# Excitation System Models of Synchronous Generator

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***Abstract*—The aim of this paper is to give short review on excitation system models of synchronous generator that have been classified so far, as well as on different possibilities to regulate those systems. First, excitation system models are described and their advantages and drawbacks are discussed. Further more, different possibilities to regulate those systems are given, with special emphasis on newly developed nonlinear system regulation. Finally, it is explained that nonlinear system regulation methods are much more complex than commonly used linear system regulations, but also have potential to improve excitation system regulation of synchronous generators if further developed.**

***Key words* – excitation system, linear regulation, nonlinear regulation, synchronous generator**

## I. INTRODUCTION

One of the most important elements of electric power system is synchronous generator, because it is the source of electrical energy. In generator, mechanical energy (usually from a turbine) is transformed into electrical energy. Energy transformation is possible only if generator excitation exists. Excitation of generator also defines generator output values: voltage and reactive power. This means that generator excitation regulation is actually regulation of generator output energy and also impacts the stability of entire electric power system. Synchronous generator stability is graphically represented by P-Q diagram (Fig. 1). As explained in [1], operating point of generator must be inside the area determined by: minimal excitation current (curve a), practical stability limit (curve b), maximal excitation current (curve c), maximal armature current (curve d), maximal turbine power (line e) and minimal turbine power (line f).

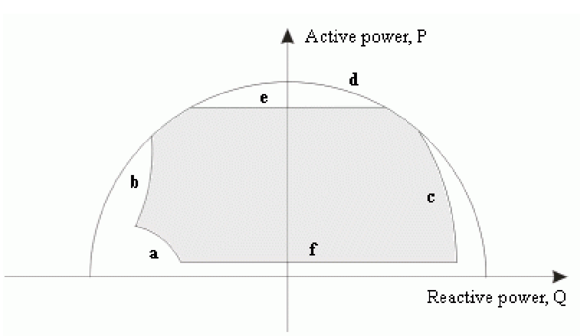


Figure 1. Synchronous generator P-Q diagram

## II. EXCITATION SYSTEM

Excitation current is provided by the excitation system, which, according to [2], usually consists of autonomic voltage regulator (AVR), exciter, measuring elements, power system stabilizer (PSS) and limitation and protection unit (Fig. 2).

Exciter is the source of electrical power for the field winding of generator and is realized as a separate DC or AC generator. Exciter has its field winding in the stator, and armature winding in the rotor. In case of AC generator, as the rotor rotates, stator DC current induces a three-phase alternating current into the rotor winding. This AC current is rectified using diode, thyristor or transistor bridge installed in the rotor.

Exciter is controlled by the AVR, which is very effective during steady-state operation, but, according to [3], in case of sudden disturbances it may have negative influence on the damping of power swings, because then it forces field current changes in the generator. This may be eliminated by introducing a supplementary control loop, the power system stabilizer (PSS), which produces an additional signal into control loop and in that way compensates voltage oscillations. The typical range of oscillation frequencies, given in [4], is of 0.1 to 3.0 Hz and insufficient damping of these oscillations may limit the ability to transmit power. PSS input quantities may be speed deviation, generator active power, frequency deviation, transient electromotive force and generator current. Usually two of these input quantities are chosen to get optimal regulation.

Measuring elements are used to obtain excitation system input values. Generator armature voltage is always measured and measurements of armature current and the excitation current and voltage are optional.

Limitation and protection unit contains larger number of circuits which ensure that certain physical values (e.g. generator armature voltage, excitation current, etc.) are limited.

### A. *Types of excitation systems*

Excitation systems for synchronous generators may be classified in the meaning of construction in two categories: static and rotating excitation systems. Static excitation systems consist of thyristor or transistor bridge and transformer. Energy needed for excitation is brought to generator field winding via slip-rings with carbon brushes from diode, thyristor or transistor bridge and transformer.

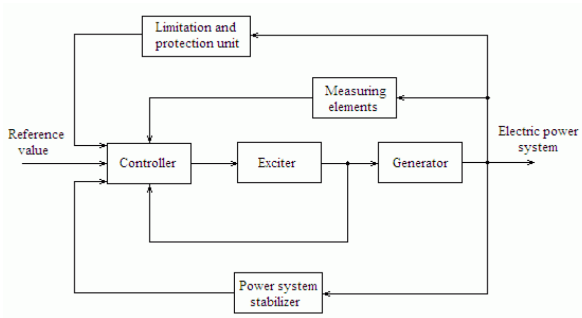


Figure 2. Excitation system of synchronous generator

Another categorization of excitation systems is made by excitation energy source. Two major classes of this categorization are: separate excitation systems and self-excitation systems.

