ELECTRIC POWER SYSTEM ANALYSIS, OPERATION AND CONTROL

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Contents

Summary

This chapter presents perspectives of electric power system analysis, operation and control. Models of power system components such as transmission lines, transformers, static loads and synchronous generators are described in power system analysis. The modeling philosophy of synchronous generators is also applicable to modeling of HVDC and FACTS. Load flow solution, which is considered as the most frequently performed routine power network calculations and can be used in power system planning, operational planning, and operation/control is presented. The concepts and techniques for dynamic simulations of power systems are discussed. (AGC) used for active power and frequency control is presented. The concepts of FACTS are briefly introduced. The concepts and methods for voltage control and VAR management are described. The SSR mainly associated with series capacitor-compensated transmission system is discussed. Finally state estimation technique as the key function of an Energy Management Systems is also presented.

1. Introduction

The commercial use of electricity began in the late 1870s when the inventive genius of Edison brought forth the electric incandescent light bulb. The first complete electric power system – The Pearl street system in New York began operation in 1882, which was actually a DC system with a steam driven DC generator. With the development of the transformer, polyphase systems and AC transmission, the first three-phase line in North America began operation in 1893. It was found that time that AC transmission with the help of transformers was more preferable since DC transmission became impractical due to higher power losses. With the development of electric power systems, interconnection of neighboring electric power systems leads to improved system security and economy. However, with the advent of interconnection of large scale power systems, operation, control and planning of such systems become challenging tasks. With the development of digital computers and modern control techniques, automatic generation control (AGC), and voltage and reactive power control techniques have been introduced to operate and control modern large scale power systems while load flow solution has become the most frequently performed routine power network calculations, which can be used in power system planning, operational planning, operation control and security analysis. With the advert of interconnected large scale electric power systems, new dynamic phenomena including transient stability, voltage stability, low-frequency oscillations, subsynchronous resonance (SSR), etc have emerged.

With the development of electricity market, electricity companies engage in as many transactions in one hour as they used to conduct in an entire day. Such increased load demand along with uncertainty of transactions will further strain electric power systems. Moreover large amounts of distributed generation, in particular wind generation, connected with the network will result in further uncertainty of load and power flow distribution and impose additional strain on electric power systems operation and control. It is a real challenge to ensure that the transmission system is flexible enough to meet new and less predictable supply and demand conditions in competitive electricity markets.

FACTS devices are considered as low-environmental-impact technologies and are a proven enabling solution for rapidly enhancing reliability and upgrading transmission capacity on a long-term cost-effective basis. FACTS can provide voltage regulation; power flow management and control; congestion management; and enhancement of transfer capability, fast control of power oscillations; voltage stability control; and fault ride-through, etc.

The ever-increasing frequency of blackouts seen in developed countries has also enhanced the need for new power system control technologies such as FACTS devices. It has been recognized that state estimation is the key function of an Energy Management Systems (EMS). For a power system state estimation problem, a set of active and reactive power flow measurements with redundancy are given, and the operating condition of the system can be determined based on state estimation theory. The estimated system data can then be used in other applications such as power flow calculations, security evaluation, operation dispatching, and stability analysis & control, etc.

2. Modeling of Power System Components

In power system analyses such as load flow, power system stability studies, power system components such as transmission lines, transformers, static loads may be represented by algebraic equations. Synchronous generators are the most important components in power system analysis. They are usually represented by algebraic and differential equations in stability studies. The modeling philosophy of synchronous generators is applicable to modeling of HVDC and Flexible AC Transmission Systems.

2.1. Transmission Lines

If it is assumed that angular frequency of the system is nearly constant and the three-phase transmission line is balanced in parameters, then the transmission line can be represented by a single-phase π section equivalent circuit as show in Figure 1.

