CHAPTER 6

GENERATORS AND GENERATOR - MOTORS

6-1. GENERAL.

a. The hydroelectric generators and generator-motors are synchronous machines. Both produce electric energy by the transformation of hydraulic power into electric power but the latter also acts in reverse rotation as a motor to drive the pump-turbine as a pump.

b. As hydraulic turbines and pump turbines must be designed to suit the specific range of conditions under which they will operate, each generator and generator-motor is unique in that the electrical and mechanical design must conform to the hydraulic characteristic of the site and to the specific requirements of the electrical system.

c. A major difference between a generator-motor and the conventional generator is the special design features incorporated in the former required for starting and operating the unit in the reverse direction as a motor.

d. Guide Specifications cover the electrical and mechanical characteristics and the structural details of generators and generator-motors.

6-2. THE SELECTION AND NUMBER OF UNITS.

a. Factors affecting the selection and number of units are outlined in Chapter 1, Paragraph 1-7.

b. The type of generator or generator-motor depends on the type of turbine or pump-turbine to which it is connected and also whether the center line of the shafts will be vertical, horizontal or inclined.

c. Vertical shaft generators connected to Francis and Fixed Blade Propeller Turbines have three basic designs:

1. Suspended Generator - a thrust bearing located on top of the generator with two guide bearings.

2. Umbrella Generator - a thrust bearing and one guide bearing located below the rotor.

3. Modified Umbrella Generator - a combination guide and thrust bearing located below the rotor and a second guide bearing located above the rotor.

d. Horizontal shaft generators usually require thrust bearings capable of taking thrust in both directions. The thrust required may not be the same in both directions.

e. While some vertical shaft generators connected to adjustable blade turbines have been of the umbrella type, the Corps requires all vertical shaft adjustable blade turbines and all vertical shaft pump-turbines to have two guide bearings and one thrust bearing located either above or below the rotor.

f. Generators and generator-motors connected to inclined axis turbines require thrust bearings capable of taking thrust in both directions (away from and towards the generator) and two guide bearings.

6-3. GENERATOR RATING. Generators are rated in kva (electrical output) with the power factor determined by consideration of anticipated loads and system characteristics to which the unit or units will be connected.

6-4. GENERATOR VOLTAGE AND FREQUENCY. Determination of generator voltage is based on economic factors which include the cost of generator leads, instrument transformers, surge protective equipment, circuit breakers, space limitations, the requirement to serve local loads and the generator costs for the various voltage levels available. The standard frequency in the U.S.A. is 60 Hz.

6-5. SPEED. The speed of the unit is established by the turbine selected speed which must take into consideration that some synchronous speeds have a number of poles which for the kva rating desired would not give an acceptable winding design. See Table of Generator Speeds in Appendix A.

6-6. POWER FACTOR. The power factor of the generator is determined by the transmission and distribution facilities involved in addition to probable loads and system characteristics. If the generator is connected to a long, high-voltage transmission line, it may be economic as well as desirable to install a generator capable of operating with leading power factors. If the project is located near a large load center it may be economical to install a generator with larger than normal reactive capability by using 0.80 or 0.90 power factor machines. For the majority of installations 0.95 power factors generators will be the economic ones to specify. In general, for best operation the power factor of the generators should match the power factor of the load.

6-7. FLYWHEEL EFFECT (WK^2).

a. While the moment of inertia (WK^2) of the rotating parts of a unit (generator plus turbine) is a factor affecting system stability, the use of high speed circuit breakers and relays has in most cases removed the need for higher than normal WK^2 from the standpoint of the electrical system. Then the need for higher than normal WK^2 depends on the WK^2 needed to keep the speed rise of the unit and the pressure rise in the water passages for the turbine or pump-turbine within acceptable limits.

b. Greater than normal WK^2 may be required for an isolated plant or a unit serving an isolated load.

