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The article covers the construction and operation of synchronous machine, focusing on the rotor and stator components. It explains the use of electromagnets to create the field in synchronous machines, comparing salient-pole and round-rotor designs. Furthermore, it highlights the concept of synchronous speed and its relationship to the number of poles and electrical frequency. In the AC Machine article, we examined a simple permanent-magnet AC machine. That machine used a rotating armature coil, which means the power to run the motor or the power from the generator must be transmitted through the brushes and slip rings. For large machines, that is not very efficient, so AC synchronous machines are built with the armature on the stator and the field on the rotor. Construction of Synchronous Machine Rotor Figure 1 is a sketch of the rotor and stator of a synchronous machine. The rotor would be placed inside the stator. Instead of a permanent magnet, this machine (as do the overwhelming majority of synchronous machines) uses an electromagnet to create the field. A DC voltage is applied to the coils on the rotor, creating north and south poles. This particular rotor is called a salient-pole rotor because the rotor is not symmetric. In particular, the air gap between the pole faces and the stator is much smaller than that between the sides of the rotor and the stator. Some machines are built with a round rotor, which has slots in the side to hold the field coils. These are referred to as round-rotor synchronous machines. Round-rotor designs are typically limited to a maximum of four poles, whereas salient-pole machines have been built with over 50 poles. In either case, the rotor only sees a DC flux, so the rotor does not have to be laminated. Figure 1. Synchronous machine components labeled diagram Figure 2 shows a salient-pole rotor. This rotor is actually part of the excitation system for a very large (345 MVA) synchronous machine that was disassembled for maintenance. It operates on the same shaft as the larger unit, which is why the shaft diameter is so large. The front pole-face is marked “stator,” indicating the direction it faces when reassembled. The field coils are located directly behind the pole-faces. Figure 2. Salient-pole rotor diagram Figure 3 shows a round rotor for a synchronous generator. The pole-faces are at the top and bottom of the rotor as it is positioned in the picture. Note that putting more than two poles on the rotor in slots becomes very complicated. Figure 4 shows slip rings and brushes that are located on the end of the shaft of a 10 MW synchronous generator. This particular generator is a two-pole machine, which means it runs at 3600 RPM. Of course, the carbon in the brushes eventually wears down and the brushes have to be replaced. To keep from shutting the machine down, that has to be done while the machine is running. Figure 5 shows a cutaway view of a synchronous generator that is designed to be driven by a diesel engine. This machine has a salient-pole rotor, and an exciter machine is located at the left end of the shaft. This exciter is a permanent- magnet machine with the armature on the rotor. The AC is rectified by diodes on the rotor to provide DC for the main field winding. This is referred to as a rotating-rectifier exciter. Figure 3 Round rotor for a synchronous generator with wound field coils Stator The other half of the machine in Figure 1 is the stator, which contains the AC armature winding. Depending on the size of the machine, the armature winding consists of coils or copper bars laid into slots on the inside surface of the stator. Figure 6 shows the armature winding that surrounds the rotor of Figure 2. This winding consists of coils in slots, and the complete structure is approximately 4 feet in diameter. Figure 7 shows a lamination for the stator of a small AC machine (the lamination is about four inches wide). For machines like the one shown in Figure 6, the coils would be wound and then placed in the slots of the stator; for small machines like the one in Figure 7, the coils would be wound directly into the stator lamination stack. Because AC currents will flow through the stator winding, the stator must be constructed of laminations to reduce the eddy current losses. The slots shown in Figure 7 are designed to have coils wound into them since there are teeth at the openings of the slots. Finally, Figure 8 shows a close-up view of several slots of the armature winding of a 345 MVA machine. The inside diameter of this machine is about 9 feet. This winding is composed of copper bars laid into the slots, so essentially each coil contains one turn. Figure 4 Slip rings and brushes diagram in a synchronous generator Before we consider the motor and generator operation of the synchronous machine, we need to first consider how a three-phase armature winding creates a rotating magnetic field. Figure 5 Cutaway view of a synchronous machine labeled diagram Figure 6 Stator (armature) winding of a synchronous machine diagram Synchronous Machine Working Principle The rotating magnetic field Figure 9 shows two stator windings from AC machines. The stator on the left contains a complete winding, so the end turns are visible. The end turns were cut off the winding on the stator on the right side, exposing the coil turns in the slots of the stator. These stators contain a three-phase, six-pole winding so there are quite a few coils visible on the winding at the left. To consider the operation of a three-phase winding, we will start by looking at a single phase. 