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PMSM Powered By Hydraulic Turbine with Excitation and Governor System

Asi Srinivas Reddy
Department of Electrical and Electronics Engineering,
BITS, Visakhapatnam,
Andhra Pradesh 530041, India.

Elipilli Anil Kumar
Department of Electrical and Electronics Engineering,
BITS, Visakhapatnam,
Andhra Pradesh 530041, India.

ABSTRACT

This paper introduced the modeling of controls (Speed governor and excitation) to a PMSM through simulation using MATLAB. The modeling of PMSM will be very similar to the ones in the machine laboratory. The simulation model will enable an easier understanding of how the actual machines in the laboratory works. It comprises the background review of the synchronous machine with a hydraulic turbine providing the mechanical power to the synchronous generator. Both speed governor and excitation system is the controls for the synchronous generator respectively. The electrical system for each phase consists of a voltage source in series with RL impedance, which implements the internal impedance of the machine. The value of R can be zero but the value of L must be positive.

INTRODUCTION

PMSM are principally used as alternating current (AC) generators. They supply the electric power used by all sectors of modern societies: industrial, commercial, agricultural, and domestic. Synchronous machines are sometimes used as constant-speed motors or as compensators for reactive power control in large power systems. This article explains the constructional features and operating principles of the synchronous machine. Generator performance for stand-alone and grid applications is discussed. The effects of load and field excitation on the synchronous motor are investigated. The hunting behavior of a synchronous machine is studied, and a review of various excitation systems provided. The synchronous machine is an important electromechanical energy converter. Synchronous generators usually operate together (or in parallel), forming a large power system supplying electrical energy to the loads or consumers. For these applications synchronous machines are built in large units, their rating ranging from tens to hundreds of megawatts. For high-speed machines, the prime movers are usually steam turbines employing fossil or nuclear energy resources. Low-speed machines are often driven by hydro-turbines that employ water power for generation. Smaller synchronous machines are sometimes used for private generation and as standby units, with diesel engines or gas turbines as prime movers [1].

Synchronous machines can also be used as motors, but they are usually built in very large sizes. The synchronous motor operates at a precise synchronous speed, and hence is a constant-speed motor. Unlike the induction motor, whose operation always involves a lagging power factor, the synchronous motor possesses a variable-power-factor characteristic, and hence is suitable for power-factor correction applications.

Types of Synchronous Machine:

According to the arrangement of the field and armature windings, synchronous machines may be classified as rotating-armature type or rotating-field type.

Rotating-Armature Type:

The armature winding is on the rotor and the field system is on the stator. The generated current is brought out to the load via three (or four) slip-rings. Insulation problems, and the difficulty involved in transmitting

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large currents via the brushes, limit the maximum power output and the generated electromagnetic field (emf). This type is only used in small units, and its main application is as the main exciter in large alternators with brushless excitation systems.

Rotating-Field Type:

The armature winding is on the stator and the field system is on the rotor. Field current is supplied from the exciter via two slip-rings, while the armature current is directly supplied to the load. This type is employed universally since very high power can be delivered. Unless otherwise stated, the subsequent discussion refers specifically to rotating-field type synchronous machines.

Based on shape of the field, synchronous machines classified as cylindrical-rotor (non-salient pole) machines:

The cylindrical-rotor construction is used in generators that operate at high speeds, such as steam-turbine generators (usually two-pole machines). This type of machine usually has a small diameter-to-length ratio, in order to avoid excessive mechanical stress on the rotor due to large centrifugal forces [2].

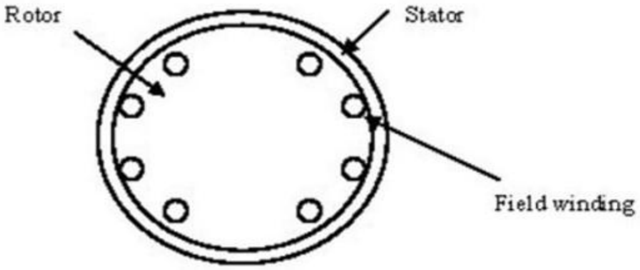

Fig.1: Construction of cylindrical-rotor synchronous machine.

The salient-pole rotor:

The salient-pole construction is used in low-speed alternating current (AC) generators (such as hydro-turbine generators), and also in synchronous motors. This type of machine usually has a large number of poles for low-speed operation, and a large diameter-to-length ratio. The field coils are wound on the bodies of projecting poles. A damper winding (which is a partial squirrel-cage winding) is usually fitted in slots at the pole surface for synchronous motor starting and for improving the stability of the machine.

