Chapter 8 - Synchronous

8.1 Introduction

AC machines are devices with ac on the armature. A synchronous machine has a stationary armature and the field is on the rotor. The armature is ac and is connected directly to the line. The field is dc. If brushes are used, then dc is provided directly to the slip rings which feed the rotor winding. A brushless machine induces ac to the rotor. The ac is converted to dc for the field winding. The typical model is a Thevenin equivalent for the armature and a magnetizing inductance for the field.

An induction machine has ac on the armature also. Induction devices have a stationary field and the armature is on the rotor. The field is connected directly to the line. The field is ac and induces current onto the rotor by transformer action.

This chapter will look at synchronous machines while the next chapter looks at induction motors.

8.2 Application

The stator of a synchronous machine can constructed as single or three-phase. A three-phase has three windings that are mechanically separated by 120º. The resulting currents are equal in magnitude but electrically separated by 120 º.

The minimum magnetic field is 2 pole (1N-1S) and results in a synchronous speed of 3600 rpm.

$$\omega = 2\pi f = speed$$

Synchronous means that the speed synchronizes or exactly matches the frequency of the power system. As a result small motors are frequently used in time clocks and recorders that require precise mechanical timing.

Synchronous motors are used for very large loads since they have less vibration. Synchronous machines tend to be relatively short in comparison to their diameter.

The most common application of synchronous machines is as generators. All utility generators are synchronous. When multiple machines are connected in parallel, they provide very stable frequency. A synchronous machine rotation locks onto the power line frequency which results in a constant speed, dependent only on the frequency.

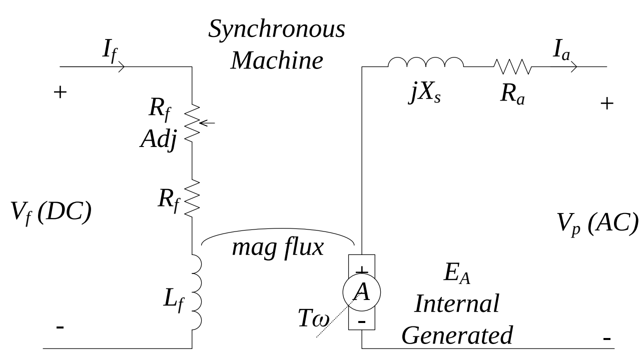
8.3 Model

The model is conducted per phase. The model is for a motor or generator.

$$E_A = V_p - jX_S I_A - R_A I_A$$

$$I_A \cos\theta = \frac{E_A \sin\delta}{X_S}$$

$$P_{out} = \frac{3V_p E_A \sin\delta}{X_S}$$



The variables have the following meanings.

X_s=Synchronous Reactance

δ = torque angle:

max τ @ 90º

$$\delta \approx 15 - 20^\circ$$

Power and torque are available on the shaft.

$$P = \tau\omega$$

$$\tau = \frac{3V_p E_A \sin\delta}{\omega_m X_s}$$

$$\tau = K\varphi I_f$$

A generator has additional considerations.

$$E_A = K\varphi\omega = K_1 i_f \omega$$

$$V_f = I_f (R_f + R_{fadj})$$

$$V_t = E_A - I_A (R_A + jX_s)$$

$$\lambda = Li = \varphi\mathcal{R}$$

EXAMPLE

Synchronous generator, 480 V, wye connected, 200 kva, 50 Hz, rated field current = 5A. Open circuit voltage at rated field current is 540 V Short circuit current at rated field current is 300 A Dc test: 25A, 10 V

armature resistance ________________________

Resistance is a dc value. For a Wye machine, the current passes through 2 windings.

$$Z = \frac{V}{I}$$

$$2R_A = \frac{10V}{25A} \Rightarrow R_A = 0.2\Omega$$

open circuit phase voltage __________________

For a wye connection,

$$\sqrt{3}V_\Phi = V_T$$

$$V_\Phi = \frac{V_T}{\sqrt{3}} = \frac{540}{\sqrt{3}} = 312V$$

internal generated voltage at the rated field current (no load) _______________________

This is open circuit, so internal = terminal voltage=312V

short circuit phase current __________________________

For wye connection,

$$I_\Phi = I_L$$

$$I_\Phi = 300A$$

synchronous impedance ______________________

Synchronous Z is internal generated voltage at short circuit I

$$Z = \frac{E_A}{I_A}$$

$$Z = \frac{312V}{300A} = 1.039\Omega$$

synchronous reactance ______________________________

$$Z = R + jX$$

$$X = \sqrt{Z^2 - R^2} = \sqrt{1.039^2 - 0.2^2} = 1.02$$

8.4 Generator operation

Generators may be operated stand-alone, in parallel with other similar sized units, or on a large bus. Regardless of the mode, only two controls are available. However, the results of control changes are very different.

