International Journal of Research
Available at https://edupediapublications.org/journals

p-ISSN: 2348-6848
e-ISSN: 2348-795X
Volume 03 Issue 09
May 2016

Design & Development of a Fresh Approach for Controlling Speed of Synchronous Machine

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Abstract

*This paper presents use of the simplified alternator for a load shedding test on a 2000 kVA, 600 V. A three-phase, four-wire alternator rated 2000 kVA, 1600 kW, 0.8 power factor, 600 V, 1800 rpm has been connected to a 1600 kW, 400 kvar inductive load. The stator neutral point is grounded. The internal impedance of the generator (Zg = 0.0036 + j*0.16 pu) represents the armature winding resistance Ra and direct axis transient reactance X'd. The total inertia constant of the generator and prime mover is H = 0.6 s, corresponding to J = 67.5 kg.m^2. Speed regulation is modeled with Simulink® blocks implementing a PI regulator. The machine is excited with a constant voltage. A three-phase breaker is used to switch out a 800 kW resistive load. The breaker is initially closed and it is opened at t = 0.2 s, resulting in a 50% load shedding. In this paper, the machine is initialized in order to start simulation in steady state and the machine dynamics with and without speed regulation has been observed.*

Key Words:

alternator, inductive load, stator neutral point, Synchronous Machine, speed regulation

INTRODUCTION

Modern electrical driver systems consist of; power electronics transformers, analog/digital controllers and sensors or observers. DC, asynchronous and synchronous motors are frequently used motor types with these driver systems. New kinds of motors are developed like linear motors, step motors, switching reluctance motors, and permanent magnet synchronous motors. Permanent magnet synchronous motors are used where in general high demands are made with regard to speed stability and the synchronous operation of several interconnected motors. They are suitable for applications where load - independent speeds or synchronous operation are required under strict observance of defined speed relations within a large frequency range [3].

Permanent Magnet Synchronous Motor Technology

Synchronous motors are generally preferred whereas constant speed is desired under varying loads. Their speed can be adjusted by using inverters or adjustable voltage or frequency source. Their size and inertia moment values are smaller compared to the

DC motors. Their efficiency and power factors are larger compared to asynchronous motors. As known an electrical motor needs two fluxes in order to constitute working induction in the air gap. This principle is the base rule for any motor design. Moreover PMSM can be constructed by replacing the DC induction coils of the rotor by permanent magnets, thus the magnetic flux on the rotor is supplied by the magnets [1].

Permanent magnet synchronous motors can be designed in different structures according to their intended application. Stator coils placed on the stator are three phase, two-layer, spreaded and cross chorded. So the coil magneto-motive force and the motion voltage approximates to sinusoidal form. The rotor magnetization is achieved by the permanent magnets installed inside the rotor. This means the amount of magnetizing current drawn from the supply network is minimal. This principle results in low losses of the rotor and excitation and this leads to a high level of efficiency comparable with other motors and savings on operating and energy costs [2]. The location of the magnets on the rotor and their specifications determine the performance of the motor therefore various designs are possible. The simple representations of the frequently used designs are given below. Other designs are derived from these two.

A) Placing the magnets on the rotor surface

B) Placing the magnets inside the rotor (buried magnets)

1) Radially located magnet structure,

2) Circular buried magnet structure.

A. Placing the magnets on the rotor surface

Magnets are mounted on the rotor in forms of strips or arcs. Due to the simplicity and magnetically symmetry of the structure, this type of machine exhibits salient pole machine behavior, has great air gap and weak armature reaction that exposed to pole flux. The greatest drawback of this common design is the low endurance of the magnets to the centrifugal forces. Therefore these motors are preferred in low-speed applications to avoid detachment of the magnets [1]. These motors are commonly known as surface permanent magnet motors (SPMSM). A simple representation is shown in Fig. 1.

