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Abstract. *This paper gives a brief evaluation of the Synchronous Machine. It describes the construction, operating principles and its applications in different operational modes: Motor, Generator and Compensator. It emphasizes the need for the use of synchronous machines for compensation purposes due to its numerous advantages in this regard in power system networks.*

Keywords

Synchronous Machine, Synchronous Motor, Synchronous Compensator, Synchronous Generator, Power System Stability.

1. Introduction

Synchronous is a Greek terminology which means operating at the same time [1]. Electric rotating machinery is an apparatus which consists of a rotating and stationery member that generates, converts, transforms or modifies electric power [2]. Faraday's Law of Electromagnetic Induction, Ampere Biot-Savart's Law of Electromagnetic Induced Forces and Lenz's Law of Action and Reaction, with the law of energy conservation, all together constitute the basic theoretical bricks on which the operation of any electrical machine can be explained. The Synchronous Machine is an alternating current machine whose rotation under steady state condition is equal to the integral number of alternating current cycles in its stator. The rotor with permanent magnets or electromagnets rotates in synchronism with the Rotating Magnetic Field (RMF) created by the stator [1], [3].

Synchronous Machines can be classified as Generators, Motors and Compensators according to their uses. Generator action is observed when the rotor runs faster than the synchronous speed of the machine which is possible by means of a prime mover, motoring action is observed when the rotor is dragged behind the air-gap flux by retarding torque of a shaft-load [3]. A Synchronous Compensator is a Synchronous Motor whose shaft is allowed to rotate freely without any load [4]. Its field winding excitation is controlled by a voltage regulator to either generate or absorb reactive power as needed to adjust the grid's voltage, or to improve power factor [5].

This work discusses the basic principles of the Synchronous Machine and its uses as Motor, Generator and Compensator; it further explain in details the advantages and applications of the synchronous machine as a compensator in power system networks.

2. Construction of the Synchronous Machine

The Synchronous Generator or Alternator was first conceptualized by Michael Faraday and Hippolyte Pixii, in accordance with the field winding of the rotor wound and the construction of the rotor frame. In its steady state the rotor rotates at a constant speed, and the rotating field also rotates with the same speed as the rotor. This speed is called synchronous speed, thus, the machine is called synchronous machine [6]. The machines construction is according to the shape of its rotors, they can be classified as Salient Pole and Cylindrical Rotor while the stator is similar for both cases, Figure 1. Shows a cross-section of both Salient Pole and Cylindrical Rotor synchronous machines.

The Stator of the Machine is made up of a Sinusoidal distributed winding wound similar to the rotor, on sheets of steel laminations whose leads are taken out of the machine for power transfer. The air gap between the stator and rotor is made as small as possible to reduce the reluctance between the Salient Pole and Cylindrical Rotor synchronous machines and to decrease the magnetization current at no load, smaller air gap may cause mechanical issues [1], [7].

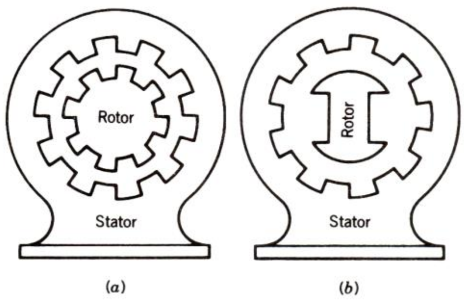

Figure 1 *(a) Cylindrical Rotor Machine cross-sectional area. (b) Salient pole Rotor Machine cross-sectional area. [8].*

The Cylindrical Rotor or Round Rotor is made up of cylindrical block of steel laminations with slots in its surface which run parallel to each other as shown in Figure 1(a). The rotors are smaller in diameter; it is usually in the range of 1.1m to 1.15m, but having maximum longer axial length of 6.5m for higher power. Cylindrical rotors are used in high speed electrical devices, say for example 1500 RPM - 3000 RPM. Windage loss as well as noise is less due to symmetry in its construction. Damper windings are not needed in these rotors. Its flux distribution is sinusoidal and hence gives better EMF waveform. The direct current field current is supplied by external direct current source by means of slip rings and brushes or by a direct current power source mounted on the shaft of the synchronous generator [1], [9].