Governor

On the mechanical side, the governor controls the power (P) and speed (*w*) of the engine. A speed increase will directly increase the power (P) available from the driver, in relation to the available torque (*T*). Power is measured in watts.

$$P = T\,w \qquad (1)$$

On the electrical side, the frequency (f) changes in proportion to the speed. Frequency is measured in Hertz (cycles / second).

$$w = 2\pi\, f \qquad (2)$$

Voltage Regulator

The voltage regulator manipulates the flux (ϕ) on the exciter, which controls the internal voltage (E) of the generator. K is a constant for the machine. Voltage is measured in volts.

$$E = K\phi f \qquad (3)$$

Outside the generator, the regulator also controls the power factor. This is the ratio of the power out of the machine divided by the voltage and current (I). The $\sqrt{3}$ is a conversion factor for three-phase power. Current is measured in amperes.

$$pf = P / \sqrt{3}\, EI \quad = P / S \;= P / P+jQ \qquad (4)$$

It can be observed that with the power controlled by the governor, and the voltage fixed, then the power factor will decrease as the current from the generator is increased.

Mode

When operating as a single stand-alone unit, the power and current requirements are set by the load connected to the generator. As a result, these are fixed. With the power (P) constrained in line 1, then a governor adjustment can only change speed (*w*) and the electrical frequency (f) in line 2. Similarly, investigate line 4. The power is fixed and the load current is fixed. The regulator only changes the voltage (E) from the generator.

When operating on a large bus, the reactions to the controls appear completely opposite. The large bus will consume as much power and current as can be delivered. The voltage and frequency of the bus are not substantially changed by a single generator. Therefore, adjusting the governor will change the power (P) but not the speed (*w*) as shown in line 1. Similarly, adjusting the regulator will change the reactive power and the power factor (pf).

When operating in parallel with similar sized units, a combination of the characteristics will be observed. The total of the power from all the machines will equal the power required by the load. One generator can be made to pick up more of the load by increasing that unit's governor speed (*w*) adjustment. If all the units' governors are raised, then the frequency will be increased. Likewise, adjusting the regulator on only one unit will change the reactive power and power factor from that machine. If all the regulators are adjusted then the voltage will be changed. Two units of similar size are more difficult to control. Any change in one will cause a swing in the other.

The power factor of the load can be changed by capacitors. This will reduce the current from the generator as shown on line 4. However, a power factor change will not impact the power delivered by the engine.

8.6 Generator curves

When load is added to a generator, the machine will have a voltage change before the regulators can operate. The quantity of dip is determined by how heavily the generator was loaded before the new load was added. The effect is shown in the first curve.

Similarly there will a voltage recovery, but again, it will be limited by the previous loading on the unit, as shown in figure two.

EXAMPLE PROBLEM

Assume 2-400 KW (500 KVA), 0.8 P.F., 900 rpm brushless type generators with static regulators on the line, carrying 600 KW. Determine the voltage dip when starting a 150 hp induction motor. Full voltage starting is to be used.

SOLUTION:

For an average induction motor, 1 hp is 1KVA The inrush current is about 550% of full load.

