International Journal of Trend in Scientific Research and Development (IJTSRD)
Volume 3 Issue 5, August 2019 Available Online: www.ijtsrd.com e-ISSN: 2456 – 6470

Static Excitation System of Generator in Hydropower Station

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***How to cite this paper**:* Thida Win | Hnin Yu Lwin | Zin Wah Aung "Static Excitation System of Generator in Hydropower Station" Published in International Journal of Trend in Scientific Research and Development (ijtsrd), ISSN: 2456-6470, Volume-3 | Issue-5, August 2019, pp.1837-1839, **https://doi.org/10.31142/ijtsrd26742**

IJTSRD26742

ABSTRACT
Excitation system is one of the most important parts of the synchronous generators. Excitation system of the generator comprises from machines, devices and appliances that are intended to provide direct current to the generator field winding and this current regulation. For a constant frequency supply, the output voltage of the machine depends on the excitation current. In this paper, static excitation system of 10 MW synchronous generator in hydropower station is described and analyzed how the excitation current can be controlled to be stable terminal voltage and reactive power of generator.

***KEYWORDS:** static excitation system, excitation current, terminal voltage, reactive power*

I. INTRODUCTION
All synchronous machines excepting certain machines like permanent magnet generators require a DC supply to excite their field winding. The generators excitation systems work when generator system operates a dc charge to the generator heads to energize the field of magnetic around them to enable the electricity that should be generated. For a constant frequency supply, the output voltage of the machine depends on the excitation current. The control of excitation current for maintaining constant voltage at generator output terminals started with control through a field rheostat, the supply being obtained from dc exciter. Exciter should be capable of supplying necessary excitation for synchronous generator in a reasonable period during normal and abnormal conditions, so that synchronous generator will be in synchronism with the national grid. [1][3]

Excitation system includes excitation power and excitation device. The main body of excitation power is exciter or excitation transformer. The excitation device is an electrical control device that controls and adjusts excitation current besides excitation power in excitation systems of synchronous generator. Excitation current is provided by the excitation system, which according to usually consists of automatic voltage regulator (AVR), exciter, measuring elements, power system stabilizer (PSS) and limitation and protection unit.[2]

II. Specification of Synchronous Generator
The specification of synchronous generator used in the hydropower station are described.

Capacity	10 MW
Rated voltage	11000 V
Rated current	656 A
Rated frequency	50 Hz
Power factor	0.8
Number of pole	28
Number of phase	3
Rated speed	214.3 rpm
Runaway speed	480 rpm
Rated excitation voltage	178 V
Rated excitation current	481 A
Direct axis synchronous reactance (X_d)	1
Quadrature axis synchronous reactance (X_q)	0.62526
Excitation winding resistance (R_f)	0.2943
Number of slot	240
Number of conductor per slot	20
Magnetic flux (φ)	0.04 Wb
Pitch factor (k_p)	1 (for full pitch winding)

III. Static Excitation System
In static excitation system, power for providing field excitation is derived from the generator output terminals. A transformer known as excitation transformer, is connected to the output terminals of generator to step down the voltage to required voltage level. As dc supply is needed, transformer output is connected to a thyristor full bridge rectifier. The firing angle of thyristor full bridge rectifier is controlled by a regulator so that require field excitation may be provided. Secondary terminal of current transformer and potential transformer connected to generator output terminal is fed to regulator. On the basic of generator terminal voltage, the regulator adjusts its firing angle generator output voltage has increased beyond its rated voltage, in that case, field current must be reduced to maintain the terminal voltage. Therefore, regulator increases the firing angle so that the average value of dc current may reduce. Similarly, if the generator terminal voltage goes below its rated value then field current must be increased. Therefore, regulator decreases the firing angle to increase the average value of field current. As in static excitation system, excitation is provided by field winding wound on the rotor therefore slip rings and carbon brushes are used. [4]