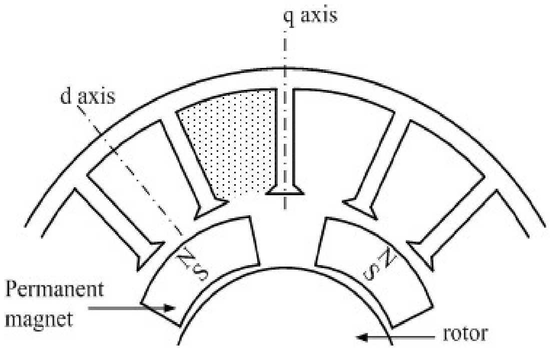


Figure 1.: Magnets placed on the rotor

B. Placing the magnets inside the rotor (Buried magnets)

Air gap induction of the previous design is limited and the magnets being exposed to high centrifugal forced under high speeds have lead to different designs. Here, the magnets are placed in the cavities bored in the rotor. The magnets are surrounded by magnetic materials instead of air. The magnets now have a better resistance to centrifugal forces therefore they are more suitable for high speed applications. The efficiency values of these motors are also higher than other magnet motors. The main disadvantage is their high costs. Placement of the magnets in the rotor is a high tech process that requires fine labour. These motors are commonly known as interior permanent magnet synchronous motor (IPMSM).

Buried magnet motor designs are mainly in two types:

1) Radially placed buried magnet structure

As seen in Fig. 2. magnets are placed around the rotor axis buried and radially magnetized. These motors have small air gap, and low armature reaction. Flux density in the air gap can be higher than inside the magnet, thus the Ferrit magnets can be utilized for high torque density. The surface where the magnets come in contact with the rotor is coated with a non magnetic material to avoid magnetic short -circuit. However these materials have high costs [1].

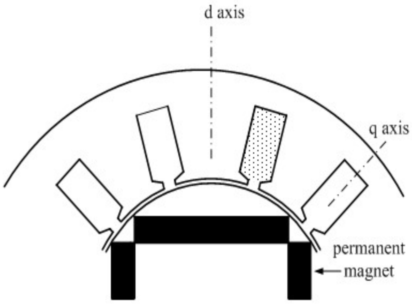


Figure 2.: Radially placed buried magnet structure

2) Circular Buried Magnet Structure

Circular buried magnet structure is shown in Fig. 3. Permanent magnets are again buried in the rotor but are placed pointing the main axis. The most important feature of this design is to constitute induction at the poles independent from the working point of magnets. Through to this feature, air gap induction can be increased to high levels. Since the magnets are buried in the rotor, they have a great resistance to the centrifugal forces.

The costs of PMSM are higher than DC and asynchronous motors because of the high permanent magnet and production costs. Also, the reliability of these motors is questionable under certain circumstances such as magnetic property loss due to high working temperatures etc. Never the less, such properties as high efficiency, high torque, high power, small volume, and accurate speed control make permanent magnet synchronous motors preferred for chemical fiber industry (spinning pumps, godets, drive rollers), texturing plants (draw godets), rolling mills (roller table motors), transport systems (conveyor belts), glass industry (t ransport belts), paper machines, robotic automation, electrical household appliances, ship engines and escalators [3].

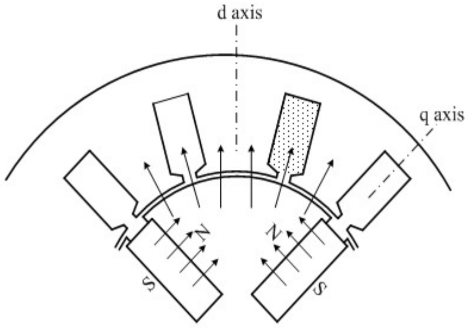


Figure 3.: Circular buried magnet structure

3. Direct Torque Control of the Permanent Magnet Synchronous Motors

The torque of the permanent magnet synchronous motor is controlled by inspecting the armature current since electromagnetic torque is proportional to the armature current. For high dynamic performance, the current control is applied on rotor flux (dq) reference system that is rotated at synchronous speed. The main principle of DTC is to select the appropriate voltage vectors according to the stator magnetic flux, difference between the reference and real torque. If the initial position of the rotor is known, it is possible to work with DTC without sensors [4].