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Figure 8 Armature winding and slots of 345 MVA synchronous machine At the opposite side (Θ = 180°), the flux enters the air gap from the rotor, so it is negative. By proper design of the winding, the flux can be made to be sinusoidally distributed in the air gap. Figure 9 Left: AC stator winding. Right: end turns cut off to expose coils in slots. Figure 10 Flux distribution in the air gap due to a single-phase coil in a synchronous machine Imagine that we could “unpeel” the air gap of the machine and view the flux distribution in the air- gap. At $\omega t=0$, the air gap and flux distribution might look like Figure 10(b). The dotted line indicates the center of the air gap, with the stator on top and the rotor on the bottom. At this instant in time, the current is constant, so B is a function only of Θ; i.e., $B\left(\theta \right)={{B}_{m}}\cos \theta $ where Bm is a function of the current, ${{I}_{m}}$. Likewise, when the current reverses, at $\omega t=\pi $, the B field will look like that shown in Figure 10(c), with the positive maximum at Θ = 180°. At other times, the flux wave will be somewhere between the extremes, as shown in 10(d). In other words, the flux density in the airgap is a standing wave. Thus, $B\left(\theta ,t \right)=B\left(\theta \right)\cos \omega t={{B}_{m}}\cos \omega t\cos \theta $ But by using trigonometric identities, $\cos \theta \cos \omega t=0.5\left[\cos \left(\theta -\omega t \right)+\cos \left(\theta +\omega t \right) \right]$ The first term on the right side, $\cos \left(\theta -\omega t \right)$ is the expression for a traveling wave in the forward direction. Since our airgap is actually circular, the wave is traveling around or rotating. Unfortunately, the second term on the right side represents a wave traveling backward around the air gap. Despite the presence of opposite traveling flux waves, single-phase motors will run once started. However, they have no starting torque because of the opposite traveling waves. A three-phase stator winding Figure 11 shows a three-phase stator winding. The phase windings would each occupy a number of slots as shown previously; however, each phase winding is represented by only one slot to keep the drawing legible. When the winding is shown in one slot, it is called a concentrated winding. Note that the windings of the three phases are physically 120° apart. Figure 11 Three-phase stator with the same current in all three phases in a synchronous machine In Figure 11, all three phases have the same current (represented by • and X). As a result, the flux distribution due to coil b is 120° behind coil a, and the flux due to coil c is 120° behind coil b, as shown. Since they have the same magnitude and are 120° apart, they will add to zero. Thus, if we apply a DC current or the same AC current to all three coils, the fluxes of the three phases would cancel. That obviously wouldn’t help much. Instead, consider what happens when a balanced three-phase set of currents is applied to the coils: $\begin{align} & {{i}_{a}}\left(t \right)={{I}_{m}}\cos \omega t \\ & {{i}_{b}}\left(t \right)={{I}_{m}}\cos \left(\omega t-{{120}^{o}} \right) \\ & {{i}_{c}}\left(t \right)={{I}_{m}}\cos \left(\omega t-{{240}^{o}} \right) \\\end{align}$ Figure 12 Balanced three-phase currents applied to the stator winding The balanced set of three-phase currents that are applied to the stator winding are shown in Figure 12. Each current will create a magnetic flux distribution, but the three phases are displaced both in time and in space. We could multiply the currents by the spacial distribution of the flux as was done previously and then add the three together. The result would be a traveling wave of constant magnitude. Rather than go through the algebra and trigonometric identities, we will instead consider a physical description of the machine. Figure 13 Rotating magnetic field created by a three-phase winding in a synchronous machine Figure 13 shows how the magnetic field of the stator varies with time as the currents in the three-phase coils change. At time zero, the current in phase a is at a positive maximum, while the other two phases have negative currents with an amplitude of 1/2 the current in phase a, as shown in Figure 12. For purposes of this discussion, let positive currents enter (designated by X) the coil side labeled by just a letter (e.g., a) and come out (designated by •) the side labeled by the letter and a prime symbol (a’). The large dot and thick X indicate a current with peak magnitude; the smaller dot and thin X indicates a smaller magnitude. Based on this, at t = 0° in Figure 13, a large positive current enters side a, while smaller negative currents enter sides b’ and c’. Conversely, the currents come out of sides a’, b, and c. Notice the pattern that is formed—all of the currents enter the coils on the left side of the machine and come out on the right side. By the right-hand flux rule, the stator flux is directed in the downward direction, as