The Salient Pole Rotor consists of a large number of projected poles mounted on a magnetic wheel; the poles are made of steel laminations supported by pole shoes on which the rotor winding is wound as shown in Figure 1(b). Salient pole rotors has maximum large diameter of 15m and shorter axial length in the range of 0.15 to 0.2. They are generally used in lower speed electrical machines, say 100 RPM - 1500 RPM. As the rotor speed is lower, the number of poles required to attain the required frequency is more, that is, the frequency is proportional to the number of poles.

$$Ns = \frac{120f}{P} \quad (1)$$

Flux distribution of the synchronous machine is relatively poor due to its asymmetrical construction. Salient pole rotors generally need damper windings to prevent rotor oscillations during operation [1], [10].

3. Operating Principle of the Synchronous Machine

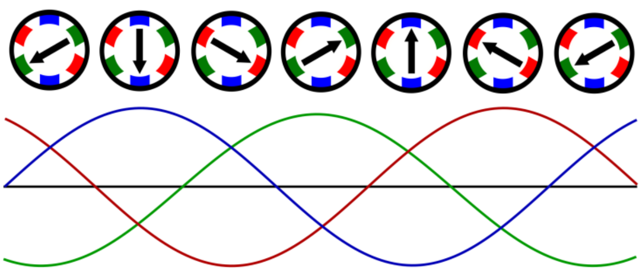

Figure 2: *Depicts the concept of a Rotating magnetic field. The colours Red, Green and Blue represent the 120°shifted and sinusoidally distributed three-phase stator winding, whereas the arrow represents the constant field flux which rotates at synchronous speed [13].*

The discovery of the rotating magnetic field is generally attributed to two inventors, the Italian physicist and electrical engineer Galileo Ferraris, and the Serbian-American inventor and electrical engineer Nikola Tesla [14]. The current flowing through a conductor produces a magnetic field associated with the current, which is Ampere's Law. It is a known fact that by coiling a conductor, a larger field is obtained without increasing the current's magnitude. If the three phases of the winding are distributed at 120 electrical degrees apart, three balanced voltages are generated, creating a three-phase system. By mathematical analysis it can be shown that if three balanced currents with equal magnitudes and 120 electrical degrees apart flow in a balanced three-phase winding, a magnetic field of constant magnitude is produced in the air gap of the machine. This magnetic field revolves around the machine at a frequency equal to the frequency of the currents flowing through the winding [1]. The result of adding three 120-degrees phased sine waves on the axis of a motor is a single rotating vector which remains always constant in magnitude, as can be seen in Figure 2 [15].

It is the distribution of the Stator winding which decides the wave shape and quality of the Machine's generated voltage in Generator mode and the Machine's rotational characteristic in motoring mode [16].

4. The Synchronous Machine used as a Generator

The Synchronous generator produces an alternating voltage when its shaft is rotated by a motor, an engine or other means, and the output frequency is directly proportional to the speed of the rotor. Synchronous machines are the primary energy conversion devices in commercial electricity network, the power rating of a synchronous generator can be several hundred M.V.A. or even to several thousand M.V.A. [6], [17]. The machine supplies active power to resistive loads and reactive power to inductive loads.

$$E_1 = V_1 + R.I_1 + jX_d.I_1 \quad (2)$$

Where E_1 is Field Excitation Voltage, V_1 and I_1 are the armature voltage and current respectively.

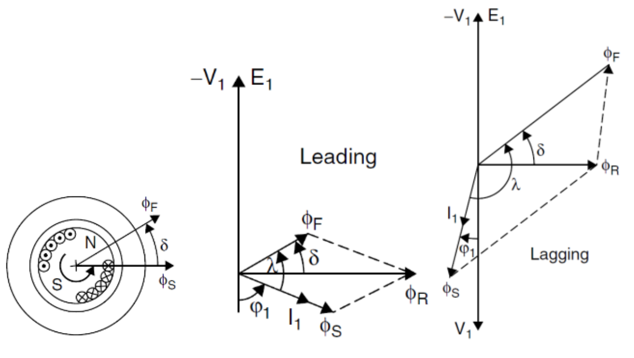

Figure 3: *Phasor Diagram of a Cylindrical Rotor ideal Synchronous Generator with its Rotor Flux ahead of Stator Flux, in Under-excited mode and Over-excited mode [1]].*

