to a severe transient disturbance.

Small-signal stability enhancement

FACTS devices can be used to improve a stability of transmission. Consider the power transmission between two interconnected power systems. According with (1), a transferred power of it transmission decreases after angle 90° for non-compensated transmission (figure 4, curve 1).

If to set a FACTS device in the middle of the line, it allows to maintaining the voltage at the constant value. In this case we can image the power transmission as two individual lines. Each line has half of length and reactance with respect of initial case. So according with (1) we can explain power transfer characteristic as a second curve on figure 4.

But there are some problems in this case. FACTS devices are very expensive, and its have limited reactive power. That is why we can obtain 3–6 characteristics on figure 4:

curve 3, 4 – with first generation FACTS devices;

curve 5, 6 – with second generation FACTS devices.

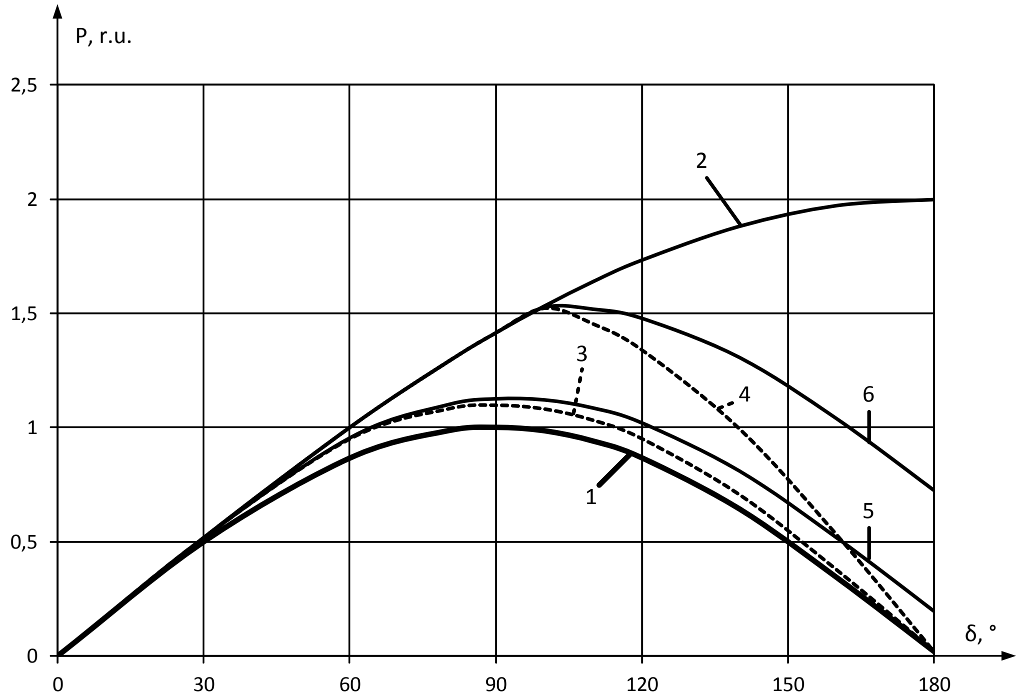


Figure 4 – Power transfer characteristics of shunt compensated power transmission

2. Практическая часть

1) Соберите модель поперечно компенсированной электропередачи в Matlab/Simulink, как показано на рисунке 5. Задайте параметры блоков в соответствии с приложением и таблицей 2.
2) Рассчитайте индуктивность и активное сопротивление линии электропередачи в соответствии с вариантом (таблица 3).
3) При заданной первой (таблица 2) номинальной мощности преобразователя (convertor rating) установите поочередно различные значения угля электропередачи δ = 0°, 30°, 60°, 90°, 120°, 150°, 180° (в блоке "Three-phase programmable voltage source"). Рассчитайте мощность потерь в электропередачи. Запишите полученные результаты в таблицу 1.
4) Повторите пункт 3 для других значений for other convertor rating value.
5) Постройте следующие диаграммы для различных номинальных мощностей преобразователя:
   a. P1(δ), Q1(δ), P2(δ), Q2(δ), ΔP(δ);
   b. U(δ).