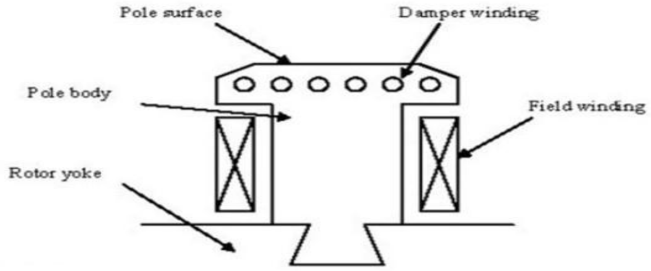

Fig.2: Salient-pole rotor construction

SYNCHRONOUS GENERATOR SUPPLYING AN ISOLATED LOAD:

Principle:

When a synchronous generator is excited with field current and is driven at a constant speed, a balanced voltage is generated in the armature winding. If a balanced load is now connected to the armature winding, a balanced armature current at the same frequency as the EMF will flow. Since the frequency of generated EMF is related to the rotor speed, while the speed of the armature rotating MMF is related to the frequency of the current, it follows that the armature MMF rotates synchronously with the rotor field. An increase in rotor speed results in a rise in the frequency of EMF and current, while the power factor is determined by the nature of the load [3].

The effect of the armature MMF on the resultant field distribution is called *armature reaction*. Since the armature MMF rotates at the same speed as the main field, it produces a corresponding EMF in the armature winding. For steady-state performance analysis, the per-phase equivalent circuit shown in Figure 3 is used. The effects of armature reaction and armature winding leakage are considered to produce an equivalent internal voltage drop across the synchronous reactance X_s, while the field excitation is accounted for by the open-circuit armature voltage E_f. The impedance $Z_s = (R + jX_s)$ is known as the synchronous impedance of the synchronous generator, where R is the armature resistance [4].

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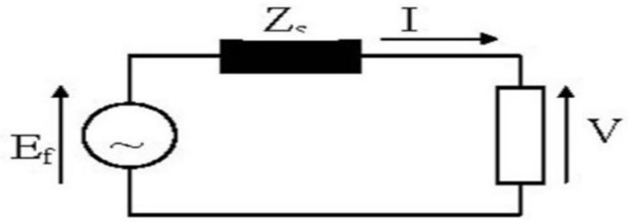


Fig.3: Per-phase equivalent circuit of synchronous generator

The circuit equation of the synchronous generator is:

$$E_f = V + IZ_s \ldots\ldots\ldots\ldots (1)$$

Due to the synchronous impedance drop, the terminal voltage is less than the open-circuit voltage E_f. For generator operation, the E_f phasor leads the terminal voltage phasor V by the angle δ, often referred to as the load angle.

Synchronous Generator Connected to the Grid :

In practice, synchronous generators seldom operate in the isolated mode. A large number of synchronous machines are usually connected in parallel to supply the loads forming a large power system known as a *grid*. The voltage and the frequency of the grid remain substantially constant. When a synchronous generator is connected to the grid, its rotor speed and terminal voltage are fixed by the grid and it is said to be operating on infinite bus bars. In general, a change in field excitation will result in a change in the operating power factor, while a change in mechanical power input will cause a corresponding change in the electrical power output.

Synchronizing Procedure:

The process of paralleling a synchronous machine onto infinite bus bars is known as synchronizing.

Before a synchronous generator can be synchronized onto live bus bars, the following conditions must be satisfied:

- The voltage of the generator must be equal to the voltage that of the bus bars
- The frequency of the generator must be equal the frequency to that of the bus bars
- The phase sequence of the generator must be the same as that of the bus bars
- At the instant of synchronizing, the voltage phases of the generator and the bus bars must coincide.

Synchronizing may be achieved with the help of synchronizing lamps, the rotary lamp method being the most popular. Alternatively, a device known as the synchroscope may conveniently be used to facilitate synchronizing.

Operating Conditions of Synchronous Generator:

Depending upon the field excitation and the mechanical power input, a synchronous generator may operate in one of the operating conditions shown in Figure 7. The phasor diagrams show that when a synchronous generator operates on infinite busbars, over excitation will cause the machine to deliver power at a lagging power factor, while under excitation will cause the generator to deliver power at a leading power factor. The synchronous generator is thus a source or sink of reactive power [5].

$P_m = 3(E_f .V/X_s)$ is known as the steady-state stability limit. This is the maximum power the generator can deliver when the load is applied gradually. Figure 8 shows the power/load angle curve of a cylindrical-rotor synchronous generator. Stable operation is theoretically possible provided the load angle is less than 90°. In practice, however, the load angle at full load is limited to around 30°–40°, in order to provide a sufficient safety margin for the synchronous generator to remain in synchronism with the grid after transients and momentary overloads.