The rotor flux angle advance ahead of the stator flux angle, when the machine is under-excited as shown in Figure 3, when referred from the terminals, with the generator operating in the under-excited mode, the power factor angle is leading, that is, I_1 leads V_1. This means that the machine is absorbing reactive power from the system. The opposite occurs when the machine is in the over-excited mode [1]. Under heavy loading condition, the current increases dramatically and the voltage drops [18]].

The machine must run with over-excitation in order to maintain the voltage by adding the reactive power to the grid as depicted in Figure 3. Contrary to this situation, under light load or no load situation the current reduces and voltage increases. The machine now runs with under-excitation and consumes part of over-voltage at its terminals. As generators are normally used to provide VARs together with watts, they are almost always operated in the over-excited condition [1], [3], [11], [12].

Synchronous generators are used to generate electricity in hydro power plant and thermal power plants with gas or steam turbine [19]. High-speed synchronous generators with special cooling techniques and designs can be used in military-like weapons [20].

5. The Synchronous Machine used as a Motor

Synchronous motors are designed to run with their speed directly proportional to the frequency of the electrical energy source [21]. Under this mode it supplies electrical power, for example $P = V_1.I_1$, to the stator winding which will produce a Rotating magnetic field by virtue of its sinusoidal distribution along the stator cross-sectional area.

$$P = V_1.I_1\cos\varphi_1 \qquad (2)$$

$$E_1 = V_1 - R.I_1 - jX_d.I_1 \qquad (3)$$

The operation of a synchronous motor is due to the interaction of the magnetic fields of the stator and the rotor, as illustrated in Figure 4. Its stator winding which consists of a three-phase or single-phase winding is provided with three-phase or single-phase supply rotor with direct current supply. The stator winding carrying current produces a rotating magnetic flux and thus a rotating magnetic field, which causes the rotor to lock in with the rotating magnetic field and rotate along with it. Once the rotor locks in with the rotating magnetic field, the motor is said to be in synchronism.

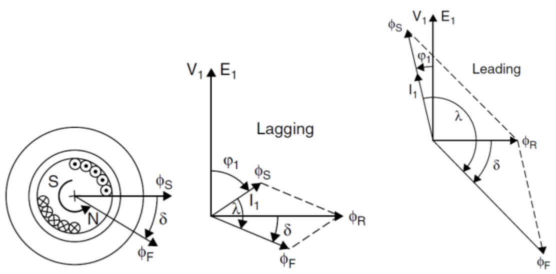

Figure 4: *Phasor Diagram of the Cylindrical Rotor of an ideal Synchronous Motor, The rotor flux dragged behind the Stator Flux in Under-excited and Over-excited modes [1].*

If the field current is not sufficient enough to produce the required air gap flux as demanded by the stator terminal voltage, additional magnetizing current or lagging reactive V.A is drawn from the alternating current source. This magnetizing current produces the deficient flux, which is a constant field-flux set up by the direct-current supply rotor winding. Therefore in this case, the motor is said to operate under lagging power factor and is said to be under-excited as depicted in Figure 4.

If the field current is more than the nominal field current, the motor is said to be over-excited. This excess field current produces an excess flux, which is the flux set up by the direct-current supply in the rotor winding, which must be neutralized by the armature winding. Hence, the armature winding draws leading reactive V.A. or de-magnetizing current leading voltage by almost 90° from the alternating current source. Hence in this case the motor operate under leading power factor as can be seen in Figure 4 [1], [11], [12].

This kind of motor has a wide range of applications because of its constant-speed operation under different load and its high efficiency. The synchronous motor can be used for compressors, pumps, extruders, rolling mills, hoists processing lines or blowers [22]. Even though the induction motor replaced the synchronous motor as the choice for the vast majority of electric motor applications, the synchronous generators still remain the universal machine of choice for the generation of electrical power [1].