shown by the arrow. As a result, the south (S) pole is at the bottom and the north (N) pole is at the top (θ = 0). Now consider what happens at ωt= 60°. Ic has reached its negative peak, while Ia and Ib are both at one-half of the positive peak. So now phase c has the large dot and thick X, while the other two phases have a small dot and thin X. Because 7b went from negative to positive, its dot and X have changed sides (X at b and • at b’) Note that the pattern of dots and Xs has rotated. Again applying the right-hand flux rule, we find the direction of the stator flux has moved by 60°. Continuing every 60°, we find that each 60° increment in time causes a 60° rotation in the magnetic flux. We are not constrained to looking at 60° intervals; however, we could look at any instant in time and find that the direction of the flux has rotated by the same angle that the currents have moved through. The stator poles are rotating, one revolution per cycle of current since this is a two- pole machine. Mathematically, it can be shown that the peak of the flux wave is constant and rotating at a) radians per second. The direction of rotation was determined by the connections to the stator windings. By switching connections to any two phases, the direction of rotation could be reversed. The rotational speed of the stator field is called synchronous speed. For a two-pole machine, the speed of the stator field in RPM is 60 times the frequency, but for more than two poles, we must divide by the number of pole pairs (P/2). Repeating equation 1, synchronous speed is defined as $\begin{matrix} {{n}_{s}}=\frac{120\times f}{P}in\text{ }RPM & {} & \left(1 \right) \\\end{matrix}$ Where f is the electrical frequency, and P is the number of poles in the machine. There are 60 seconds per minute, so dividing equation 1 by 60 yields the synchronous speed in revolutions per second: $\begin{matrix} {{n}_{s}}=\frac{2\times f}{P}in & rev/s & \left(2 \right) \\\end{matrix}$ The electrical frequency determines the speed of the rotating magnetic field, which in turn determines how fast the motor will run. Synchronous Machine Key Takeaways Understanding the construction and operation of synchronous machines is essential due to their critical role in modern electrical and industrial applications. The use of electromagnets in rotors—whether in salient-pole or round-rotor configurations—offers design flexibility for machines of various sizes and speeds. The stator’s distributed three-phase windings create a rotating magnetic field, a key principle that ensures efficient torque production and synchronous operation with the power supply. These machines are widely used in power generation (e.g., synchronous generators in power plants), industrial motor drives, and grid stability systems due to their constant-speed characteristics and high efficiency. The working principle of a synchronous machine is based on electromagnetic induction and the concept of synchronous speed. It operates by rotating the magnetic field of the stator and the rotor at the same speed, meaning the rotor turns in exact synchronism with the rotating magnetic field of the stator. When three-phase AC supply is given to the stator, it creates a rotating magnetic field. The rotor, excited with DC, locks with this rotating field and rotates at the same speed. This synchronized movement makes the machine suitable for both generator and motor applications with constant speed operation. Detailed Explanation: A synchronous machine is a type of AC machine that works with the rotor speed equal to the rotating magnetic field speed in the stator. The name “synchronous” itself means that the rotor rotates in step with the stator’s magnetic field. It is used as both synchronous motor and alternator (generator) in various electrical applications such as power stations, industrial drives, and large-scale grid systems. Let’s break down the working principle in a very simple way. A synchronous machine has two main parts: Stator: The stationary outer part. It has three-phase windings and is supplied with a three-phase AC voltage. This creates a rotating magnetic field (RMF) inside the stator. Rotor: The rotating inner part. It is given DC supply through slip rings or brushes, which produces a constant magnetic field. Generation of Rotating Magnetic Field: When a three-phase AC supply is given to the stator windings, it generates a rotating magnetic field. This field rotates at a fixed speed called synchronous speed (Ns), calculated using the formula: Ns = (120 × f) / P Where: f = frequency of the AC supply (in Hz) P = number of poles of the machine This magnetic field continuously rotates around the stator at synchronous speed. Rotor Movement and Synchronization: The rotor is excited with DC current, producing a constant magnetic field on it. When the machine is started (using an external motor or damper winding in case of motors), and the rotor speed matches the rotating magnetic field speed of the stator, a locking effect occurs. The rotor poles align with the rotating field poles, and the rotor starts rotating at the same speed as the stator field—this is called synchronism. Unlike induction motors, where the rotor lags behind the stator field, synchronous machines run without slip—their speed is always constant and equal to synchronous