

Generator Design for Bidding Purpose on Upper Kotmale Hydropower Project

M. IORI

Abstract: In case of preparing a bidding document for hydropower project based on Conditions of Contract for Plant and Design-Build, the Employer/the Engineer shall provide a basic requirement/design for the equipment. The paper presents major points of basic design of generator referring to the actual design of Upper Kotmale Hydropower Project.

Keywords: Hydroelectric, Generators, Design

1. Introduction

The following basic aspects and ratings shall be decided to prepare a bidding document for hydropower projects by Plant and Design-Build Contract, but not limited;

- Bearing arrangement
- Capacity and Power Factor
- Rotating speed
- Rated Voltage
- Flywheel Effect
- Excitation System
- Line Charging Capacity
- Cooling System of Generator

2. Bearing Arrangement

There are four (4) major bearing arrangements of vertical generators such as suspended type, umbrella type, semi-umbrella type and head cover supported type as shown in Fig.1. (order from the left)

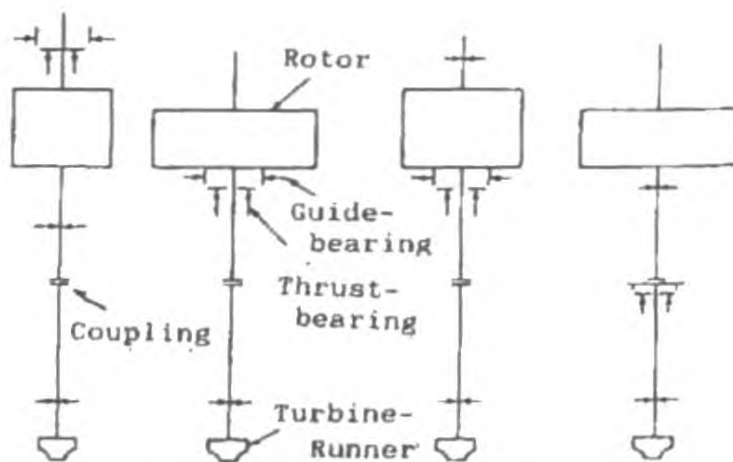


Fig.1 Bearing Arrangement

Selection of the bearing arrangement type is decided mainly by unit rotating speed and unit capacity. The suspended type is selected for 300min⁻¹ and more rotating speed units, the umbrella type is selected for 200min⁻¹ and less rotating speed machine, the semi-umbrella type

is generally selected for large capacity and medium speed units. The head cover supported type is selected for very large capacity units or for Kaplan turbine units.

Rotating speed of units of Upper Kotmale P/S is 600min⁻¹ and its capacity is 88MVA. This is high speed units in hydropower unit; therefore, we selected the suspended type bearing arrangement for the Project.

Other factor of selection of bearing arrangement is height of generator. Fig.2 shows difference of height of generator between suspended type and umbrella type. Umbrella type can reduce height of powerhouse comparing with suspended type.

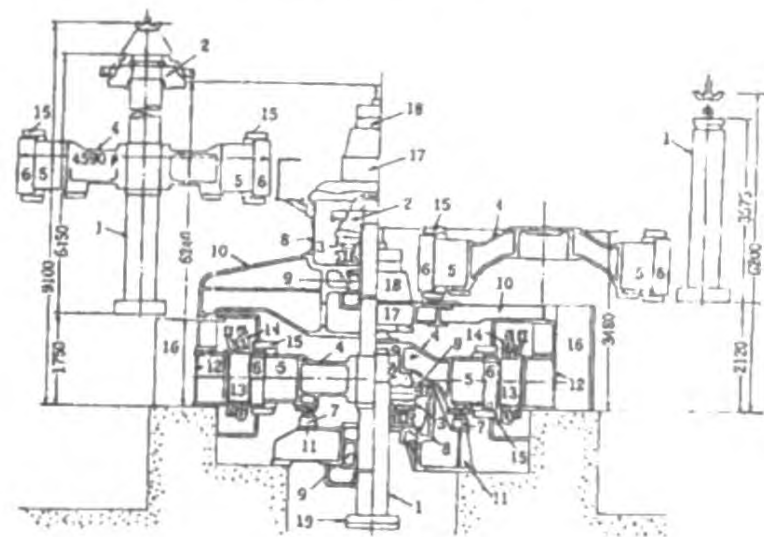


Fig.2 Comparison of Suspended type (left) and Umbrella type (right)

3. Capacity and Power Factor

Rated capacity of the generator for Upper Kotmale Power Station is specified to be 88,000kVA and 0.85 (lagging) power factor.