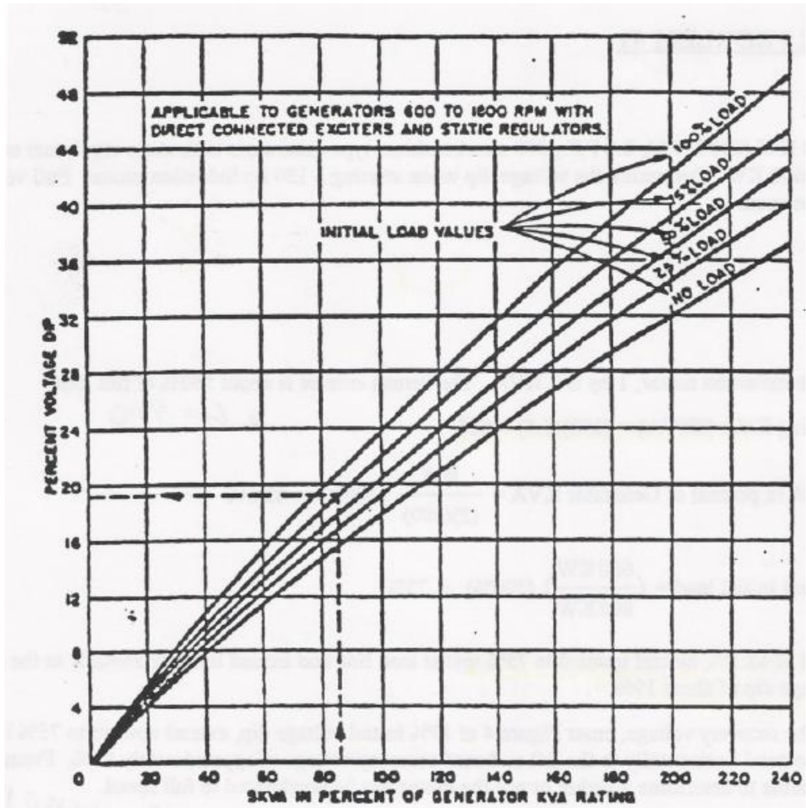
Starting KVA (SKVA) = (150)(5.5) = 825

SKVA in percent of Generator KVA = 825 / 2(500) * 100 = 82.5%

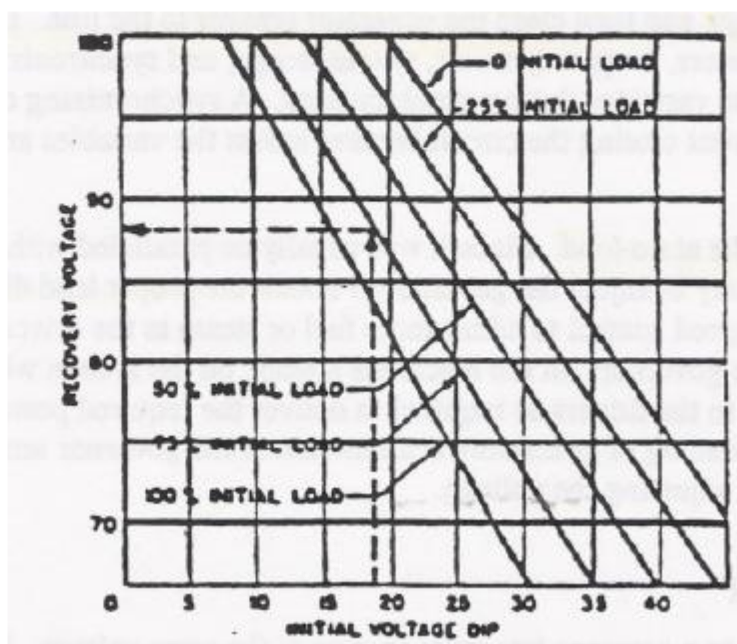
Percent initial load = (600 / 800) (100%) =75%

Enter Figure at 82.5%, extend upward to 75% initial load line and extend line horizontally to the left and read voltage dip of about 19%.

To calculate the recovery voltage, enter Figure 2 at 19% initial voltage dip, extend upward to 75% initial load line and extend horizontally to the left .and read recovery voltage of approximately 88%. From this value, it is possible to determine whether or not the motor can be accelerated to full speed.



Voltage Dip with Motor Starting Loads



Recovery Voltage for Generator

8.7 Speed / frequency

To put a generator on the line, it is necessary to bring it up to speed to match the frequency of the system. Next adjust the voltage and then close the generator breaker to the line. Instruments on the generator Switchboard (voltmeters, frequency meter, synchroscope, and synchronizing lights) are normally provided to observe all of these variables during synchronizing. A synchronizing check relay is generally provided and arranged to prevent closing the.circuit breaker unless the variables are within acceptable limits.

The incoming generator will be at no-load. Since it will usually be paralleled with units carrying considerable load, .it is necessary to adjust the governor to .obtain the proper load division. This is accomplished by raising the speed control to admit more fuel or steam to the driver. As the load increases on the incoming :machine the governors on the machine already on the system will sense the load change and will reduce fuel or steam to the drivers as required to deliver the required power. It is important to remember loading or unloading of generators is a function of the governor setting (speed control) and should never be attempted by adjusting the voltage.

Control and Regulation

All AC genenerators connected to a common bus must operate at the same voltage. If the voltage is increased either manually or by improper voltage regulator action, its associated generator will be overexcited. It will operate at a lower power factor than the other machines. This will cause the generator to supply an excessive amount of KVAR (magnetizing current). Circulating currents can result in excessive heating of the over excited generator.

8.8 Comparison of synchronous and induction generators

There are two types of generators available: Synchronous and Induction types.

Synchronous generators have the DC field excitation supplied from batteries, DC generators or a rectified AC source. When DC generators are used they may be driven from the AC generator shaft directly or by. means of a belt drive or they may be separately driven, independent from the AC generator. In any of the above applications, DC is applied to the field through brushes riding on slip rings attached to the rotor.

