AUTOMATION AND CONTROL OF ELECTRICAL POWER GENERATION AND TRANSMISSION SYSTEMS

Hans Glavitsch

Swiss Federal Institute of Technology, ETH Zentrum, CH 8092 Zurich, Switzerland

Keywords: Electric power system, stability and security of operation, synchronous machines, automatic voltage regulation, speed governor, droop, frequency control, power-frequency characteristic, excitation systems, small signal stability, damping, transient stability, load-frequency control, automatic generation control, area control, multi-machine stability, system states, system matrix, eigenvalues, eigenvectors, Routh criterion, sequence control, automatic startup and shutdown, FACTS (flexible AC transmission systems), inter-area oscillations, system control centers, substation control, protection

Contents

Summary

The treatment of automation and control of power generation is focused on voltage regulation and stability improvement of synchronous machines in the ideal configuration when the generator is connected to an infinite bus and in multi-machine configurations. Emphasis is put on the 3rd order model of the generator with and without controls whereby the basic behavior and control principles are developed. Further, speed regulation and frequency control for single machines and for turbine-generators within several

areas, as well as the centralized control structures are presented. Sequence control for startup and shutdown of generating units are briefly discussed.

1. General

1.1 Objectives

As electrical power generation and consumption are characterized by a continuous balance of momentary generation and usage their control becomes and is a pre-eminent issue of the operation of the electrical power system. Automation and control of a system appear in a transparent form whenever the possible disturbances and irregularities are defined and put forward as a challenge. Generally speaking there are external and internal sources of disturbances. Since the power system is geographically widely spread and exposed to nature there are influences due to weather, forestry and agriculture. On the other hand the system may be affected by human failures or malfunction of equipment. Finally, disturbances may due to aging of components.

In any of these cases the design of control systems has been oriented to counteract these influences and to maintain the operation and in particular the security of supply of electrical power to the consumers. The key word or key concept is stability of operation in the sense of control systems and automatic control. In more detail stability means maintaining key variables such as voltages, currents and frequency within narrow limits and their fast return to their steady state values or prefault conditions. More recently a term has evolved which goes beyond the usual concept of stability and this is power quality. Power quality defines deviations of variables in the system which need not endanger the stability of the system but are aimed to guarantee a minimum of disturbances to the users – mostly delicate users. An example is a limit of the deviation of the voltage wave form from its nominal sinusoidal form.

Since automation includes the procedures of startup and shutdown of generating units their smooth evolution, i.e. time-wise and according to their pre-programmed sequences is understood under security of operation and stability as well.

Security of operation and stability in a wider sense involve operational concepts which do not affect the life of components or systems in an adverse manner. Hence, control concepts in the electrical power system aim at maintaining and extending the life of machinery and apparatus.

1.2. Control Concepts

The electrical power system is a decentralized and dispersed system. Power inputs and outputs are located in many places spread over a wide geographical area. Since power is the predominant agent of control its coordinated action is decentralized as well. It starts at the individual components such as the transmission circuit which is protected by a fast acting local system aimed at avoiding the destruction of the component itself but also of the associated subsystem in case of an overload. It may be termed as a feedback system but with the difference that it acts only once when a threshold is exceeded. Further, it acts completely independently of any other system which is characteristic for a protective system. Associated with active and reactive power devices there are control

systems which are responsible for maintaining the voltage magnitude and the frequency. Thereby it is interesting to note that frequency control in an electromechanical system is at the same time power control.

Control devices mentioned so far are acting locally, also by observing local variables. Contrary to these there is a first system which may be termed as a true "system" control arrangement. It is the area control system or load-frequency system (AGC = automatic generation control). It is responsible for the power balance and the frequency of an interconnected system of generators and consumers. It is able to cooperate with neighboring systems which pursue the same objectives. Set-points for these systems are the schedules of power to be exchanged between areas. Thereby the frequency of the overall system is controlled and maintained at the same time. Within the individual areas the output of generators may be determined according to economic objectives. It supersedes the area control system and is a control system of its own, namely the economic dispatch system.