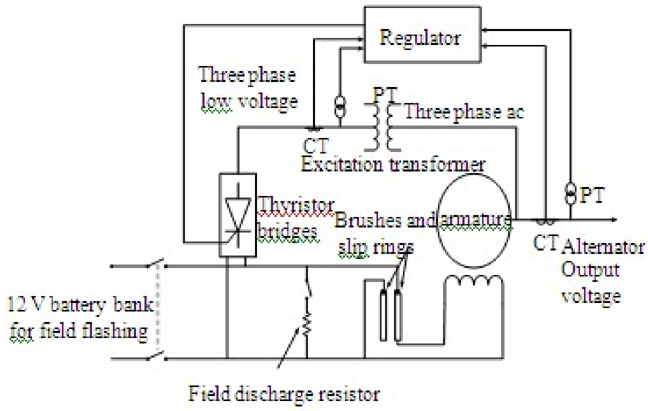

Figure 1 Static Excitation System

In static excitation system, field excitation power is derived from the generator output terminals therefore it can only work during the normal and steady operation of generator. To start a generator, it is not possible to have field excitation using static excitation system as there is no generator terminal voltage. In such case, excitation power shall be provided using separate source. As shown in figure 1, this is normally made available using a battery bank. As soon as the generator reaches its rated speed, its terminal voltage reaches to rated voltage and static excitation system comes in picture. Thus, as soon as generator reaches its rated speed, battery bank is isolated and excitation power is fed by static excitation system.[4]

Static excitation system use reliable and high power thyristor, is simple in design and provides fast response characteristics as needed in modern power system. As there is no separate rotating type exciter, the system is free from friction, windage and commutator loss occurring in the exciter. Since excitation energy is directly taken from generator output terminals therefore excitation voltage is directly proportional to the generator speed. This improves the overall system performance.

IV. Working Principle of Static Excitation in the Hydropower Station

In the hydropower station, three ac synchronous generators are used. Each generator has 10 MW installed capacity and produce 11 kV rated voltage. The rotor of each generator has 28 magnetic poles and the windings which produce electricity are fixed in the stator. As the standard frequency of Myanmar is 50 Hz, the speed of generator is 214.3 rpm.

Initial field flashing is taken from dc battery bank (220 V) for producing generator power. Excitation starts when the rotor speed reaches 95 percent of the rated speed. When the power for providing field excitation is derived from the generator output terminals, the static excitation system starts. A transformer known as the excitation transformer, is connected to the output terminals of generator to step down the voltage to required voltage level. As the generator need dc supply, transformer output is connected to a thyristor full bridge rectifier.

The firing angle of thyristor full bridge rectifier is controlled by a regulator so that required field excitation may be provided. The converted dc voltage is provided to field winding through the slip rings and carbon brushes. In this way, the excitation voltage needed for generator is produced.

V. Mathematical Equations

A. Two-reaction Theory

The theory proposes to resolve the given armature mmfs into two mutually perpendicular components, with one located along the axis of the rotor salient pole. It is known as the direct-axis (or d-axis) component. The other axis is located perpendicular to the axis of the rotor salient pole. It is known as the quadrature-axis (or q-axis) component. The d-axis component of the armature mmf F_d is denoted by F_d and the q-axis component by F_q. The component F_d is either magnetizing or demagnetizing. The component F_q results in a cross-magnetizing effect. [5]

$$F_d = F_a \sin \psi \qquad (1)$$

$$F_q = F_a \cos \psi \qquad (2)$$

Salient-pole generators, such as hydroelectric generators, have armature inductances that are a function of rotor position, making analysis one step more complicated. The key to analysis of such machines is to separate mmf and flux into two orthogonal components. The direct axis is aligned with the field winding, while the quadrature axis leads the direct by 90 degrees.

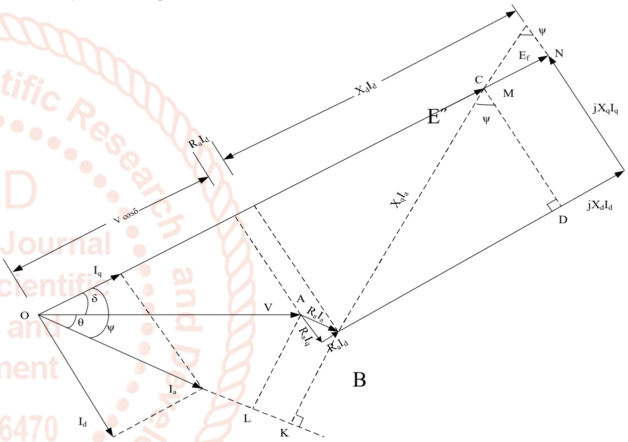

Figure 2 Determination of δ from the Phasor Diagram

The voltage E″ is equal at the terminal voltage V plus the voltage drops in the resistance and leakage reactance of the armature, so that

$$E'' = V + (R_a + j X_q) I_a \qquad (3)$$

$$\tan \delta = \frac{ImOC}{ReOC} = \frac{ImE''}{ReE''} \qquad (4)$$

$$E_f = E'' + (X_d - X_q) I_d \qquad (5)$$

$$Q = \frac{|V_t||E_f|}{X_d}\cos\delta - |V_t|^2 \left(\frac{\sin^2(\delta)}{X_q} + \frac{\cos^2(\delta)}{X_d}\right) \qquad (6)$$