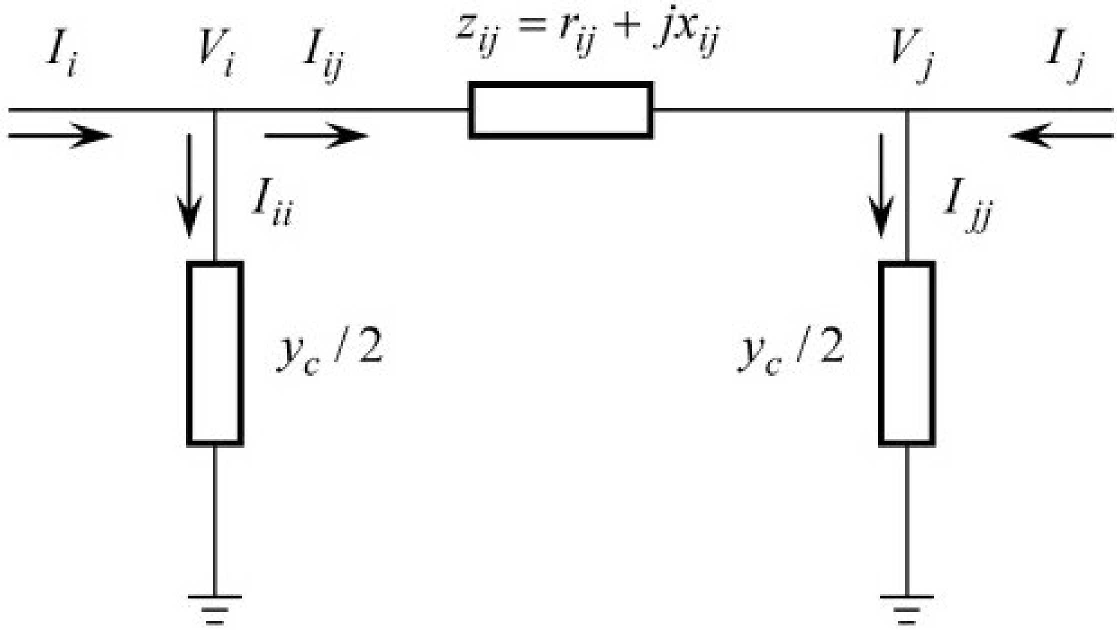

Figure 1. Equivalent π circuit model of transmission line

In Figure 1, $z_{ij} = r_{ij} + jx_{ij}$, y_c are the series impedance and shunt admittance of the transmission lines.

According to Kirchoff's current law, we have

$$I_i = I_{ij} + I_{ii} = (V_i - V_j) / z_{ij} + V_i(y_c / 2) \quad (1)$$

$$I_j = -I_{ij} + I_{jj} = (V_j - V_i) / z_{ij} + V_j(y_c / 2) \quad (2)$$

Equations (1) and (2) may be written as compact form as follows

$$\begin{bmatrix} 1/z_{ij} + y_c/2 & -1/z_{ij} \\ -1/z_{ij} & 1/z_{ij} + y_c/2 \end{bmatrix} \begin{bmatrix} V_i \\ V_j \end{bmatrix} = \begin{bmatrix} I_i \\ I_j \end{bmatrix} \quad (3)$$

This is bus voltage equation of the transmission line, which can be directly incorporated into the network voltage equation for system analysis.

2.2. Transformers

Similar to the modeling of transmission lines, transformers can also be represented equivalent circuit and bus voltage equation. A transformer represented by an ideal transformer $t:1$ in series with an impedance z_{ij} is shown in Figure 2 (a). The equivalent circuit in Figure 2 (a) can be transformed into Figure 2 (b).