Masafumi IORI., BSc. Eng. (Electrical Engineering)
Deputy Project Manager of UKHP
J-Power., Japan

The rating is determined upon consideration of the turbine output and generator power factor as stated herein.

Capacity of generator is given by the following equation.

$$P_g = P_t \times \eta_g \times \frac{1}{p_f} \quad (1)$$

Where,

P_g : Generator capacity (kVA)
 P_t : Turbine output (kW)
 η_g : Generator efficiency 0.975
 p_f : Power factor 0.85

The power factor of synchronous generator driven by hydraulic turbine is normally designed at 0.90 to 0.95 (lagging). In case a low power factor is adopted, the cost of generator increases; however, the power system stability and the regulating capacity of reactive power are improved. 0.85 power factor is selected for more voltage regulation of the Network for Upper Kotmale Project.

The turbine output at normal and maximum effective heads is specified to be 77,000 kW at design stage.

Therefore, the generator capacity corresponding to the turbine output, adopting 0.85 power factor and 0.975 generator efficiency, is;

$$P_g = 77,000 \times 0.975 \times \frac{1}{0.85} \quad (2)$$

$$= 88,323$$

$$\cong 88,000 \text{ (kVA)}$$

4. Rotating Speed

Rated speed of unit is decided to consider following aspects:

- Limit of specific speed (N_s lim.) of Francis turbine
- Draft head (H_s) and center level of turbine casing
- Generator synchronous speed

4.1 Limit of specific speed (N_s lim.)

Rated speed of turbine (N) is calculated by the following formula:

$$N = \frac{N_s \times Hd^{1.25}}{P_t^{0.5}} \text{ (min}^{-1}\text{)} \quad (3)$$

Where,

N : Rotating Speed (min^{-1})
 N_s : Specific speed ($m\text{-kW}$)
 Hd : Normal effective head (m)
 P_t : Turbine output (kW)

N_s limit of Francis turbine is given in Japanese Standard JEC-4001 (1992) as follows:

$$N_s \text{ lim.} = \frac{21,000}{Hd + 25} + 35 \quad (4)$$

$$= 77.2(m - kW)$$

$$N = \frac{77.2 \times 473.1^{1.25}}{77,000^{0.5}} \quad (5)$$

$$= 613 \text{ (min}^{-1}\text{)}$$

Therefore, the turbine rated speed is selected around or lower than 600 min^{-1} .

4.2 Draft head and center level of casing

Draft head (H_s) is calculated as follows:

$$H_s = H_a - H_v - \delta p H_d \quad (6)$$

Where,

H_s : Draft head (m)
 H_a : Atmospheric pressure at tailrace
 H_v : Vapour pressure at 30°C
 δp : Plant cavitation coefficient

This paper does not describe on turbine design issue; therefore, only result of study is summarized in the following table.

Table-1 Rated speed / Turbine characteristics

Rated speed : N (min^{-1})	500	600	750
Specific speed : N_s ($m\text{-kW}$)	62.9	75.5	95.1
N_s/N_s lim.	0.815	0.978	1.23
Draft head : H_s (m)	-0.87	-4.7	-11.5
Center level of casing (EL.m)	699	695	688

4.3 Generator synchronous speed

The generator synchronous speed calculated from following formula.

$$N = \frac{120 \times f}{P} \text{ (min}^{-1}\text{)} \quad (7)$$

Where,

N : Generator Rotating speed 600 min^{-1}
 f : Rated frequency 50 Hz
 P : Number of poles

$$P = \frac{120 \times 50}{600} = 10 \quad (8)$$

P must be integral number.