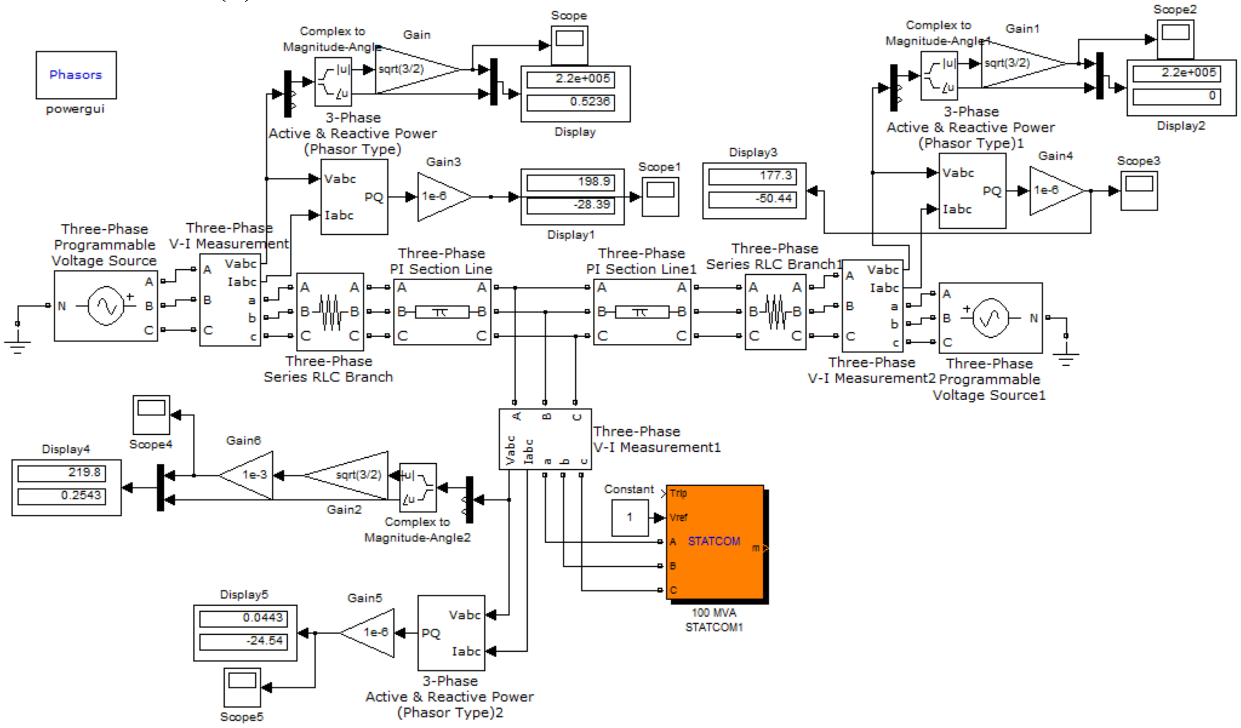


Figure 5 – Matlab model review of Shunt compensated power transmission

Table 1

Angle, degree	First system		Second system		Compensator		Power loss of transmission ΔP, MW
	Active power P1, MW	Reactive power Q1, MVar	Active power P1, MW	Reactive power, MVar	Reactive power Q1, MVar	Voltage, kV	
0							
30							
60							