6. The Synchronous Machine used as a Synchronous Compensator

When the synchronous machine runs on no-load, such as, on a freely rotating shaft, with controlled excitation, it is called a synchronous condenser or compensator. Using it in this configuration we can add reactive power unto the grid by over-excitation and consume reactive power from the grid by under-excitation of its field windings.

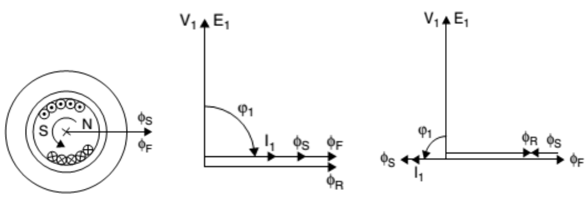

Figure 5: *Phasor Diagram of the Cylindrical Rotor of an ideal Synchronous Compensator. Rotor Flux is equal and in phase with the Stator Flux in Under-excited and Over-excited modes [1].*

When the rotor's excitation is slightly increased, and no torque is applied to the shaft, the rotor provides some of the excitation required to produce E_1, causing an equivalent reduction of φ_s. This situation represents the under-excited condition as can be seen in Figure 5. When operating under this condition, the machine is said to behave as a lagging condenser, meaning, it absorbs reactive power from the network. [11], [12].

If the field excitation is increased over the value required to produce E_1, the stator currents generate a flux that counteracts the field-generated flux. Under this condition, the machine is said to be over-excited. The machine thus behaves as a leading condenser; that is, it is delivering reactive power to the network [1], [11], [12].

7. Advantages and Applications of the Synchronous Compensator

With proper excitation by means of a solid-state voltage regulator the Synchronous Compensator is a continuously variable sink/source of reactive power [23].
A Synchronous Compensator will provide step-less automatic power factor correction along with the ability to produce up to 150% additional VARs [1].
The Synchronous Compensator is not a source of harmonics. This quality makes the Synchronous Compensator friendly to the surrounding power grid and other devices. And bring about ease of integration into existing networks [24].
The Synchronous Compensator system does not produce switching transients and is not affected by system electrical harmonics and synchronous compensators can absorb harmonics. They do not produce excessive voltage levels and are not susceptible to electrical resonances [25]. However, inertia is an inherent feature of a Synchronous Compensator, since it is a rotating machine [24]. Because of the rotating inertia of the Synchronous Compensator, it can provide limited voltage support during very short power drops [25].
If the compensator is made of a permanent magnet rotor, the machine will ensure 300% of short circuit current during fault conditions and provide the regulator with input power that is isolated from load fluctuations and distortions [23].
Synchronous Compensators provide real short circuit strength to the grid, Increase short circuit handling capacity, improves the system stability with even weak interconnections, facilitates systems protection and can improve the operation of modern power electronics installations [24].

Today’s power systems are dominated by Turbine powered Synchronous Generators. These machines will become outdated when traditional generation methods will be replaced by renewable systems. These machines can be efficiently used to regulate reactive power of transmission lines by some degree of modification.

The capacity of a synchronous condenser can be increased by replacing the copper wound iron field rotor with an ironless rotor of high temperature superconducting wire, which must be cooled to liquid nitrogen boiling point of 77ºK (-196ºC). The superconducting wire carries 160 times the current of comparable copper wire, while producing a flux density of 3 Tesla or higher, an iron core would saturate at 2 Tesla in the rotor air gap. Such a machine is said to have considerable additional transient ability to supply reactive power to troublesome loads like metal melting arc furnaces. it is a reactive power shock absorber. And has higher power density and physically small than a switched capacitor bank. The ability to absorb or produce reactive power on a transient basis stabilizes the overall power grid against fault conditions [26].

8. Conclusion

In this paper we have reviewed the operating theory of the Synchronous Machine along with its important applications in Power Systems. Even though the era of Synchronous Machines began in mid-18th century; Synchronous Machines still proves to be useful in a lot of applications of the 21st century. In the future, Synchronous Machines will continue to be of great use as dynamic compensation machines to stabilize and regulate power flow of electrical transmission systems.

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