A. Motor Equations at the Stator Flux Reference

The equations given below are mathematical model equations. Stator current vector can be represented on rotor flux (dq) reference system as id iq and the electromagnetic torque is related with these vectors. Equations (1), (2) and (3) used in simulation are electrical model equations, and equation (4) is mechanical model equation.

$$\frac{d}{dt}i_d = \frac{1}{L_d}u_d - \frac{R_s}{L_d}i_d + \frac{L_q}{L_d}\omega_r i_q \qquad (1)$$

$$\frac{d}{dt}i_q = \frac{1}{L_q}u_q - \frac{R_s}{L_q}i_q + \frac{L_d}{L_q}\omega_r i_d - \frac{\psi_M\omega_r}{L_q} \qquad (2)$$

$$T_e = 1.5p\ [\psi_M i_q - (L_q - L_d)i_d i_q] \qquad (3)$$

$$\frac{d}{dt}\omega_m = \frac{1}{J}(T_e - B\omega_m - T_L) \qquad (4)$$

$$\omega_r = \omega_m\ p \qquad (5)$$

B. Determination of the Voltage Space Vector

The main principle of DTC is determination of correct voltage vectors using the appropriate switching table. The determination process is based on the torque and stator magnetic flux hysteresis control. Stator magnetic flux can be calculated using equation (6).

$$\overline{\psi_s} = \int_t^{t+\Delta t} (\overline{u_s} - R_s\overline{i_s})\, dt \qquad (6)$$

Equation (6) shows that the stator magnetic flux and the voltage space vector have the same direction [5]. Therefore, stator magnetic flux’s amplitude and direction is controlled by means of keeping in specified bandwidth by using the correct voltage space vector. The voltage vectors are determined to control the stator magnetic flux amplitude depending on switching table. The switching table is formed by dividing voltage vector plane into six sections as shown in Fig. 4. Two adjacent voltage vectors that yield the lowest switching frequency are selected in order to increase or decrease the amplitude of ψs .

Here, when the stator magnetic flux is moved clockwise in section 1, voltage space vector v2 is selected in order to increase the stator magnetic flux amplitude and voltage space vector v3 is selected in order to decrease the amplitude. When the stator magnetic flux moves clockwise, if still in section 1, v6 is used to increase the amplitude and v5 is used to decrease the amplitude. The torque of the permanent magnet synchronous motor can be controlled using DTC by means of controlling the stator magnetic flux rotation speed in cases where the stator magnetic flux amplitude is kept constant [6].

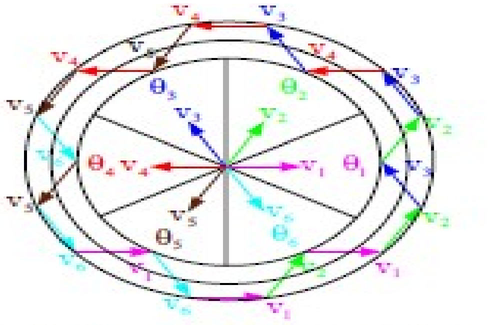


Fig. 4. Vectors of space vector modulation

MODEL VERIFICATION

The MATLAB Model File may be shown as:

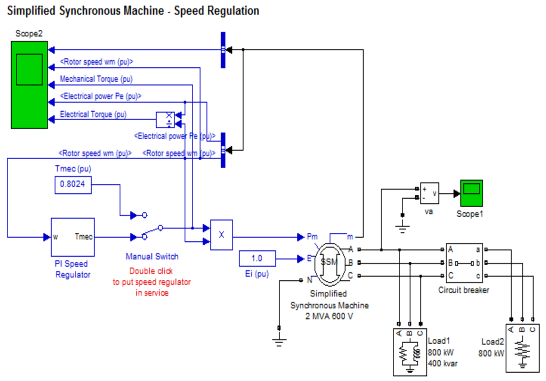
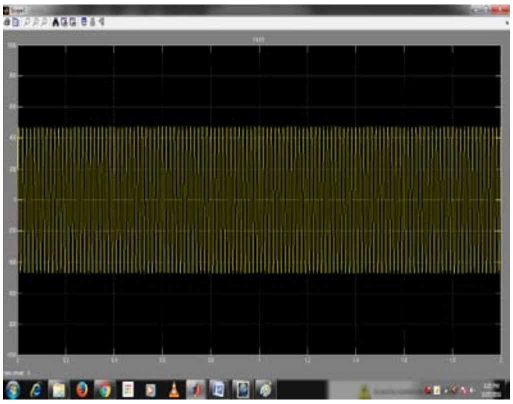
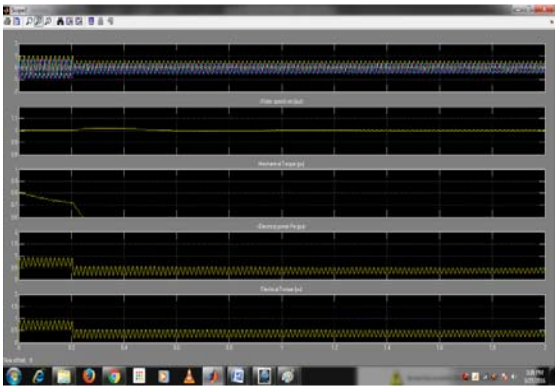