Looking at these systems it is to be noted that they act in different time frames, from fast to slow. In a schematic they may be pictured in function of the degree of decentralization and
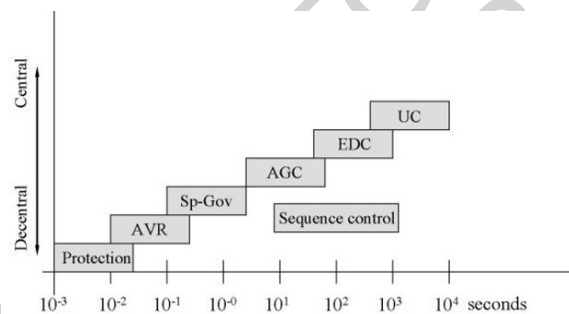

Figure 1: Hierarchy of control systems

the time response, see Figure 1. The meanings of the abbreviations in the figure are as follows:

Protection	protective devices at the component level
AVR	automatic voltage regulation at generator location
Sp-Gov	speed governor at the turbine (prime mover) location
AGC	automatic generation control in a central location of an area
EDC	economic dispatch control in a system control center
UC	unit commitment in a system control center
Sequence control	startup and shutdown systems in power stations

At the local level protective devices are found acting within several cycles of the system frequency. Associated with active and reactive power devices (generators) is the voltage control system. The time frame is fractions of a second. Further, the speed governing (frequency control) system can be found at some slower pace. It acts in the second's time frame. On top the load-frequency system (AGC) is placed and, as can be seen, the

time frame is extended towards minutes. Further on, the economic dispatch system which is associated with unit commitment is to be seen. The time frame is governed by the change of the load pattern which takes place within minutes up to tens of minutes. Determining the engagement of generating units can also be taking place on an hourly or half-hourly basis.

The degree of decentralization or centralization is given on the ordinate of the schematic in Figure 1. Hence, it is quite natural that the economic dispatch system is a centralized system.

So far control concepts acting in the normal operation of the systems have been discussed. However, automatic control systems have been introduced in power stations for the purposes of startup and shutdown (see *Decontic*). Generally speaking these systems are sequence control systems, partly open loop, partly closed loop. They replace the manual control actions with numerous variables to be observed. Of course, they are an orderly replica of the actions necessary formerly done by the human operator. As to the time frame they are to be placed at the right end of the time scale in Figure 1. Such systems are governed by security and protective aspects. As the name suggests it is a sequence of actions where the next action is allowed to be executed "if and only if" the foregoing action is completed (if-then). Startup and shutdown systems are applied both to thermal and hydraulic power stations. On a smaller scale they can also be found in switching stations for the orderly opening and closing of circuits.

In many cases human interaction is still possible, in particular in systems acting beyond the minute-time frame. However, interaction with protective systems, voltage and frequency control systems is not possible and not reasonable.

1.3. Historical Review

Automatic control concepts have already been applied in ancient times, mainly in connection with water and flood control. Not as far back in history a device can be found which is already intimately related to the control of power systems and this is Watt's speed governor as applied to the steam engine. In Figure 2 a schematic of a steam driven turbine-generator is shown. It could just as well be taken for a hydraulic system. The prime mover is symbolized by the turbine symbol.

In this system the turbine drives a rotating load which could be a generator feeding an electrical load. The speed of the turbine-generator system is measured by a centrifugal governor which adjusts the flow of water or steam to the prime mover. The output of the governor is not directly fed to the prime mover but is combined with the position of a manually operated wheel acting as the set-point to the system.
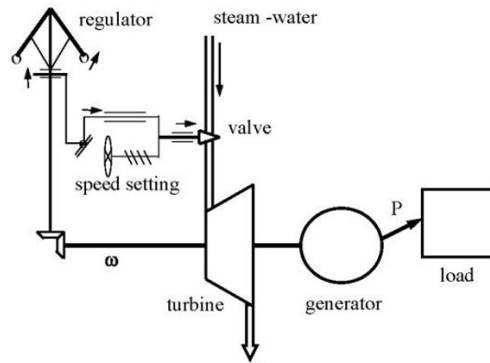
Figure 2: Schematic of a speed regulated system
(The arrows indicate the reaction of the regulator to an increase in speed, i.e. closing of valve)

The system exhibits the features of a feedback system in a perfect way. First, it is to be shown in which way an equilibrium situation can be achieved. This is done by resorting to a graphical representation of the relations between speed and power. On the load side there is a dependence of the power P of the load on speed ω and on the other hand the regulating system produces power as a function of speed ω as well. These two relations can be shown in a graph. In general these relations are nonlinear. A typical example is given in Figure 3.