6-8. GENERATOR - MOTOR RATING.

a. The generator-motor rating depends on the pump-turbine characteristics and the system to which it will be connected.

b. Having selected a pump-turbine to meet the required capacity head conditions, the motor rating can be determined. In pump-turbine installations there may be considerable variations in head and consequently a variation in the motor requirements. The motor requirements may dictate the maximum rating of the generator-motor but in no case should the maximum horsepower required in the pumping mode be more than 94 percent of the 100 percent, 75 degree Centigrade nameplate rating, the motor rating being in KW (shaft output) or its horsepower equivalent.

c. The power factor depends on the system voltage conditions and transformer impedance and usually results in selecting a power factor of 0.95 (over-excited). There may be cases, during the hours of pumping, in which the system voltage may be reduced to where voltage studies show it is necessary for the machine to operate in the pumping mode at a lower voltage than in the generating mode. The range may be such as to require a dual voltage rating. Usually a difference in ratings for generating and motoring of about three percent less can be furnished without undue cost or complication.

6-9. EXCITATION SYSTEMS.

a. While for many years the excitation for synchronous generators was provided by directly connected main and pilot exciters, the pilot exciter was later eliminated and a rotating and/or a static voltage regulator system was used in connection with the direct-connected main exciter. Currently, except for very small generators, a static excitation system is specified. A static excitation system is specified for all reversible units.

b. The static excitation system is a static potential-source-rectified type with power for the excitation circuit normally taken directly from the generator or generator-motor leads. The complete excitation equipment consists of the excitation transformer, rectifiers, a-c excitation power circuit breaker, a-c bus between the transformer and rectifier, silicon controlled rectifiers, d-c bus from the rectifier cubicle to the generator or generator-motor field brush terminals, and a static automatic voltage regulator which controls the firing of the SCR's. The system designed for a generator-motor includes the necessary provisions for both directions of operation.

c. Most of the recent excitation systems have been provided with power system stabilizing equipment which changes the generator field current in proportion to instantaneous deviations from normal frequency to help dampen oscillations. This equipment should usually be furnished with solid-state excitation systems.

d. The Institute of Electrical and Electronics Engineers "Standard Definitions for Excitation Systems for Synchronous Machines," ANSI/IEEE Std 421.1-1986 should be consulted for an understanding of the application of solid-state devices to excitation systems. This report includes the new and revised definitions for excitation systems as applied to synchronous machines and gives particular emphasis on solid-state devices. The report includes figures illustrating the essential elements of an automatic control system, the components commonly used and figures which show the actual configuration of principal excitation systems supplied by domestic manufacturers.

6-10. <u>THRUST AND GUIDE BEARINGS.</u>

a. The Guide Specifications require that the generator and or generator-motor be provided with a nonspherical, adjustable-shoe or self-equalizing Kingsbury type or a General Electric spring type thrust bearing and for a generator-motor be suitable for rotation in either direction. For vertical machines the thrust bearing may be above or below the rotor. Units with very high thrust bearing loads and areas where space below the rotor is limited generally have the thrust bearing located above the rotor. Locating the thrust bearing below the rotor can reduce costs. Effects of the bearing location on vibration should be considered.

b. The generator of a vertical machine may be provided with one guide bearing below the rotor if the generator is connected to a Francis or fixed blade propeller turbine. An upper guide bearing must be provided if its installation is deemed necessary by the manufacturer for satisfactory operation or if the thrust bearing provided is of the self-equalizing type.

c. The generator of a vertical machine connected to an adjustable blade propeller turbine must be provided with two guide bearings.

d. The generator-motor of a vertical machine must be provided with two guide bearings with provisions for adequate lubrication in both directions of rotation.

c. It is now common practice to require that thrust bearings be provided with an externally pressurized system for providing high pressure oil to the thrust bearing surfaces during the starting and stopping of the machine.