Brushless generators use a small AC generator driven directly from the shaft. The AC output is rectified and the DC is applied directly to the main generator field. The exciter generator configuration is reversed from the normal generator in that the armature is rotated with the main generator shaft and the field is fixed. In this way, the AC output can be fed to a rectifier assembly which also rotates and the resulting DC connected directly to the main generator field without brushes or slip rings.

Synchronous generators are rated in accordance with NEMA Standards on a continuous duty basis. The rating is expressed in KVA available at the terminals at 0.80 power factor. The corresponding KW should also be stated. For example, a 400 KW generator would be rated 500 KV A at 0.80 power factor.

An induction generator receives its excitation (magnetizing current) from the system to which it is connected. It consumes rather than supplies reactive power (KVAR) and supplies only real power (KW) to the system. The KVAR required by the induction generator plus the KVAR requirements of all other loads on the system must be supplied from synchronous generators or static capacitors on the system.

When a squirrel cage induction motor is energized from a power system and is mechanically driven above its synchronous speed it will deliver power to the system. Operating as a generator at a given percentage slip above synchronous speed, the torque, current, efficiency and power factor will not differ greatly from that when operating as a motor. The same slip below synchronous speed, the shaft torque and electric power flow is reversed. For example, a 3600 RPM squirrel cage induction motor which delivers full load output at 3550 RPM as a motor will deliver full rated power as a generator at 3650 RPM If the haJf-load motor speed is 3570 RPM, the output as a generator will be one-half of rated value when driven at 3630 RPM, etc.

Since the induction generator is actually an induction motor being driven by a prime mover, it has severaI advantages.

1. It is less expensive and more readily available than a synchronous generator.

2. It does not require a DC field excitation voltage.

3. It automatically synchronizes with the power system, so its controls are simpler and less expensive.

The principal disadvantages of an induction generator are listed.

1. It is not suitable for separate, isolated operation

2. It consumes rather than supplies magnetizing KVAR

3. It cannot contribute to the maintenance of system voltage levels (this is left entirely to the synchronous generators or capacitors)

4. In general it has a lower efficiency.

8.9 Exemplars

An exemplar is typical or representative of a system. These examples are representative of real world situations.

Practice Problem 3-2 (old style) 136

A generator is connected through a step-up transformer to a very large system (infinite bus).

The generator is rated: The transformer is rated:

840 MVA
90% power factor
24kV
$X_d = 160\%$
$X_d' = 25\%$
$X_d'' = 18\%$

800 MVA
22 – 500 kV
X = 14%

The transformer is delivering 600MW at 85% power factor to the system at 500kV when the operator increases the output to 750MW without changing the setting of the generator voltage regulator so that the generator terminal voltage is unchanged.

The operator then adjusts the voltage regulator so that the output of the transformer is 800VA.

REQUIREMENTS:

a) Determine the generator terminal voltage and the new transformer power factor and MVA output after the power output is increased, but before the voltage regulator is adjusted.

b) Determine the generator terminal voltage and the transformer output power factor after the voltage regulator is adjusted

Note: Answer to at least four (4) significant figures.

SOLUTION:

Generator: 840MVA, 90% pf, 24kV

Transformer: 800MVA, 22kV pri/500kV sec, $X_t = 14\%$

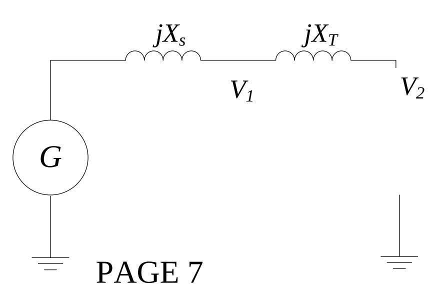
Secondary connected to infinite bus – V fixed, f fixed

Select Per Unit Base – use transformer

$$S_{base} = 800MVA$$

$$V_{2-base} = 500kV$$

$$V_{1-base} = 22kV$$



$$I_{2-base} = \frac{800}{500} 1.6kA$$

$$S = VI^* \qquad I = |I|(\cos\theta + j\sin\theta) \qquad P = S * pf$$

$$P_{1-2} = \frac{V_1 V_2 \sin(\delta_1 - \delta_2)}{X} \qquad Q_{1-2} = \frac{V_1^{\ 2} - |V_1||V_2|\cos(\delta_1 - \delta_2)}{X}$$