Separate excitation systems may be static or brushless. These systems are independent of disruptions and faults that occur in electric power system, and have possibility to force excitation.

Brushless systems are used for excitation of larger generators (power over 600 MVA) and in flammable and explosive environments. Brushless system consists of AC exciter, rotating diode bridge and auxiliary AC generator realized with permanent magnet excitation. Attempts to build brushless system with thyristor bridge were not successful because of problems with thyristor control reliability. The result of this problem is significant disadvantage of these systems, inability of generator de-excitation. Another disadvantage is slower response of system, especially in case of low excitation.

Self-excitation system advantages are simplicity and low costs. Thyristor or transistor bridge is supplied from generator terminals via transformer. The main disadvantage is that excitation supply voltage, and thereby excitation current, depends directly on generator output voltage. Brushless self-excitation systems with diode bridge also exist.

### *B. Classification of excitation system models*

To examine the operation of synchronous generator and its excitation system and to determine how synchronous generator affects electric power system stability mathematical models of generator and excitation system are developed. Changes of reference values and disturbances that are typical for real systems are also modeled. Since a large number of excitation systems for synchronous generators exist in practice, classification of excitation system models was necessary. IEEE issued Recommended Practice for Excitation System Models for Power Stability Studies, document which classifies excitation systems introduced in engineering practice so far.

There are three major groups of generator excitation systems, with nineteen different excitation system models altogether: Direct Current Commutator Exciters (type DC), Alternator Supplied Rectifier Excitation Systems (type AC) and Static Excitation Systems (type ST).

Nowadays, DC type exciters are mainly suppressed by other two types and a few new synchronous machines are being equipped with these. This group consists of four models, detail described in [5]. DC1A model is used for self-excited shunt fields with voltage regulator operating in a buck-boost mode. It represents field-controlled DC commutator exciters with continuously acting voltage regulators that have generator output voltage as main input. DC2A model differs from DC1A only in voltage regulator output limits. DC3A model is used to represent older systems, especially those DC commutators with non-continuously acting regulators. DC4B is newly added model that differs from DC1A in implemented controls. This model contains PID controller.

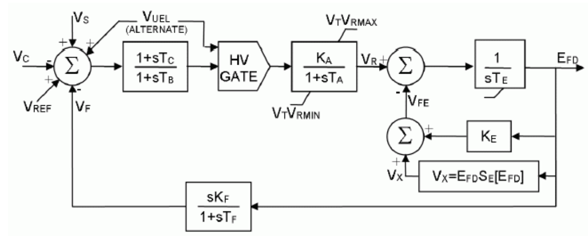

Figure 3. Excitation system type DC2A [5]

AC type of excitation systems contains AC generator and either stationary or rotating rectifier to produce direct current needed for generator excitation. This is the largest group of excitation models including eight models. These systems do not allow negative field current and only AC4A model allows negative field voltage forcing. This is significant disadvantage of this type of systems because it does not allow de-excitation of generator. AC1A model is used for field-controlled alternator-rectifier excitation systems, with non-controlled (diode) rectifier in case of separate excitation. AC2A differs from AC1A in additional compensation of exciter time and exciter field current limiting elements. AC3A model is used for self-excitation systems, which bring additional nonlinearity. Model AC4A is used for systems with full thyristor bridge in the exciter output circuit. AC5A is simplified model for brushless excitation systems with separate excitation. AC6A represents field-controlled alternator-rectifier excitation systems with system supplied electronic voltage regulators. AC7B model incorporates newer controls and PID controller. Model AC8B differs in form of PID controller. Here, proportional, integral and differential gains are defined with separate constants.