4.4 Conclusion

As the results mentioned above, the unit rated rotating speed is selected 600 min⁻¹ because of the most economical design.

5. Rated Voltage

Generator voltage is mainly decided by its capacity to optimize the dimension of the generator. Tendency of the selection of generator voltage is as follows

- Less Than 20MVA : 6.6kV or 6.9kV
- From 20 to 70MVA : 11kV
- From 50 to 200MVA : 13.2, 13.8 or 14.4kV
- More than 200MVA : 16, 16.5 or 18kV

In general, the higher terminal voltage of generator, thicker insulating material of stator coil is required, then restricts the heat radiation of the coil is occurred due to the large area ratio of insulating material occupied inside the stator slots. Therefore, current density of stator coil must be decreased in order to decrease the quantity of heat radiated on stator coil. Result of this countermeasure, the dimension and equipment cost of generator will be increased.

The lower terminal voltage of generator increase the current and stray load losses of stator coil, therefore, the stator coil circuit must be divided into some parallel circuits to decrease the current of each circuit, these parallel circuit of stator coil cause the higher cost of equipment and complication of the stator winding connection. The current per one circuit of stator coil is normally limited at 1,500 to 2,800 amperes. In this case, the voltage between phases and between each parallel circuit should be necessary balanced. Since the generator of the project has 10 poles, the parallel circuits of stator coil is 2 circuits accommodating with the current limitation value of one circuit.

From above concept and consideration with the capacity of isolated phase bus (IPB), the terminal voltage of generator is decided as 13.8 kV, and the parallel circuits of stator coil are two (2) circuits with 1,855 amperes per each circuit of stator coil. However, number of parallel circuits will be proposed by a

manufacturer of generator in bidding stage normally.

Current of one circuit of stator coil and parallel number of stator coil are given in Table 2.

Table-2 Current of one circuit of stator coil

Generator voltage (kV)	Parallel number of stator coil				
	1	2	3	4	5
11.0	4,650	2,325	1,550	1,163	930
13.2	3,880	1,940	1,293	970	776
13.8	3,710	1,855	1,237	928	742
15.4	3,320	1,660	1,107	830	664
16.5	3,100	1,550	1,034	775	620
18.0	2,840	1,420	947	710	568
20.0	2,560	1,280	854	640	512

Note: Generator Rated Output is 88 MVA and shading cells are applicable

6. Flywheel Effect

Normal flywheel effect (GD²) of the synchronous generator driven by large vertical hydraulic turbine is given as follows;

According to the CIGRE-REPORT 102, 1984 (The Choice of Moment of Inertia for Hydro-electric Installation);

$$GD^2 = \frac{T_a \times (P_g)}{2.74 \times (N)^2} \times 10^3 (t - m^2) \quad (9)$$

Where,

GD² : Normal flywheel effect (t-m²)

P_g : Generator Capacity (kVA)

T_a : Acceleration constant (sec.)

N : Revolving speed (N = 600 min⁻¹)

And, acceleration constant (T_a) is given as follows according to the CIGRE-REPORT 142, 1964:

$$T_a \cong \frac{1.8}{p_f} \times (P_g \times 10^{-3})^{0.25} \times \left(1 - \frac{3}{2P}\right) \text{ (sec.)} \quad (10)$$

Where,

P_g : Generator Capacity (kVA)

p_f : Power factor (0.85)

$$T_a \cong \frac{1.8}{p_f} \times (P_g \times 10^{-3})^{0.25} \times \left(1 - \frac{3}{2P}\right) \text{ (sec.)}$$

$$\cong 5.5 \text{ (sec)}$$

2P : Number of poles (20)

Then,

$$GD^2 = \frac{5.5 \times 88,000}{2.74 \times 600^2} \times 10^3$$

$$\cong 490 \text{ (t-m}^2\text{)}$$

According to the NEMA Pub. No. LG2-1959;

$$GD^2 \cong 0.6 \times 10^6 (Pg \times 10^{-3})^{1.25} \times N^{-1.98} \quad (11)$$