The system is in equilibrium at the intersection of the two characteristics shown. The power-speed characteristic of the load is normally a monotonically growing curve where the power increases progressively with speed. A typical example is a pump or ventilator. The speed-power characteristic of the regulator-valve system is designed to result in a decreasing behavior of the speed in function of the power. The non-linearity is due to the characteristics of the valve and of the prime mover as well as of the oil-hydraulic control system.
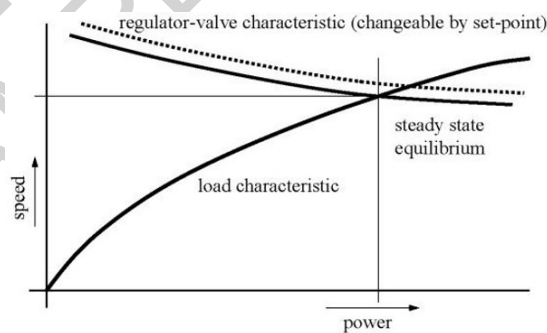

Figure 3: Speed-power relations of a regulated system

The dotted line is a regulator-valve characteristic modified by a change in the set-point. The intersection would correspond to a higher power and a higher speed.

For small deviations of the rotor speed around the steady state load point the following relations can be set up (The variables and constants stand for: ω speed in radian/s; T_m,

T_e mechanical, electrical torque; P_m, P_e mechanical, electrical power; J inertia; K slope of regulator/valve; K_L slope of load characteristic; ω_o speed at equilibrium point ; P_{mo}, P_{eo} steady state values)

$$J\frac{d\omega}{dt} = T_m - T_e = \frac{P_m - P_e}{\omega} = \frac{P_m - P_e}{\omega_o + \Delta\omega} \cong \frac{P_m - P_e}{\omega_o} \qquad (1)$$

By linearization around the point of equilibrium of the load the power relations reduce to the following

$$P_m - P_e = P_{mo} - K(\Delta\omega - \Delta\omega_{ref}) - P_{eo} - K_L\Delta\omega \qquad (2)$$

Thereby the incremental change of the electrical power is due to both the actual frequency $\Delta\omega$ and the reference frequency $\Delta\omega_{ref}$. The steady state values add up to zero. Thus the mechanical equation results in

$$J\frac{d\Delta\omega}{dt} = -\frac{K + K_L}{\omega_o}\Delta\omega + \frac{K}{\omega_o}\Delta\omega_{ref} \qquad (3)$$

Since $\Delta\omega_{ref}$ can be considered as an input a transfer function can be formed. The result is

$$\frac{\Delta\omega}{\Delta\omega_{ref}} = \frac{K}{\omega_o Js + K + K_L} \qquad (4)$$

The transfer function exhibits the character of a first order delay (one time constant). It is to be observed that the slope of the regulator characteristic and that of the load characteristic add up and determine the effective slope. Since the load characteristic affects the effective slope the steady state gain of the transfer function is not unity. If the load would be independent of speed the gain would be unity.

1.4. Sensors and Actuators

It is of interest to see that there are very few types of actuators and sensors which are employed in the control and automation of electrical power systems. Examples have already been introduced in Section 1.3, namely the steam or water valve and the speed sensor. With the introduction of electronic devices sensors nowadays are predominantly electronic. Speed, frequency, voltage, active and reactive power, current can all be measured and converted by electronic means. As far as the electrical system is concerned this set of quantities already exhausts those which are at the disposal of control inputs. Mechanical and thermal quantities as they appear in thermal and hydraulic power stations are also measured by this technology but are not treated here in detail. Moreover, modern control systems work with digital signals, i.e. the physical quantity is coded in numerical form with an appropriate degree of accuracy. Signal processing is done by analog means and nowadays more and more by digital computers.

The number of possible actuators is also limited. On the turbine side it is the valve and on the generator side it is the excitation current which determines the output voltage magnitude. Auxiliary control inputs are the tap changer position of transformers and the grid controls of FACTS devices. The latter are power electronic devices allowing current flow by firing thyristors or gate-turn-off units.

Control of the system is also possible by switching, i.e. operating breakers thereby modifying the topology of the transmission and distribution system. Controlled switching complements the spectrum of actions in the system.

2. Unit Control

2.1. Synchronous machines

For the conversion of mechanical power of steam and hydro turbines to electrical power the synchronous machine has become the key device which exhibits highest efficiencies and operational advantages. For purposes of modeling dynamics, stability analysis and control the synchronous machine is presented in a transformed framework, namely by means of the so called two-reaction theory. Thereby phase quantities and machine reactances are converted by a matrix based on angular relationships. The angle which plays the key role is the variable position of a rotating reference frame and the axis of one of the three-phase armature windings. The effect of the transformation is that ac-quantities appear as dc-quantities which vary with deviations from the synchronous motion of the rotor.