According to [5], ST type group of excitation systems consists of seven models. Field winding is supplied by rectifiers which can be controlled or non-controlled. Most of these systems allow negative excitation voltage, but only few provide negative excitation current. Possibility to produce negative excitation current is significant advantage, because it provides quick de-excitation, which may be needed in case of generator internal fault. ST1A model represents systems in which excitation power is supplied trough transformer from generator terminals or

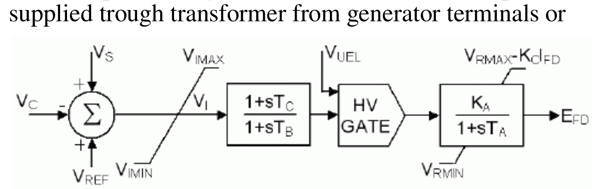

Figure 4. Excitation system type AC4A [5]

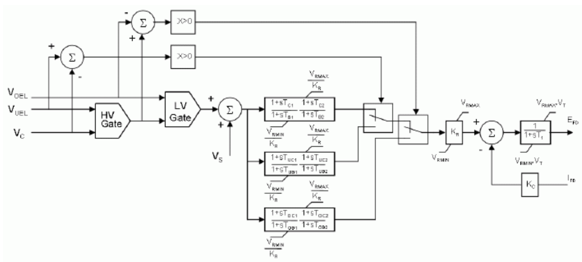


Figure 5. Excitation system type ST5B [5]

separate bus. It contains controlled rectifier. ST2A is model for systems that utilize both current and voltage generator terminal quantities to comprise power source. Model ST3A uses a field voltage control loop to linearize control characteristic of the exciter and may represent a lot of controlled-rectifier designs: full thyristor or hybrid bridge in either series or shunt configuration. ST4B is variation of ST3A model with PI instead lag-lead controller. ST5B is variation of ST1A with alternative overexcitation and underexcitation inputs and additional limits. Voltage regulator of ST6B model consists of a PI voltage regulator with an inner loop of field voltage regulation and pre-control. ST7B model represents static potential-source excitation systems, with PI controller which may be turned into PID controller if phase lead-leg filter used in series, which is typical case for brushless excitation systems.

## III. Linear Regulation of Synchronous Generator Excitation

There are three main properties of excitation systems that must be considered in regulation: speed of system operation, autonomy of excitation system and maximal drive security. Speed of operation is important to maintain stability of electric power system in the meaning of reactive power transmitting and receiving, fast de-excitation in case of internal failure and overvoltage limitation in case of sudden unloading. Autonomy of excitation systems means that excitation system supply must be ensured in every condition of a drive. Drive security is function of reliabilities of all incorporated components. To insure maximal drive security, components are overdimensioned.

All of excitation system models given above include linear controllers. Linear controllers are made of combination of three basic elements: proportional (P), integral (I) and derivative (D). Types of linear regulators in common use are: P, PI and PID controller. Lead-lag is also a type of linear controller which improves an undesirable frequency respond by introducing pole-zero pair.

P controller is the simplest controller for it has only one parameter. Main disadvantage of this controller is divergence in stationary state. The increase of gain (i.e. increase of regulator parameter value) reduces this divergence, but also decreases stability of the system.

PI controller eliminates divergence in stationary state. Disadvantage of this controller is that integral gain decreases system dynamics and increases phase delay, which also decreases system stability.

PID controller has additional derivative element which responds to divergence change speed, increases system dynamics and compensates system deceleration caused by integral element.

Parameters of linear controllers may be adjusted using analytical or experimental methods. Analytical methods for parameter adjustment require mathematical model of the whole regulation system. Synchronous generator model is nonlinear system, hence system linearization is needed. Parameters adjusted this way are valid in the operation point region. If the synchronous generator operating point is changed, parameters must be readjusted. Experimental methods do not require knowledge of system mathematical model, but also give optimal parameters only in the region of operation point in which experiment was performed.

## IV. Nonlinear Regulation of Synchronous Generator Excitation

Linear controllers yield good regulation properties of synchronous generator operation in stationary state, i.e. in one operating point. In practice, it is important to maintain system stability in transition state of synchronous generator or electric power system, e.g. synchronous generator synchronization, short circuit in electric power system, etc. To achieve stability during transition state, operation with nonlinear models and controllers is required. Methods for construction such controllers are newly developed and are not widely used in practice. Three of these methods will be explained in this chapter: neural networks, fuzzy control and adaptive control.

The operational value which provides virtually direct information about the generator working point position in relation to the stability limit is the load angle of the operating synchronous generator on the electric power system. Transition from one to another steady operating condition is often accompanied by significant changes in the dynamic load angle [6].

Information about change of the load angle can be used in implementation of the PSS stabilizer, as an input signal. Load angle can be measured or estimated. Direct measurement requires implementation of special measuring elements, and is rarely used solution. More often, load angle is determined from values that can be measured more easily, e.g. rotor mechanical angle and electrical angle of the base harmonic of rotating magnetic field, or electrical values together with parameters of system model.