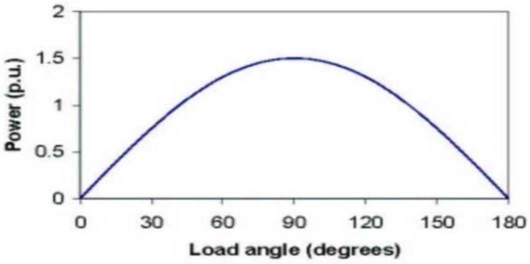


Fig.4: Power-load angle curve of a cylindrical-rotor synchronous machine

HYDRAULIC TURBINES

Hydraulic Turbines have a row of blades fitted to the rotating shaft or a rotating plate. Flowing liquid, mostly water, when pass through the Hydraulic Turbine it strikes the blades of the turbine and makes the shaft rotate. While flowing through the Hydraulic Turbine the velocity and pressure of the liquid reduce, these result in the development of torque and rotation of the turbine shaft. There are different forms of Hydraulic Turbines in use depending on the operational requirements. For every specific use a particular type of Hydraulic Turbine provides the optimum output.

Classification of Hydraulic Turbines: Based on flow path:

Water can pass through the Hydraulic Turbines in different flow paths. Based on the flow path of the liquid Hydraulic Turbines can be categorized into three types.

Axial Flow Hydraulic Turbines:

This category of Hydraulic Turbines has the flow path of the liquid mainly parallel to the axis of rotation. Kaplan Turbines has liquid flow mainly in axial direction.

Radial Flow Hydraulic Turbines:

Such Hydraulic Turbines has the liquid flowing mainly in a plane perpendicular to the axis of rotation.

Mixed Flow Hydraulic Turbines:

For most of the Hydraulic Turbines used there is a significant component of both axial and radial flows. Such types of Hydraulic Turbines are called as Mixed Flow Turbines. Francis Turbine is an example of mixed flow type, in Francis Turbine water enters in radial direction and exits in axial direction.

Based on the flow rates turbines are classified as follows:

Kaplan Turbine:

It is designed for low water head applications. Kaplan Turbine has propeller like blades but works just reverse. Instead of displacing the water axially using shaft power and creating axial thrust, the axial force of water acts on the blades of Kaplan Turbine and generating shaft power. With increasing demand of power need was felt to harness power from sources of low head water, such as, rivers flowing at low heights. For such low head applications Viktor Kaplan designed a turbine similar to the propellers of ships. Its working is just reverse to that of propellers. The Kaplan Turbine is also called as Propeller Turbine. They are designed with twist along the length so as to allow swirling flow at entry and axial flow at exit.

Francis Turbine:

In this turbine water flow is radial into the turbine and exits the Turbine axially. Water pressure decreases as it passes through the turbine imparting reaction on the turbine blades making the turbine rotate. Francis Turbine is the first hydraulic turbine with radial inflow. The major part of pressure drop occurs in the turbine itself, unlike the impulse turbine where complete pressure drop takes place up to the entry point and the turbine passage is completely filled by the water flow during the operation [6].

Pelton Wheel Turbine:

In a Pelton Turbine or Pelton Wheel water jets impact on the blades of the turbine making the wheel rotate, producing torque and power. Learn more about design, analysis, working principle and applications of Pelton Wheel Turbine.

SPEED GOVERNOR

In most speed and torque controlled drive systems, closed loop control is based on measurement of speed or position of the motor using a shaft encoder. However, in some cases it is difficult (e.g. a compact drive system) or extremely expensive (e.g. submarine applications) to use sensors for speed measurement. Eliminating the speed sensor and measurement cables results in lower cost, and at the same time increases the reliability and ruggedness of the overall drive system. Over the past decade, Speed sensor less control strategies has aroused great interest among induction motor control researchers. In these strategies, the motor speed is estimated and used as feedback signal for closed- loop speed control.

Open loop control:

The DC motor is turning the synchronous generator at synchronous speed at all loads during steady state operation. The speed of the DC motor can be varied by adjusting the armature current supply to the armature of the drive motor shown in Fig.3 As the load increases the speed of the motor drops as the armature current is held at a constant value. Therefore, the open loop control of speed is not desirable here.