The classical set of equations of an unsaturated machine where one set of damper windings is considered is given below. The set includes relations between flux linkages and currents, voltages appearing at terminals of windings and mechanical torques. All quantities are given in per unit (p.u.). The base power is the rated power of the generator in MVA, the base voltage of the armature is the rated voltage, the base voltage of the field is the dc-voltage which generates the nominal voltage at the armature under no load. Flux linkages and currents – direct axis armature circuits

$$\psi_{d} = -x_{d}\, i_{d}\ + x_{afd} i_{fd}\ + x_{a1d}\, i_{id}$$
$$\psi_{fd} = -x_{afd}\, i_{d} + x_{ffd} i_{fd} + x_{f1d}\, i_{id} \tag{5}$$
$$\psi_{1d} = -x_{a1d}\, i_{d} + x_{f1d} i_{fd} + x_{11d}\, i_{id}$$

Flux linkages and currents – quadrature axis armature circuits

$$\psi_{q} = -x_{q}\, i_{q}\ + x_{a1q}\, i_{1q}$$
$$\psi_{1q} = -x_{a1q}\, i_{q} + x_{11q}\, i_{1q} \tag{6}$$

The flux-current relations can be made transparent in equivalent circuits as given in Figure 4 and 5. The parameters x_{d}, x_{ffd}, x_{q}, etc. are per unit reactances, the quantities $\psi_{d}, \psi_{ffd}, \psi_{q}$, etc. and $i_{d}, i_{f}, i_{q}, etc.$ are per unit flux linkages and currents respectively. Voltage-current relations –direct axis and quadrature rotor circuits

$$e_{fd} = \frac{d\psi_{fd}}{dt} + r_{fd}\, i_{fd}, \ 0\ = \frac{d\psi_{1d}}{dt} + r_{11d}\, i_{1d}, \ 0\ = \frac{d\psi_{1q}}{dt} + r_{11q}\, i_{1q} \tag{7}$$

Armature voltages

$$e_{d} = \frac{d\psi_{d}}{dt} - \psi_{q}\, \frac{\omega}{\omega_{n}} - r\, i_{d}$$
$$e_{q} = \frac{d\psi_{q}}{dt} + \psi_{d}\, \frac{\omega}{\omega_{n}} - r\, i_{q} \tag{8}$$

Electrical torque and rotor acceleration

$$2H\, \frac{d\omega/\omega_{n}}{dt} = T_{m} - T_{e} = T_{m} - i_{q}\psi_{d} + i_{d}\psi_{q} \cong T_{m} - i_{q}\, e_{q} - i_{d}\, e_{d} \tag{9}$$
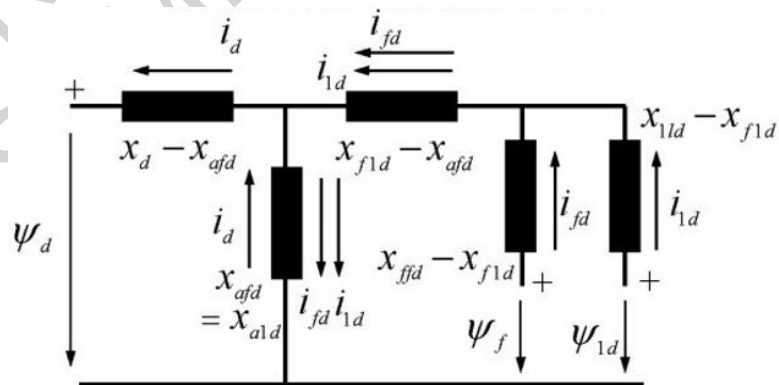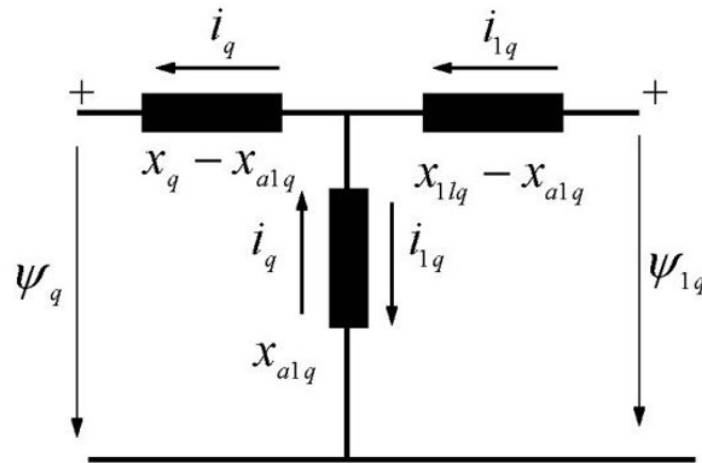
Figure 4: d-axis equivalent circuit

Figure 5: q-axis equivalent circuit

Due to the per unit system the inertia J (see (1)) is replaced by $J = 1/2\omega_n^2$ /base power. The time frame is in seconds and not in radians as given in the original reference (*synchronous machines)*. This system of equations will be used in reduced form for stability analysis and voltage regulation in the subsequent Section.