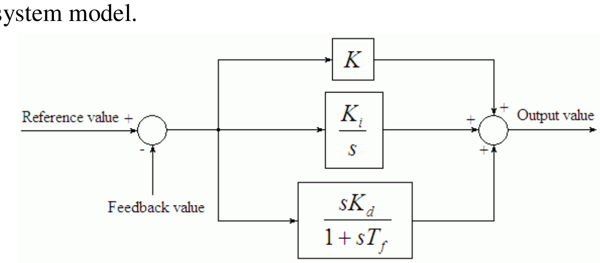


Figure 6. Structure of PID controller

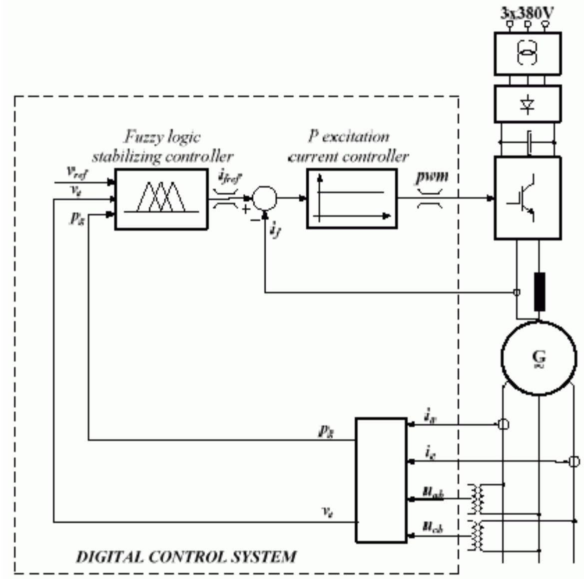


Figure 7. Structure of fuzzy logic excitation control [4]

The most novel method for load angle estimation is use of neural networks. In [6] double dynamic neural network is used. Estimation results show high accuracy in the process of load angle estimation. The network learned in such a way can be implemented into the digitized excitation as software extension. It is also concluded that another dynamic neural networks can be applied in the realization of additional excitation system regulator functions whereat additional measurements are not necessary.

Another type of nonlinear regulation is Fuzzy controller. Fuzzy controller uses fuzzy sets, linguistic variables, possibility distributions and fuzzy rules, thus has a very simple structure. An example of simple fuzzy logic excitation control of a synchronous generator is explained in [4]. Introduced controller type is used for voltage control and generator stabilization. The main advantage is that there is no need of knowing electric power system mathematical model, which is highly nonlinear. The fuzzy controller has two control loops: voltage control loop and damping control loop, and in that way unifies AVR and PSS. Simulation and experiment indicated that, compared to linear PI voltage controller and conventional PSS, fuzzy controller shows improved static as well as dynamic operating conditions.

Adaptive control is special form of regulation in which system parameter information are acquired in operation cycle, i.e. on-line. Adaptive regulator compensates influence of disturbance (input value in system, parameter or structural change). It consists of two closed loops: negative feedback and adaptive feedback. Negative feedback ensures process stability with classic linear regulator (e.g. PI regulator). Adaptive feedback is nonlinear mechanism that consists of algorithm for compensation of parameter changes in regulated system. There are three types of adaptive control: Gain Scheduling, Model Reference Adaptive Control and Self Tuning Control. This is effective regulation method for systems with slow but significant parameter changes.

## V. CONCLUSION

Synchronous generator is the source of energy in electrical power system and therefore regulation of synchronous generator affects not only generator itself, but also entire power system. In synchronous generator mechanical energy of rotor is transformed into electrical energy in stator winding. This energy transformation is provided by excitation of synchronous generator and is regulated by excitation system. Excitation system usually consists of autonomic voltage regulator, exciter, measuring elements, power system stabilizer and limitation and protection unit. Excitation system models in the meaning of structure and implemented controller type are classified and standardized. There are nineteen different excitation types in three major groups: Direct Current Commutator Exciters (type DC), Alternator Supplied Rectifier Excitation Systems (type AC) and Static Excitation Systems (type ST). All these models include linear controllers (P, PI or PID controllers) because they are mostly used in practice. Linear regulation is good for stationary state, but in transition state quality of regulation changes with change of operating point, for synchronous generator is a nonlinear system. To solve this problem nonlinear regulation is introduced. Nonlinear regulation may be implemented in form of neural networks, fuzzy control or adaptive control. These structures are more complex than structures of linear regulation, but have potential to improve excitation system regulation with further development.

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