$$\delta_1 = \measuredangle V_1; \delta_2 = \measuredangle V_2$$

For infinite bus, fixed V&f , vary P&Q

For fixed load, fixed P&Q, vary V&f

Start Solution

Initial Conditions:

$$S = \frac{600MW}{0.85\,pf} = 705.88MVA$$

$$S_{pu} = \frac{705.88MVA}{800MVA} = 0.8824\measuredangle(\cos^{-1} 0.85) = 0.8824\measuredangle 31.79$$

$$V_{2-pu} = 1.0\measuredangle 0 \text{ (infinite bus)}$$

$$I_{pu}{}^{*} = \frac{S_{pu}}{V_{pu}} = \frac{0.8824\measuredangle 31.79}{1.0\measuredangle 0} = 0.8824\measuredangle 31.79$$

$$I_{pu} = 0.8824\measuredangle -31.79 = (0.75 - j4649)$$

$$V_{21} = IjX_t = (0.75 - j0.4649)(j0.14) = (0.6508 + 0.105)$$

$$\begin{aligned} V_1 = V_2 + V_{21} &= (1 + j0) + (0.06508 + j0.105) \\ &= 1.0651 + j0.105 \\ &= 1.0703\measuredangle 5.6303 \end{aligned}$$

Check using power transfer equation

$$\begin{aligned} P_{1-2} &= \frac{V_1 V_2 \sin(\delta_1 - \delta_2)}{X} \\ &= \frac{1.0702 * 1 * \sin(5.6303 - 0)}{0.14} = 0.75 = 600MW \end{aligned}$$

c) Increase power to 750MW – no change to voltage

$$P_{pu} = \frac{750}{800} = 0.9375$$

$V_2 = 1\measuredangle 0$ (infinite bus)

$$|V_1| = 1.0702$$

The angle will change since P increases, but voltage magnitude has not changed

$$P_{1-2} = \frac{V_1 V_2 \sin(\delta_1 - \delta_2)}{X} \Rightarrow \frac{P_1 X}{|V_1||V_2|} = \sin(\delta_1 - \delta_2)$$

$$\frac{0.9375 * 0.14}{1.0702 * 1} = \sin(\delta_1 - 0) \Rightarrow \delta_1 = 7.0445^\circ$$

$$V_1 = 1.0702\measuredangle 7.0445^\circ = 1.0621 + j0.1313$$

$$I = \frac{(V_1 - V_2)}{jX_t} = \frac{(1.0621 + j0.1313) - (1 + j0)}{j0.14}$$

$$= 0.9375 - j0.4436 = 1.0375\measuredangle -25.31$$

$$\measuredangle S = \measuredangle Z = \measuredangle I = -25.31$$

$$pf = \cos^{-1}(-25.31) = 0.904$$

$$S_{out} = VI^* = 1\measuredangle 0 * 1.0375\measuredangle -25.31 = 1.0375\measuredangle -25.31$$

$$S_{rate} = S_{base} * S_{pu} = 800 * 1.0375 = 830MVA$$

$$V_{1rate} = V_{1base} * V_{1pu} = 22kV * 1.0702 = 23.54kV$$

- Change voltage so transformer is at rated MVA (800MVA)

$$S = 800MVA \Rightarrow |S_{pu}| = 1.0$$

$$|I_{pu}| = \frac{|S_{pu}|}{|V_{pu}|} = \frac{1}{1} = 1$$

$$P_2 = 750MW \Rightarrow P_{2pu} = \frac{750}{800} = 0.9375$$

$$|P_2| = |V_2||I_2|\cos\theta \Rightarrow$$

$$\cos\theta = \frac{|P_2|}{|V_2||I_2|} = \frac{0.9375}{1*1} = 0.9375 \Rightarrow$$

$$\theta = -20.364^\circ$$

$$I = |I|(\cos\theta + j\sin\theta)$$

$$= 1(0.9375 - j0.3480) = 1\measuredangle -20.364$$

$$V_1 = V_2 + IjX_t$$

$$= 1 + (0.9375 - j0.3480)(j0.14)$$

$$= 1 + 0.0487 + j0.13125 = 1.0487 + j0.13125$$

$$= 1.05689\measuredangle 7.13363$$

Check using power transfer equation

$$P_{1-2} = \frac{V_1 V_2 \sin(\delta_1 - \delta_2)}{X}$$

$$= \frac{1.05689 * 1 * \sin(7.133 - 0)}{0.14} = 0.9375 = 750MW$$

$$V_{1rate} = 22kV * 1.05689 = 23.252kV$$

8.10 Applications

Applications are an opportunity to demonstrate familiarity, comfort, and comprehension of the topics.

Chapter 8 Problems