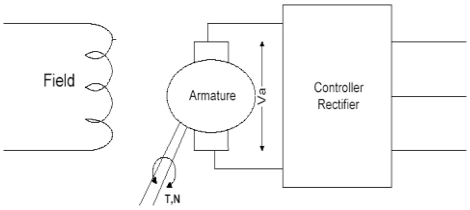


Fig.5: Open loop control

Closed loop control:

Closed loop control is similar to open loop control, only an additional comparator to compare the actual speed with the reference speed and output the difference back into the controller. This can be seen from Fig.6. The difference of the 2 signals is essential in order to obtain accurate control of the speed.

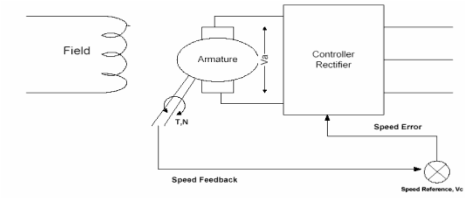


Fig.6: Closed loop control

Excitation System:

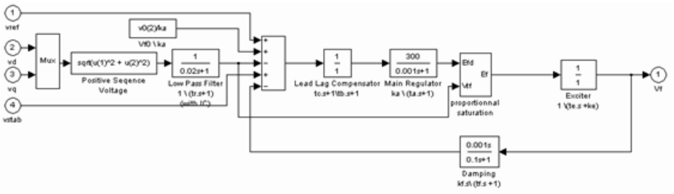
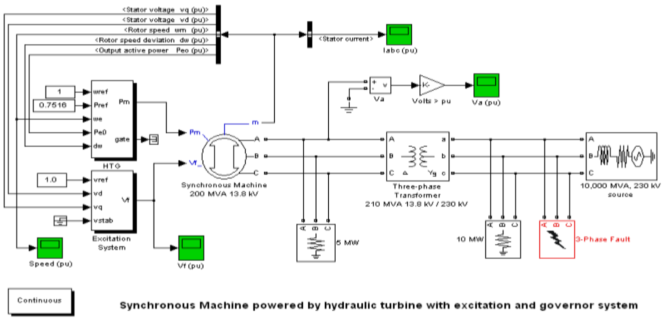


Fig.7: Control system of Excitation System

The excitation system varies the field voltage, V_f of the synchronous generator to control the output terminal 3 phase voltage. The output terminal voltages have to be kept constant at all time even there is a load disturbance. Fig.7 shows the overall view of the excitation system. The individual blocks that makes up the exciter. The inputs to the excitation system are V_{ref}, V_d, V_q and V_{stab}. The single output is V_f. V_D and V_q will go into a multiplexer then into a positive sequence voltage which is just taking the peaks of the two signals and adding together. It will then be passed through a low-pass filter (LPF), the LPF can be design to the required responses needed. The time constant of the LPF, T_r, in seconds (s), of the first-order system that represents the stator terminal voltage transducer. All these will come to a summer and outputs to a lead-lag compensator.

The time constants T_b, in seconds (s), and T_c, in seconds (s), are of first- order system representing a lead-lag compensator. After which it is pass into the main regulator. The gain K_a and time constant T_a, in seconds (s), are of first-order system. The output of the main regulator will be fed into a saturator with output of the LPF. The saturator sets the limits of the regulators Ef_{min} and Ef_{max}. Limits Ef_{min} and Ef_{max}

SIMULINK BLOCK DIAGRAM:



Circuit Description:

A three-phase generator rated 200 MVA, 13.8 kV, 112.5 rpm is connected to a 230 kV, 10,000 MVA network through a Delta-Wye 210 MVA transformer. At t = 0.1

s, a three-phase to ground fault occurs on the 230 kV bus. The fault is cleared after 6 cycles (t = 0.2 s). During this demo, you will initialize the system in order to start in steady-state with the generator supplying 150 MW of active power and observe the dynamic response of the machine and of its voltage and speed regulators.

Demonstration:

1. Start Simulation and observe the three machine currents on the Iabc scope. If the 9 parameters defining initial conditions for the Synchronous Machine are set at zero or not set correctly, the simulation will not start in steady state.
2. In order to start the simulation in steady-state you must initialize the synchronous machine for the desired load flow. Open the Power gui and select 'Load Flow and Machine Initialization'. A new window appears. The machine 'Bus type' should be already initialized as 'PV generator', indicating that the load flow will be performed with the machine controlling the active power and its terminal voltage. Specify the desired values by entering the following parameters: Load flow: Terminal voltage (V_{rms}) = 13800; Active Power = 150e6. Then press the 'Execute Load Flow' button. Once the load flow has been solved the phasors of AB and BC machine voltages as well as the currents flowing out of phases A and B are updated. The machine reactive power, mechanical power and field voltage requested to supply the electrical power should also be displayed: Q = 3.4 Mvar; P_{mec} = 150.32 MW (0.7516 pu); field voltage E_f = 1.291 pu.
3. In order to start the simulation in steady state with the HTG and excitation system connected, these two Simulink blocks must also be initialized according to the values calculated by the load flow. This initialization is automatically performed when you execute the Load Flow, as long as you connect at the P_m and V_f inputs of the machine either Constant blocks or regulation blocks from the machine library (HTG, STG, or Excitation System). Open the HTG block menu and notice that the initial mechanical power has been automatically set to 0.5007 pu (100.14 MW) by the Load Flow. Then, open the Excitation System block menu and note that the initial terminal voltage and field voltage have been set respectively to 1.0 and 1.1291 pu.