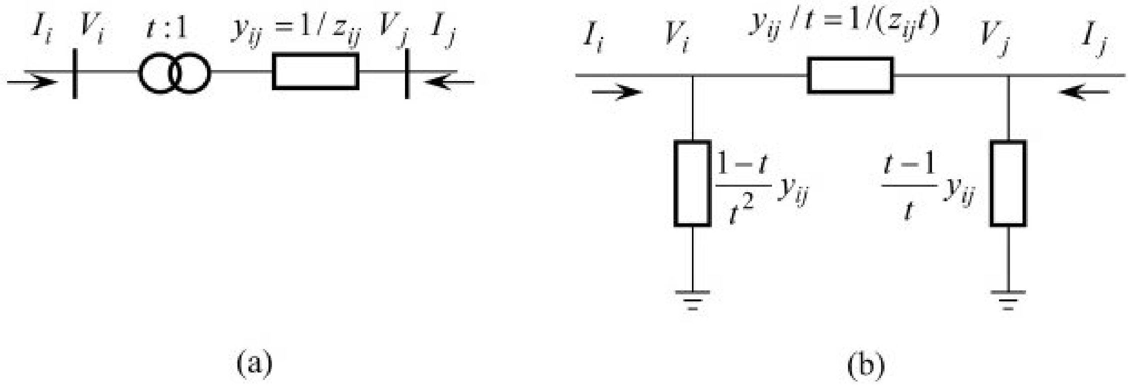

Figure 2. Transformer equivalent circuit with off-nominal tap ratio

In Figure 2, t is the off nominal tap ratio, y_{ij} is the short-circuit or leakage admittance.

The bus voltage equation of the transformer is given by

$$\begin{bmatrix} \frac{y_{ij}}{t^2} & -ty_{ij} \\ -ty_{ij} & y_{ij} \end{bmatrix} \begin{bmatrix} V_i \\ V_j \end{bmatrix} = \begin{bmatrix} I_i \\ I_j \end{bmatrix} \quad (4)$$

2.3. Loads

The static loads may be classified into three categories:

Constant power:

$$P = P_0(V)^0, \quad Q = Q_0(V)^0 \quad (5)$$

where P_0, Q_0 are constant powers at nominal voltage.

Constant current:

$$P = P_0(V)^1, \quad Q = Q_0(V)^1 \quad (6)$$

Constant impedance:

$$P = P_0(V)^2, \quad Q = Q_0(V)^2 \quad (7)$$

A general representation of the static loads as functions of voltage magnitude and frequency deviation may be given by

$$P = P_0[a_0(V)^0 + a_1(V)^1 + a_2(V)^2](1 + K_P\Delta f) \quad (8)$$

$$P = P_0[b_0(V)^0 + b_1(V)^1 + b_2(V)^2](1 + K_Q\Delta f) \quad (9)$$

where a_0, a_1, a_2, b_0, b_1 and b_2 are voltage coefficients while K_P and K_Q are frequency coefficients.

2.4. Synchronous Generators

In load flow analysis, a synchronous generator is simply represented by algebraic constraints. For instance, a Slack generator is represented by a constant voltage source. A PV generator is represented by constant active power injection and controlled voltage bus.

In power system stability studies, synchronous generators are usually represented by equivalent circuits and algebraic and differential equations.

In the following, a few dynamic models of synchronous generators in stability analysis will be presented.

2nd order model

In this model, electrical circuit of a synchronous generator is represented by the d and q axes equations with $E_d^{'} = E_q^{'} = \text{const}$

$$\begin{cases} V_d = E_d^{'} + x_q^{'} I_d - r_a I_d \\ V_q = E_q^{'} + x_d^{'} I_d - r_a I_q \\ 2H \dfrac{d\Delta\omega}{dt} = P_{mech} - P_{elec} - D\Delta\omega \\ \dfrac{d\delta}{dt} = \omega_0 \Delta\omega \end{cases} \tag{10}$$

where V_d and V_q are d and q axes voltage components of generator terminal. I_d and I_q are d and q axes current components of generator. $E_d^{'}$ and $E_q^{'}$ are the subtransient voltage components in d and q axes, respectively. $x_d^{'}$ and $x_q^{'}$ are the subtransient reactances of d and q axes, respectively while r_a is the stator winding resistance. P_{mech}, P_{elec} are the mechanical and electrical powers while D is the damping coefficient. ω and δ are the angular speed and power angle, respectively while H is time constant of the inertia.

4th order model

In this model, electrical circuits of a synchronous generator is represented by the d and q axes equations

$$\begin{cases} V_d = E_d' + x_q' I_d - r_a I_d \\ V_q = E_q' + x_d' I_d - r_a I_q \\ \dfrac{dE_d'}{dt} = \dfrac{1}{T_{q0}'}[-E_d' + (x_q - x_q')I_q] \\ \dfrac{dE_q'}{dt} = \dfrac{1}{T_{d0}'}[E_f - E_q' + (x_d - x_d')I_d] \\ 2H\dfrac{d\Delta\omega}{dt} = P_{mech} - P_{elec} - D\Delta\omega \\ \dfrac{d\delta}{dt} = \omega_0 \Delta\omega \end{cases} \tag{11}$$

where T_{d0}' and T_{q0}' are time constants. E_f is the excitation voltage. In this 4th order model, E_d' and E_q' are not constant.