90							
120							
150							
180							

Power loss can be obtained as

$$\Delta P = P1 - P2$$

Parameters by variants

Table 2 – Variants

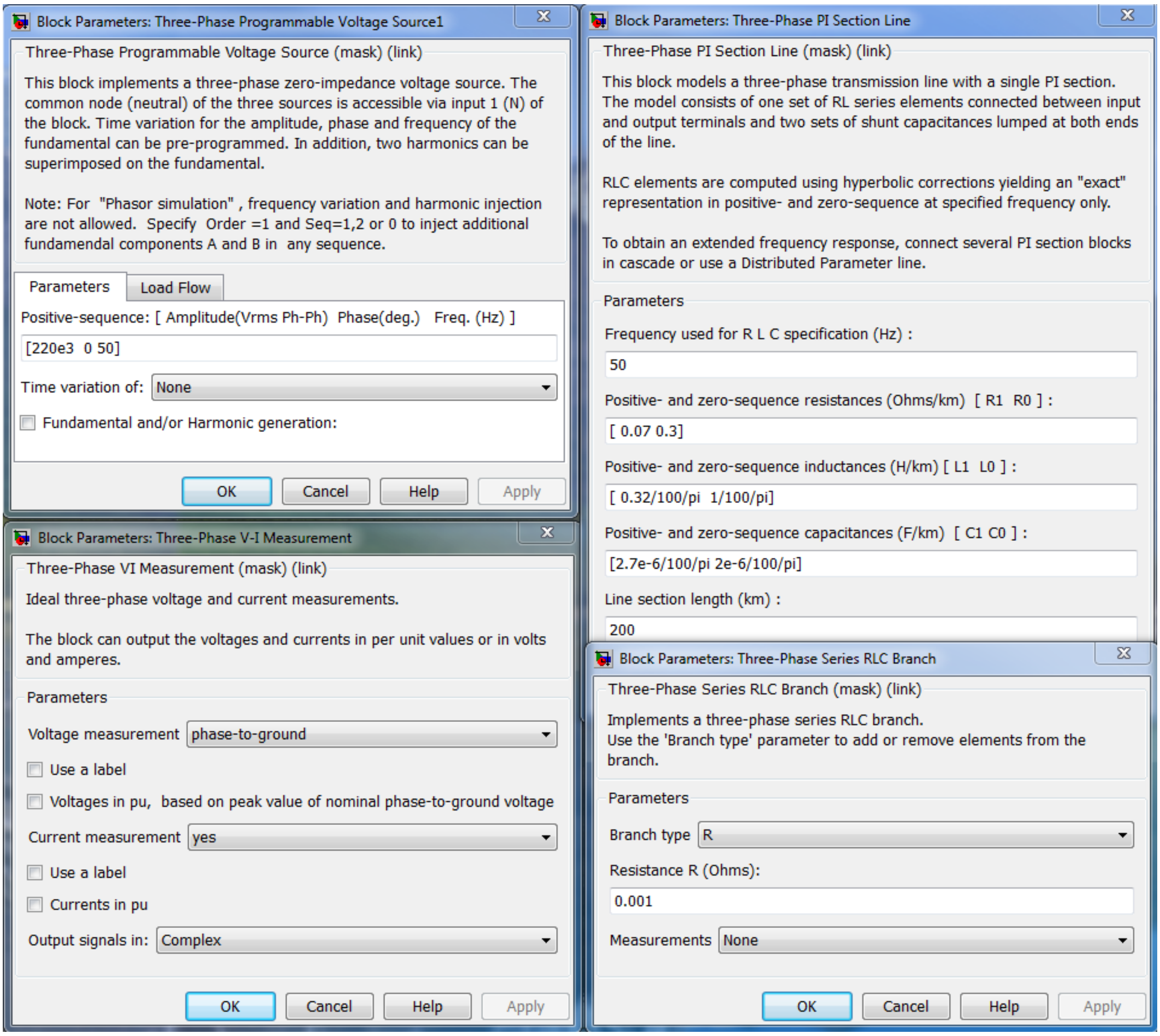
Number of variant	Rated Voltage rms value V_{rated}, kV	Full length of power transmission, km	Convertor rating of FACTS device, MVA
1	220	100	50 / 100 / 300
2	220	200	100 / 200 / 600
3	500	200	200 / 400 / 800
4	500	300	200 / 400 / 800
5	330	200	100 / 200 / 400
6	330	300	100 / 200 / 800
7	750	400	250 / 500 / 1000
8	750	500	250 / 500 / 1000
9	400	200	200 / 400 /800
10	400	300	200 / 400 / 1000