Figure 5: The proposed Model

Output of scope 1 may be shown as:



Output of scope 2 may be shown as:



Demonstration

1. **Initializing the machine to start in steady state**

After Starting simulation, it has been observed that the three machine currents on trace 1 of Scope2. If the 8 parameters defining initial conditions for the machine are left at zero or not set correctly, the simulation will not start in steady state. In order to start the simulation in steady-state you must first initialize the machine for the desired load flow.

Open the POWERGUI and select 'Load Flow & Machine Initialization'. A new window appears. As the circuit contains no voltage source imposing the reference angle, 'Swing Bus' must be selected for the machine 'Bus type'. This means that the load flow will be performed with the machine controlling the voltage and the angle at its terminals. The desired terminal voltage should be already initialized at 600 V (machine nominal voltage); by leaving the phase angle of UAN angle at 0 degree and not specifying any power guess. Then 'Update Load Flow' button should be pressed.

Once the load flow is solved the three line-to-line machine voltages as well as the three machine output currents are updated. The machine active and reactive powers as well as the required mechanical power Pmec and field voltage E are also displayed. The following values are obtained: P = 1600kW, Q = 400 kvar, Pmec = 1604.7kW (0.8024 pu), field voltage E = 1.0247 pu. The Load Flow also prompts with a warning to set initial condition for mechanical power to 0.8024 pu. This is because the Pm input of the machine is not connected to a constant block or to a library block (HTG or STG). Notice that the mechanical torque (Tmec block) is already set at 0.8024 pu. Disregard this message. Notice also that the constant block Ei connected at the E input of the machine is automatically updated (E = 1.04268 pu).

2. Simulation at constant torque - No speed regulator

The speed regulator is not in service (Manual Switch is in the upper position) . After starting the simulation and observing signals on Scope2. The three Iabc currents should start with steady-state sinusoidal waveforms. It has been observed that when the circuit breaker opens at t = 0.2 s, the electrical power (trace 4) drops from 0.8 pu to 0.4 pu and that the machine starts to accelerate. The rate of speed increase is dN/dt = 1/2H = 0.833 pu speed/ pu torque / s. As the net electromechanical torque is now Tmec-Telec = 0.8 - 0.4 = 0.4 pu, the speed increases at a rate of 0.833*0.4 = 0.33 pu/s. At t = 1.2s, the expected speed increase is therefore 0.33 pu. In fact, the speed measured at t = 1.2 s is slightly higher than the theoretical value (1.38 pu as compared to 1.33 pu). This is because the electrical torque (trace 5) decreases as speed is increasing, resulting in a net acceleration torque higher than 0.4 pu.

3. Simulation with speed regulator

Now double click on the Manual Switch block in order to put the speed regulator in service. Restart the simulation and observe the dynamic response of the speed regulator on Scope 2. It has been noticed that in order to maintain speed at its reference value (1 pu), the speed regulator has reduced the mechanical torque to 0.4 pu.

CONCLUSION

From the results it is obvious that the use of the simplified alternator for a load shedding test on a 2000 kVA, 600 V alternator is giving the satisfactory output. It has been observed that when the circuit breaker opens at t = 0.2 s, the electrical power (trace 4) drops from 0.8 pu to 0.4 pu and that the machine starts to accelerate. The rate of speed increase is dN/dt = 1/2H = 0.833 pu speed/ pu torque / s. As the net electromechanical torque is now Tmec-Telec = 0.8 - 0.4 = 0.4 pu, the speed increases at a rate of 0.833*0.4 = 0.33 pu/s. At t = 1.2s, the expected speed increase is therefore 0.33 pu. In fact, the speed measured at t = 1.2 s is slightly higher than the theoretical value (1.38 pu as compared to 1.33 pu). This is because the electrical torque (trace 5) decreases as speed is increasing, resulting in a net acceleration torque higher than 0.4 pu. In order to maintain speed at its reference value (1 pu), the speed regulator has reduced the mechanical torque to 0.4 pu.

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