Then,

$$GD^2 \cong 0.6 \times 10^6 \times 88^{1.25} \times 600^{-1.98}$$

$$\cong 510 \text{ (t-m}^2\text{)}$$

According to J-POWER experience;

$$GD^2 \cong 0.333 \times 10^6 \times (Pg \times 10^{-3})^{1.295} \times N^{-1.947} \quad (12)$$

Then,

$$GD^2 \cong 0.333 \times 10^6 \times 88^{1.295} \times 600^{-1.945}$$

$$\cong 430 \text{ (t-m}^2\text{)}$$

Required flywheel effect (GD^2) of generator is 550 t-m² which is calculated from speed rise of unit at the time of full load rejection.

Therefore, the normal flywheel effect of generator is specified to be not less than 550 t-m² in the Bidding documents, which is more than value from the result of the calculation mentioned above.

7. Excitation System

There are three (3) major systems of excitation system as follows;

- Self-excited shunt system
- Separately-excited station power source system
- Separately-excited brushless generator system

Connection diagrams of these systems are shown in Figure. 3.

The comparison of these systems is made as shown in the Table. 3.

From the said comparison sheet, the self-excited shunt system has been adopted in a great number of hydro power plants for its inexpensive cost and easy maintenance.

Taking account of easy maintenance, the brushless excitation system is also widely applied up to middle class generators. It is difficult to apply the brushless excitation system for large capacity generators.

Upper Kotmale P/S was selected self-excited shunt system.

In case of self-excited shunt system is applied, an initial excitation power source must be

separately provided to build-up the generator voltage up to a certain voltage at which AVR and thyristor gate circuits are adequately activated at standard design which an exciter transformer is located generator side of Generator circuit-breaker. Please refer Fig.4 "Schematic Diagram of Excitation System for Upper Kotmale", the exciter transformer is located main transformer side of generator circuit-breaker. In this arrangement, initial excitation at normal generating mode is not necessary.