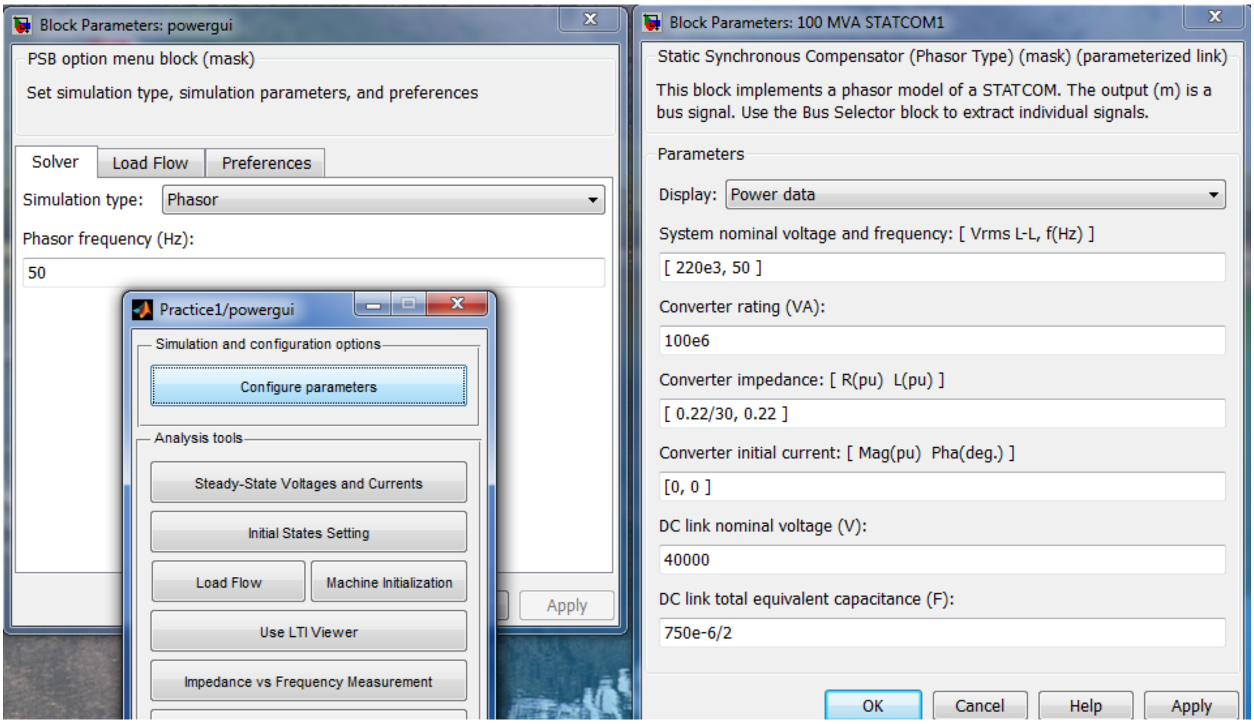
Table 3 – Overhead line parameters

Rated Voltage rms value V_{rated}, kV	Resistance, Ohm/km	Reactance, Ohm/km	Susceptance, μS/km
220	0,07	0,42	2,7
330	0,05	0,33	3,4
400	0,036	0,32	3,5
500	0,024	0,31	3,6
750	0,015	0,3	3,9

Appendix

Parameters configuration in power and control elements




Block Parameters: powergui
PSB option menu block (mask)
Set simulation type, simulation parameters, and preferences
Solver
Load Flow
Preferences
Simulation type:
Phasor
Phasor frequency (Hz):
50
Apply
Practice1/powergui
Simulation and configuration options
Configure parameters
Analysis tools
Steady-State Voltages and Currents
Initial States Setting
Load Flow
Machine Initialization
Use LTI Viewer
Impedance vs Frequency Measurement
Block Parameters: 100 MVA STATCOM1
Static Synchronous Compensator (Phasor Type) (mask) (parameterized link)
This block implements a phasor model of a STATCOM. The output (m) is a bus signal. Use the Bus Selector block to extract individual signals.
Parameters
Display:
Power data
System nominal voltage and frequency: [Vrms L-L, f(Hz)]
[220e3, 50]
Converter rating (VA):
100e6
Converter impedance: [R(pu) L(pu)]
[0.22/30, 0.22]
Converter initial current: [Mag(pu) Pha(deg.)]
[0, 0]
DC link nominal voltage (V):
40000
DC link total equivalent capacitance (F):
750e-6/2
OK
Cancel
Help
Apply