6-11. THRUST BEARING BELOW THE ROTOR.

a. When the thrust bearing is located below the rotor the shaft coupling must be located farther below the stator than when the thrust bearing is located above the rotor.

b. The thrust bearing block is required by specifications to be forged integrally with the shaft.

c. Thrust bearings located below the rotor must be larger in diameter (for the same load carrying ability) than thrust bearings located above the rotor, due to the larger diameter of the shaft at the bearing location.

d. Two methods of inspection and removal of thrust bearing parts are provided, depending on the manufacturer of the generator or generator-motor. One method provides removable bearing housing covers in a bridge type lower bearing bracket. With the covers removed the thrust bearing is exposed for inspection and can be removed through the space between the bracket arms without disturbing the main support. The second method involves the lowering of the thrust bearing by use of a specially designed lowering device into the turbine pit. This design requires that the shaft coupling be located at a greater distance below the stator.

6-12. THRUST BEARING ABOVE THE ROTOR.

a. This design permits access to the bearing parts by overhead crane and assures adequate working space regardless of machine size and thrust bearing capacity.

b. This location is the standard location for small and high speed machines where the space below the rotor is limited.

c. This location does not place a limitation on the size of shaft forging facilities available. Large structural members are required to support the thrust bearing located above the rotor. These members support the thrust bearing loads and must be stiff enough to minimize deflections. They have to bridge a larger span than the bearing bracket located below the rotor.

d. The location does not require as large a diameter of bearings as does the thrust bearing located below the rotor and consequently the bearing losses are lower.

e. The bearing may be split when required for installations, such as with Kaplan turbines. This not only facilitates handling, but permits removal of bearing and parts without dismantling the Kaplan piping.

6-13. THRUST BEARING NOT INCORPORATED IN THE GENERATOR OR GENERATOR-MOTOR.

a. Slant axis adjustable blade turbines and pump turbines require a thrust bearing design to take thrust in both directions and may or may not be purchased with the generator depending on its location.

b. It is the common practice in Europe to procure the thrust bearing with the turbine and to mount the thrust bearing on the turbine head cover. Some savings is claimed in certain installations by so doing as it omits the large thrust bearing supports.

c. This location presents problems in coordinating the procurement and installation of the bearing. Thrust bearings are customarily furnished by the generator manufacturers in the U.S. and installed by them in the generator.

d. For very large capacity slow speed units it may be necessary for economic reasons to locate the thrust bearing on the turbine head cover.

6-14. HIGH PRESSURE OIL SYSTEM. High pressure oil starting system in a thrust bearing is essential for the operation of a reversible unit and should be specified for any unit over 31,260 kva in rating. To start these units, the oil is pumped under high pressure through openings in the stationary segments, forcing lubricating oil between the stationary and rotating parts of the bearing before the unit is started. This reduces the friction and breakaway torque to very low values, and reducing wear. It is also in service during shut-down.

6-15. ELECTRICAL CHARACTERISTICS.

a. The electrical characteristics of a generator and generator-motor, in addition to determining its individual performance, will affect the performance of the power system to which it will be connected. These characteristics can be varied within limits to best suit overall performance. The values for these characteristics must be included in the procurement specifications.

b. Characteristics of a generator or generator-motor which have an important effect on the stability characteristics of the electrical system are Short Circuit Ratio, Transient Reactance, Exciter System Performance, and the electrical damping provided by the WK^2 of the rotating parts of the units.

c. A short circuit ratio (SCR) is the ratio of the field current required to produce rated voltage at no load to the field current required to circulate rated current or short circuit. With no saturation, it is the reciprocal of the synchronous impedance (Xd) and a convenient factor for comparing and specifying the relative steady-state characteristics of generators and generator-motors. The higher the ratio, the greater the inherent stability of the machine. A system stability study is necessary to determine whether a higher-than-normal short-circuit ratio is required. Increasing the ratio above normal increases the machine size (the machine being de-rated), the normal flywheel effect (WK^2) and the machine costs, and decreases the efficiency and the transient reactance of the machine.

d. Some electrical systems require a lower than normal transient reactance. However, when a higher than normal SCR is specified, the transient reactance will be less than normal. Either the lower than normal transient reactance or the higher than normal SCR, but not both, will increase the cost. The cost increase is determined by the more expensive option. Decreasing transient reactance increases fault currents.

e. An increase in the rotor inertia (WK^2) above normal increases the cost, size and weight of the machine and decreases the efficiency. In a pump-turbine installation increasing the WK^2 of the generator-motor increases the starting time in the pumping mode. See Paragraph 6-7.

f. Exciter System Performance (See IEEE 69TP154 - PWR).