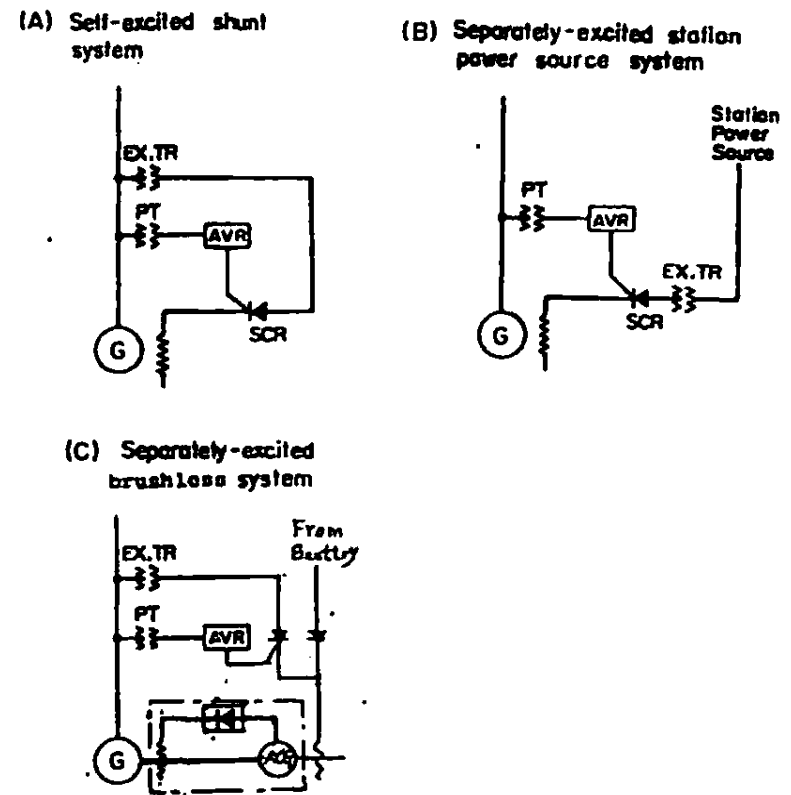


Fig.3 Comparison of Excitation Systems

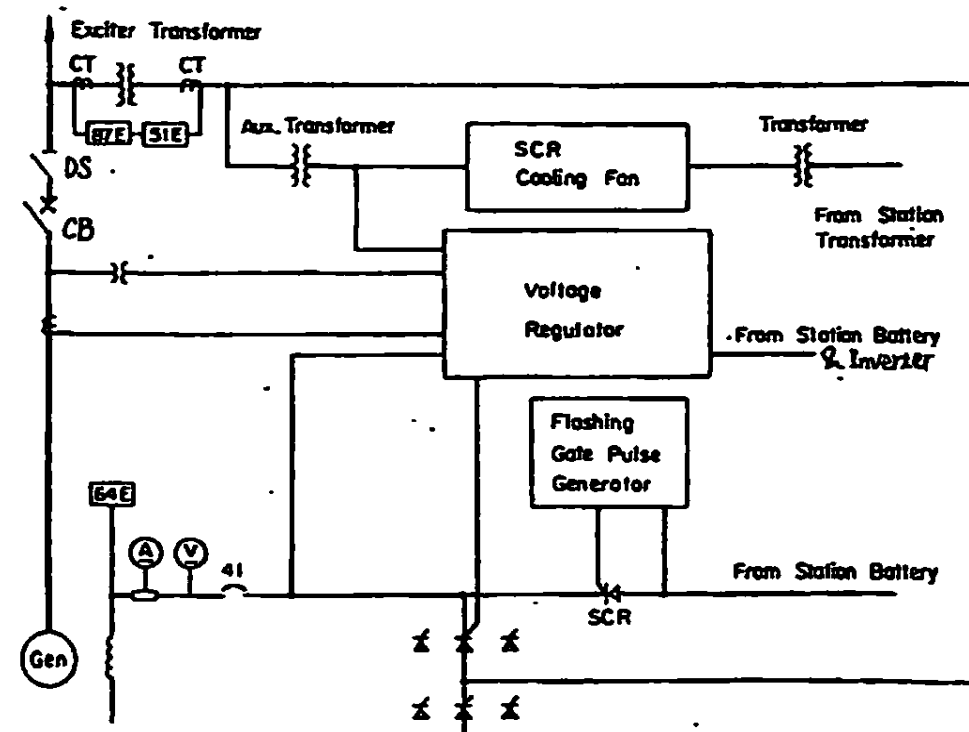


Fig.4 Schematic Diagram of Excitation System for Upper Kotmale

Table-3 Comparison of Excitation System

	Self-excited Shunt System	Separately-excited Static Power Source System	Separately-excited Brushless Generator System
Connection Diagram	(A)	(B)	(C)
Quick Response	good	good	good
Trials-charging Transmission Line Voltage Build-up	Limited range	Full range	Limited range
Excitation Capability at the time of Short Circuit Fault	Not maintained	Maintained	Maintained
Maintenance Requirement	Little	Little	Little
Separate Power Source for Initial Excitation	required	Not required	required
Price (Approximately)	100%	100%	120%

8. Line Charging Capacity

The limitation of line charging capacity of generator without over-voltage due to self-excitation is calculated by the following formula:

$$Q_g \leq P_g \times \left(\frac{V_g'}{V_g} \right)^2 \times \frac{r}{1+\sigma} \quad (13)$$

Where,

- Q_g : Line charging capacity (kVA)
- P_g : Generator Capacity (kVA)
- V_g : Rated voltage of generator
- V_g' : Charging voltage (0.9 V_g)
- r : Short-circuit ratio (1.0)
- σ : Saturation factor (0.1)

Therefore,

$$Q_g \leq 88,000 \times 0.9^2 \times \frac{1.0}{1+0.1} \cong 64,800 \text{ (kVA)}$$