Similarly, dynamic motors can also be represented by algebraic and differential equations. In addition to the modeling of synchronous generators, excitation systems and speed-governing systems, which are usually described by differential equations, also need to be represented.

2.5. HVDC Systems and Flexible AC Transmission Systems (FACTS)

In load flow analysis, HVDC systems and Flexible AC Transmission Systems are represented by algebraic equations while in stability studies they are represented by algebraic and differential equations.

3. Load Flow Analysis

It is well known that load flow solution is the most frequently performed routine power network calculations, which can be used in power system planning, operational planning, and operation/control. It is also considered as the fundamental of power system network calculations. From a load flow solution, the voltage magnitude and angle at each bus and active and reactive power flows and power losses in each line can be obtained. In the following, classifications of buses for load flow analysis are introduced first. Then load flow solution methods are presented. Numerical examples on a simple system are used to show the principles of load flow analysis.

3.1. Classifications of Buses for Load Flow Analysis

Slack bus: For the sake of requirement of load flow analysis, a slack bus should be selected, whose voltage magnitude and angle are given and kept constant while the active and reactive power injections are not known before a load flow solution is found. Actually the voltage angle is taken as the angle reference of the whole system and usually set to 0 degree. The slack bus basically serves two functions: (a) the reference of the system; (b) balancing the active and reactive powers of the system. In load flow analysis, usually there is only one slack bus in the system. For a Slack bus, the voltage magnitude and angle are given while the active and reactive power injections need to be determined by load flow analysis.

PV buses: A PV bus is a bus whose voltage magnitude is given and kept constant and active power injection is specified. A PV bus may also be called voltage-controlled bus. A generator bus may be considered as a PV bus if the voltage of the bus and the active power output from the generator are controlled to the specified values. Sometime, a bus, with which reactive control resource like synchronous condenser is connected with, may also be taken as a PV bus. For a practical interconnected power system, there may be one or more PV buses. For a PV bus, the voltage magnitude and active power injection are given while the voltage angle and the reactive power injection need to be determined by load flow analysis.

PQ buses: A PQ bus is a bus, to which active and reactive power injections are given and kept constant. Usually a non-generator bus is a PQ bus. For a PQ bus, the active and reactive power injections at the bus are given while the voltage magnitude and angle at the bus need to be determined by load flow analysis.

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Biographical Sketch

Xiao-Ping Zhang received his PhD degree from Southeast University, China in 1993. He then joined Nanjing Automation Research Institute (NARI), State Grid Corporation of China as EMS R&D Manager until 1998. He was an academic visitor with UMIST from 1998 to 1999. He was an Alexander Von Humboldt Research Fellow in Germany from 1999 to 2000. He was a Lecturer, and then an Associate Professor at the University of Warwick, UK from 2000 to early 2007. He is currently Reader in Energy Distribution Systems and also Director of the University Institute for Energy Research and Policy at the University of Birmingham, UK.

He is on the Editorial Board of Electric Power Components & Systems. He is a senior member of IEEE and a member of CIGRE. He is a member of IFAC Technical Committee on Power Plants and Power Systems. He is the Co-Chair of the IEEE PES Working Group on Test Systems for Economic Analysis. He is an expert of CIGRE Study Committee C6 - Distribution Systems and Dispersed Generation. He was a member of the TPC of the 8th IEE International Conference on AC-DC Power Transmission in 2006 and Transmission and Distribution Europe 2007. He is a member of the Program Committee of Bulk Power Systems Dynamics and Control–VII (IREP 2007) and Co-Chair of the Technical Program Committee of the IEEE International Conference on Electric Utility Deregulation, Restructuring and Power Technologies in 2008. He published the monograph "Flexible AC Transmission Systems: Modelling and Control" by Springer in 2006.