(1) Modern voltage regulator systems have increased the dynamic as well as the steady state stability of electrical systems.

(2) The excitation system should be capable of reversing the excitation voltage of full negative voltage to rapidly reduce field current when required. Capability to reverse field current, however, is normally not required.

(3) It must be recognized that some systems, at times, require operation of the generating equipment at voltages below normal. It must also be recognized that the excitation system should be capable of achieving the required performance at a specified voltage available from the generator terminals. However, specifying a voltage materially below normal will increase the size of the excitation equipment, the space required to house it, and its cost.

h. Amortisseur Windings.

(1) While many hydroelectric generators have been provided with non-continuous amortisseur windings in the past, continuous amortisseur windings are now normally specified for all Corps of Engineers machines. Continuous amortisseur windings provide substantial benefits over non-connected windings regarding stability, supplying unbalanced loads, effects on hunting etc., as described below. These benefits are particularly advantageous because of the difficulty in prior determination of system conditions. Continuous, heavy-duty amortisseur windings are required for generator-motors which are to be started as induction motors.

(2) Amortisseur windings are designed for a calculated ratio of quadrature-axis subtransient reactance to direct-axis subtransient reactance not to exceed 1.35 for an open amortisseur winding and not to exceed 1.10 for a closed winding.

(3) The advantages of amortisseur windings are:

(a) They reduce and in some cases eliminate hunting or sustained pulsations in current and voltage that occur under certain conditions of operation of a synchronous generator.

(b) They are effective in reducing the overvoltages due to unbalanced loads and faults, which can be an important factor in the application of lightning arrestors and in the coordination of insulation levels.

(c) Because they are a material aid in damping out oscillation they are of benefit in improving the ability of the machines to ride through system disturbances.

(d) They provide additional stabilizing torque for generators which are automatically synchronized.

(e) They reduce circuit breaker recovery voltages but tend to increase the magnitude of the current required to be interrupted.

(f) They aid in protecting field windings against current surges caused by lightning or internal faults and in case of the latter are effective in reducing additional damage to the machine.

(g) They permit pump-turbine motor-generators to be started as induction motors.

(4) Amortisseur windings increase stresses in the machine and connected equipment due to the increase in short-circuit current. The additional winding in the rotor must be built to withstand the stresses at maximum overspeed conditions and the stresses in the rotor parts are also increased. A continuous amortisseur winding complicates the cooling and disassembly of the field coils.

(5) An amortisseur winding designed for a calculated ratio of quadrature-axis subtransient reactance to direct-axis subtransient reactance not to exceed 1.35 will increase the price of the machine by approximately one percent. For a ratio not to exceed 1.10, the price increase is approximately three percent. For a continuous winding suitable for use in starting, the price increase is five percent due to the increase in thermal capacity of the winding required.

6-16. METHODS AVAILABLE FOR STARTING PUMP-TURBINES IN THE PUMPING MODE OF OPERATION.

a. The methods for starting pump-turbines in the pumping mode of operation can be classified into three groups, namely: Group 1 which requires continuous amortisseur winding; Group 2 which does not require continuous amortisseur windings; and Group 3 which requires separate starting devices.

b. Group 1 Starting Methods: Four methods of starting the unit as an induction motor with full or reduced voltage applied to the generator-motor terminal as follows:

(1) Full voltage start.

(2) Reduced voltage start.

(3) Part winding start.

(4) Reduced frequency induction start. This method utilizes another generator or generator-motor which may be isolated for starting duty.

c. Group 2 Starting Methods:

(1) Synchronous start.

(2) Static converter start.

d. Group 3 Starting Methods:

(1) Wound rotor induction motor start - Pony motor.

(2) Shaft connected starting turbine.