B. Equation for Induced E.M.F in an Alternator

If P is number of poles in the machine, and φ is flux per pole, magnetic flux cut by a conductor in one revolution of the rotor is P φ. If N is the R.P.M, then, time taken by the rotor to make one revolution is 60/seconds. Therefore,

$$\text{Flux cut per second by a conductor} = \frac{p\varphi}{60/N} \qquad (7)$$

But average induced E.M.F in a conductor = flux cut per second. Therefore

Average induced E.M.F in a conductor = $\frac{p\varphi N}{60}$ (8)

If T is total number of turns connected in series per phase, and since each turn will have two conductors, Z is total number of conductor in series per phase (2T). So,

Average E.M.F induced per phase, $E_{av} = \frac{p\varphi N}{60} \times 2T$ (9)

The air gap flux in the generator will have more or less sinusoidal. For a sinusoidal waveform

Form Factor = $\frac{E_{ph}}{E_{av}}$ (10)

Pitch factor, $k_p = \cos\frac{\alpha}{2}$ (11)

Number of slot per pole per phase, $m = \frac{\text{slot}}{\text{pole} \times \text{phase}}$ (12)

Slot angle, $\beta = 180^o /$ no of slot per pole (13)

distribution factor, $k_d = \frac{\sin\frac{m\beta}{2}}{m\sin\frac{\beta}{2}}$ (14)

Winding factor, $k_w = k_p k_d$ (15)

Number of turns per phase, $T_{ph} = \frac{Z_{ph}}{2}$ (16)

Z_{ph} = (no of slots × no of conductor) / 3 (17)

In practical machines the windings will be generally short pitched and distributed over the periphery of the machine. Hence in reducing the emf equation both pitch factor and distribution factor has to be considered.[6]

Hence the general emf equation including pitch factor and distribution factor can be given as

emf induced per phase, $E_{ph} = 4.44\, f\, \varphi\, T_{ph} \times k_p k_d$ volts

$E_{ph} = 4.44\, k_w\, f\, \varphi\, T_{ph}$ volts (18)

Hence line voltage $E_L = \sqrt{3} \times$ phase voltage

$= \sqrt{3}\, E_{ph}$ (19)

VI. Result Based on Actual Data

The following conditions are calculated to stabilize the terminal voltage by changing the excitation current (I_f). It is described five conditions to analyze how much excitation current is adjusted on various load demand changes. The data of the calculation is based on the actual operating data of synchronous generator in hydropower station.

Table .1 Result Data Obtained from Five Conditions

	Condition I	Condition II	Condition III	Condition IV	Condition V
Terminal Voltage Change(kV)	6.35	6.06 to 6.35	5.77 to 6.35	6.64 to 6.35	6.93 to 6.35
E_f(V)	6593.72	6605.85	6619.51	6582.23	6572
I_f(V)	469.94	470.78	471.74	469.1	468.39
Q(MVAR)	1.45	1.52	1.6	1.39	1.33

In condition 1, the excitation current and induced voltage must be 478.6 A and 6718.95 V to generate the desired line voltage (11 KV). This condition is a normal condition.

In condition 2 and 3, the terminal voltage drops and armature current increases when the load demand rises. So, excitation current needs to increase to stabilize the desired terminal voltage. The generator will then increase its supply of reactive power.

In condition 4 and 5, if a generator is experience a voltage rise, the AVR will reduce the field current to maintain the desired voltage at the terminals. The generator will then decrease its supply of reactive power.

The excitation current is reduced when the generator terminal voltage rise. And also, the excitation current is more supplied if the terminal voltage decrease. In this way, the excitation current is adjusted to stabilize the desired terminal voltage. For generator protection, the excitation current is cut off when the generator terminal voltage is either below 90% or above 110% of the rated terminal voltage.

VII. Conclusion

It is found that the variations of the voltage at the generator terminal are mainly related to the change of reactive power. The variations of the voltage are almost unaffected by the active power. The functions of excitation system are to supply direct current to the field winding of generator, regulate the generator terminal voltage, control the reactive power flow between the generator & the power grid and improve the stability of the power system. If the generator terminal voltage is not stable, synchronization cannot be done between the generators and the grid. So, excitation system is important to improve the stability of the power system.

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