4. Open the 4 scopes and restart the simulation. The simulation now starts in steady state. Observe that the terminal voltage V_a is 1.0 p.u. at the beginning of the simulation. It falls to about 0.4 pu during the fault and returns to nominal quickly after the fault is cleared. This quick response in terminal voltage is due to the fact that the Excitation System output V_f can go as high as 11.5 pu which it does during the fault. The speed of the machine increases to 1.01 pu during the fault then it oscillates around 1 p.u. as the governor system regulates it. The speed takes much longer than the terminal voltage to stabilize mainly because the rate of valve opening/closing in the governor system is limited to 0.1pu/s.

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SIMULATION RESULTS:

The synchronous generator will react differently with different types of load applied at the output. Loads with different frequencies, reactive powers and voltages will produce different kinds of results. We will further investigate the different responses in this section.

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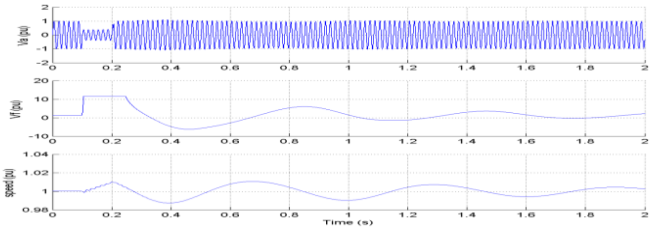
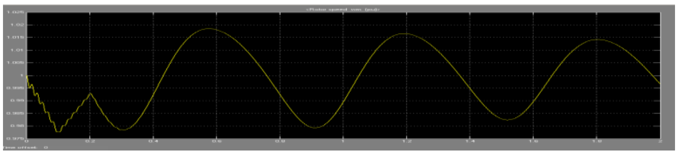
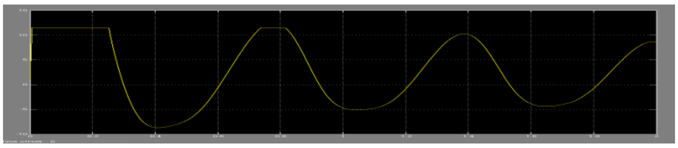
For Resistive load:



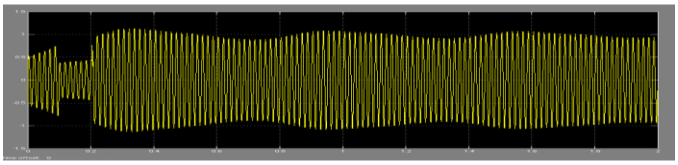
Rotor speed:



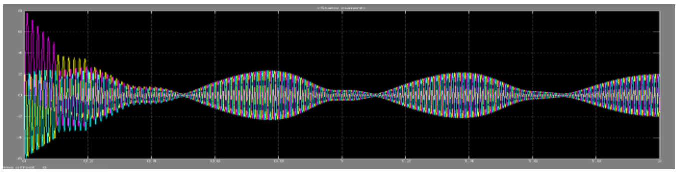
VolageV$_f$:

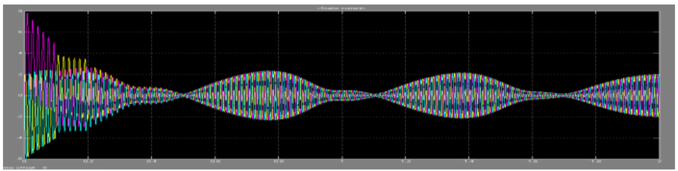


Voltage V$_a$:



Current I$_{abc}$:





CONCLUSION:

This paper shows the complete system to working as a whole with controls to control the output voltage on MATLAB Simulink. The synchronous generator response differently when resistive loads are added to the system. The results of the simulation will be check against those results from the actual machine in the laboratory. The types of controller in the speed governor had been decided. A PI controller is used as the steady state error is needed to be corrected, on the other hand not affecting the transient. It is also more flexible to use PI controller instead.

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