On the other hand, the extent of charged transmission line is assumed from Upper Kotmale Power Plant to Kotmale Power station (220 kV, 2 circuits, 17km). Line charging capacity (Q_l) is given by the following equation.

$$Q_l = 2\pi f C_L V_L^2 L \times 10^{-3} \text{ (kVA)} \quad (14)$$

Where,

- f : Frequency (50 Hz)
- C_L : Line capacitance (0.012 $\mu\text{F}/\text{km}$)
- V_L : Line voltage (220 kV)
- L : Line length (17 km)

Therefore;

$$Q_l = 2\pi \times 50 \times (0.012 \times 10^{-6}) \times (220 \times 10^3)^2 \times 17 \times 10^{-3} = 3,100 \text{ (kVA)}$$

Therefore, the generator has a sufficient charging capacity for the transmission line.

During the Commissioning test of Upper Kotmale Project, line charging test by Biyagama Line (72km) via Kotmale Switchyard was performed successfully.

9. Cooling System of Generator

The generator for Upper Kotmale P/S has a conventional type of cooling system, i.e., surface air coolers. The air coolers shall have a sufficient cooling capacity to maintain within 45°C the air temperature of the outlet of cooler. Each air cooler has a plate fin type fixed with tube sheets.

The circulation of air will be performed by fan action of rotor spider, rotor rim and field poles so-called rim duct air circulation. The air will circulate through the open parts of the stator frame and the coolers, and will flow out into the top and bottom of the rotor.

The cooling system of each generator shall have a sufficient capacity so as to operate the generator continuously at rated output without exceeding the specified maximum temperature rise.

Temperature class of the insulating material of stator is normally F Class (max. temperature is 155°C); therefore, F class insulation and F class permissible temperature rise is the most economical design. However, commonly F class insulation and B class (max. temperature is 130°C) permissible temperature rise is widely applied for many hydro-generators. Approximately 5% cost different between B class and F class temperature rise generators.

The quantity of water required for cooling the generator when operating at rated kVA can be calculated as follows:

$$Q_w = \frac{860 \times Lt \times k}{60 \times \sigma t} \quad (15)$$

Where,

- Q_w : quantity of cooling water (L/min.)
- Lt : total losses (1,900 kW)
- σt : cooling water temperature rise (before and after cooling) (°C): 9 °C
- k : aging factor (1.1)

$$Q_w = \frac{860 \times 1,900 \times 1.1}{60 \times 9} \cong 3,300 \text{ (liters/min)}$$

10. Conclusion

Very basic study of generator design for bidding purpose is introduced in this paper

referring to actual design of Upper Kotmale Project.

Necessary information for civil construction such as dimensions of generator, loading weight, arrangement of block out of concrete and so on is also essential study at design stage of Hydropower Project. Furthermore, split number of stator is decided by weight of stator and limitation of transportation, and lifting height Overhead Traveling Crane is decided required lifting height of generator parts.

The followings are summary of ratings of generator for Upper Kotmale P/S.

- (a) Type : 3-phase, alternating-current synchronous generator, vertical shaft, rotating field, enclosed hood, air-cooled type
- (b) Capacity : 88,000kVA at 0.85 lagging (over excited)
- (c) Armature Voltage : 13.8kV

- (c) Armature Voltage : 13.8kV
- (d) Armature Current : 3,700A
- (e) Power Factor : 0.85 lagging
- (f) Frequency : 50Hz
- (g) Rotating Speed : 600min⁻¹
- (h) Direction of Speed : Clockwise viewed from the top of generator
- (i) Stator winding connection : Y connection
- (j) Short circuit ratio : not less than 1.0
- (k) Fly-wheel effect : not less than 550ton-m²
- (l) Temperature rise : not more than 85°C (embedded RTD measurement)
- (m) Dielectric strength : 28.6kV 1min
- (n) Degree of protection: IP54
- (o) Method of cooling : IC8A1W7
- (p) Deviation of waveform : not more than 5%
- (q) Telephone Influence Factor (TIF) : not exceed 1.5%



Break Through of Headrace tunnel