(3) Exciter starting.

e. The first three methods under Group 1 are applicable only to moderately sized units. Of these methods, the full voltage method has the lowest cost in its applicable range because no extra switching equipment is required. It also has the shortest starting time of any method (approximately 20 to 30 seconds). Because of the large starting kva that the full voltage method requires (unless the unit will be connected to a very stiff system), the system voltage drop may be too great for the system to tolerate when a unit is being started. Methods

(2), (3) and (4) are applicable within the range of metal clad type breakers. The start up time will be of two to three minutes and the starting kva in the neighborhood of the machine rating. The part winding start, Method (3) of Group 1 requires a careful investigation in each case. The difficulties in design of the motor-generator may make this type of starting impractical. The reduced frequency induction start method, Group 1, Method (4), sometimes referred to as the semi-synchronous start method, is applicable to plants having conventional generating units as well as generator-motor units, where provision is made so that a generator unit and a generator-motor unit may be isolated for starting or where a remote unit and transmission line may be isolated to start or be started by an isolated unit in the plant. This method is the one that has been most applicable for the Corps pump-turbine installations. The amortisseur duty for this type of start is much less than for the other methods in Group 1. In this method of starting, the water in the pump-turbine draft tube is depressed, the generator unit is brought up to approximately 80 percent speed without excitation and then connected to the generator motor, field current is then applied to the generating unit and the generator-motor accelerates as an induction motor and the generating unit will decelerate until the same speed is reached usually 30 to 40 percent rated speed. At this point field current is applied to the motor synchronizing it to the generator, the turbine wicket gates opened and the units brought up to rated speed and synchronized to the system. The pumping load can now be transferred to the system at the rate desired and the generating unit shut down or used to start another pumping unit if so required. This method of starting and synchronizing to the system eliminates any sudden load change on the system. This method of starting is applicable to all ratings but requires a careful study of starting conditions be made. Usually the rating of the generating unit is about equal to that of the unit to be started, but its WK^2 can be as little as 50 percent of the WK^2 of the unit to be started.

f. The synchronous start method, Method (1) of Group 2 as in the semi-synchronous start method uses an isolated generating unit to provide the starting power. Water is depressed in the pump-turbine draft tube and both units are electrically connected at standstill. Excitation is applied to both machines at rest and they are then brought up to speed in synchronism by admitting water to the turbine. This system provides smooth and rapid starting in 1-5 minutes. A separate source of excitation is required for each unit. A continuous amortisseur winding is not required for this method of starting. It is applicable for all ratings. The units have the same rated speed and the starting unit can be as small as 15 percent of the rating of the maximum unit to be started. This system will permit start-up without the normal tailwater depression. As soon as the unit reaches a speed high enough to prime the pump-turbine, the gates of the pump turbine are opened. This avoids a rough pump-start condition at shut-off head and synchronous speed and provides smooth and rapid starting and transfer of load to the system.

g. The static converter start, Method (2) of Group 3 is applicable to all ratings but its cost limits its use to a plant having 3 or 4 units of large capacity. The static converter is connected to a starting bus which in turn is connected to the unit to be started. During starting, the converter supplies a variable frequency output to the motor. The generator-motor is connected to the starting bus with zero frequency, and the input frequency during acceleration up to synchronous speed is controlled by silicon-controlled rectifier thyristors. As soon as the pumping unit has been synchronized to the power systems, the static converter can be de-energized and the starting bus and converter connected for starting the next unit. The static converter can be used as a brake to reduce deceleration time when a unit is being removed from service to maintenance, or in an emergency. Its use will also reduce wear on the generator.

h. Wound rotor induction motor start (Pony motor), Method (1) of Group 3 is applicable to any size unit, but because of its high cost for small units, its use is usually limited to large units. The starting time depends on the motor capacity provided, but usually is of the order of ten minutes with an approximate starting kva of five percent. This is probably the most costly method because starting motors are required for each unit. The starting control also requires a large floor area. It does provide for a very smooth starting system, however, and permits balancing of the complete unit in both directions of rotation without watering the unit.