-
-
-

TO ACCESS ALL THE **49 PAGES** OF THIS CHAPTER,
Click here

Bibliography

P. Kundur(1994) ; *Power System Stability and Control,* Electric Power Research Institute – Power System Engineering Series McGraw Hill [This book gives a comprehensive treatment of power system stability and control]

A. J. Wood, B. F. Wollenberg (1984); *Power Generation, Operation & Control,* John Wiley & Sons, New York [This book treats fundamentals of speed, frequency and area control of turbine-generators sets and systems]

UCPTE (1991) – Union for the coordination of production and transmission of electricity, Voltage and reactive-power control in the UCPTE system Active power control in the UCPTE system, Offprint of the Annual Report 1990 (July 31, 1991) UCPTE-secretariate, Utrechtseweg 310, NL 6812 AR Arnhem, (UCPTE is now UCTE – Union for the coordination of transmission of electricity) [The brochure contains the rules of frequency and voltage control for the European interconnected system]

F. P. deMello, C. Concordia (1969) ; *Concepts of Synchronous Machine Stability as Affected by Excitation Control*, IEEE Trans. Power Apparatus and Systems, vol. PAS-88, No. 4, April 1969, [The key paper develops the concepts of synchronous generator stability and the use of supplemental signals by means of the 3rd order generator model]

C. Concordia (1951) ; *Synchronous Machines, Theory and Performance,* John Wiley & Sons, New York [This book gives a profound treatment of the synchronous machine model based on the two-reaction theory]

Semlyen (1974); *Analysis of Disturbance Propagation in Power Systems Based on Homogeneous Dynamic Model*, IEEE Trans. on Power Apparatus and Systems, vol. PAS-93, March/April 1974, No. 2, pp. 676-684 [The paper develops the continuous longitudinal model of generators and transmission lines]

Y. Bao; (1994) *Control of Inter-Area Oscillations in Power Systems Using Regularity Concepts*; PhD-Thesis Swiss Federal Institute of Technology Zurich, Switzerland, Diss. ETH No. 10843 [The thesis treats interconnected power systems and works out the properties of regular systems and of special configurations which exhibit inter-area oscillations]

N. G. Hingorani, L. Gyugyi (2000); *Understanding FACTS – Concepts and Technology of Flexible AC Transmission Systems,* IEEE Press IEEE Order No. PC5713 [This book gives a comprehensive treatment of FACTS]

M. Salm, W. Schneider (1975); *Decontic K, ein modernes elektronisches Steuersystem für Kraftwerke,* Brown Boveri Review, vol. 62, 1975 (9) [The paper describes the structure and the functionalities of a control system for monitoring, startup and shutdown of power stations)

P. Kundur, G. J. Rogers, D. J. Wong, L. Wang, M. G. Lauby (1990) ; *A Comprehensive Computer Program for Small Signal Stability Analysis of Power Systems,* IEEE Trans. vol. PWRS-5, pp. 1076-1083, Nov. 1990

Biographical Sketch

Hans Glavitsch has received his diploma of Engineering (Dipl.-Ing.) from the Technische Hochschule Graz (today Technische Universität), Austria in 1958. After completing further studies at Stanford University, California he obtained a Master of Science (M.S.) degree in 1960. He joined the Brown Boveri Cie. in Baden, Switzerland in 1961 where he has been in charge of system studies in the power systems area, of engineering computing and of research in automatic control. During his association with the Brown Boveri Research Center he earned a PhD-degree (Dr.-Ing.) from the Technische Hochschule Aachen, Germany in 1974. In 1978 he was appointed professor of power transmission systems at the Swiss Federal Institute of Technology Zurich and from this institute he retired in 1999. His scientific contributions and technical papers (more than 140) have been published in Transactions and Proceedings of IEEE, CIGRE, IFAC, PICA, PSCC (Power Systems Computation Conference), in the Brown Boveri Review and in German/Austrian technical journals (ETZ, EW, SEV, E+M). In 1991 he has been elected to the Fellow grade of IEEE.