speed. As a Generator (Alternator): When the rotor is driven mechanically (e.g., by a turbine), and DC excitation is given, it cuts the rotating magnetic field across stator windings, inducing AC voltage due to Faraday’s law. As a Motor: When AC is supplied to the stator and the rotor is excited by DC, the rotor gets pulled into synchronism with the stator field, and mechanical torque is developed. Since there’s no relative motion between stator field and rotor, it keeps running at a constant speed regardless of the load. Applications of Synchronous Machines: Power plants (as alternators) Large industrial motors Grid voltage regulation (synchronous condensers) High-precision machines requiring constant speed Conclusion: The working principle of a synchronous machine is based on the interaction of a rotating magnetic field from the stator and a constant magnetic field from the rotor. The machine works only when both rotate at the same speed, making it highly stable and reliable. This synchronous operation allows the machine to be used effectively in generating and maintaining steady AC power in electrical networks and industries. The article covers the construction and operation of synchronous machine, focusing on the rotor and stator components. It explains the use of electromagnets to create the field in synchronous machines, comparing salient-pole and round-rotor designs. Furthermore, it highlights the concept of synchronous speed and its relationship to the number of poles and electrical frequency. 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We are not constrained to looking at 60° intervals; however, we could look at any instant in time and find that the direction of the flux has rotated by the same angle that the currents have moved through. The stator poles are rotating, one revolution per cycle of current since this is a two- pole machine. Mathematically, it can be shown that the peak of the flux wave is constant and rotating at a) radians per second. The direction of rotation was determined by the connections to the stator windings. By switching connections to any two phases, the direction of rotation could be reversed. The rotational speed of the stator field is called synchronous speed. For a two-pole machine, the speed of the stator field in RPM is 60 times the frequency, but for more than two poles, we must divide by the number of pole pairs (P/2). 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The stator’s distributed three-phase windings create a rotating magnetic field, a key principle that ensures efficient torque production and synchronous operation with the power supply. These machines are widely used in power generation (e.g., synchronous generators in power plants), industrial motor drives, and grid stability systems due to their constant-speed characteristics and high efficiency. A synchronous Machine includes both a synchronous motor and a synchronous generator. As a synchronous machine, a synchronous generator generates AC voltage, and a synchronous motor utilizes the AC voltage to drive the mechanical load. AC systems have many advantages over DC systems and are exclusively used for generating, transmitting, and distributing electric power.The synchronous machine rotates at the synchronous speed. The actual rotor speed of the synchronous machine equals its synchronous speed. The machine that converts mechanical power into AC electrical power is called a synchronous generator or alternator. However, if the same machine is operated as a motor, it is known as a synchronous motor.The synchronous machine has a certain relationship between the rotor speed, number of poles, and supply frequency. The relationship is given below.When a synchronous machine is operating as a motor, it runs at the synchronous speed if the supply frequency is the rated frequency of the motor, and it produces enough torque and keeps rotating. If the frequency of the supply source falls below the specified range, the motor fails to maintain the synchronous speed, and it won’t generate enough torque to sustain its rotation and will eventually come to a stop. This situation is known as being “pulled out of step.” Thus, a synchronous machine working as a motor does not produce torque if operated below the synchronous speed.When a synchronous machine operates as a generator, the generator’s rotor must maintain a constant speed known as Synchronous speed to produce power at a specific frequency. This frequency is designed to operate all appliances and machines. In certain countries, the frequency value is set at 50 hertz. A 2-pole synchronous generator rotating at 3000 RPM will generate power at a frequency of 50 Hz.What happens when the speed of the rotor in the generator drops below the synchronous speed? At this point, the frequency of the power supply will no longer be the rated frequency of the generator, and it can negatively affect the functioning of equipment that is designed to operate at 50 Hz.A synchronous machine is an electromechanical device that can convert mechanical energy into electrical energy or vice versa. Synchronous motors and generators function as synchronous machines based on the two fundamental laws of electromagnetic induction and interaction, which are explained below.The law of electromagnetic induction is a fundamental principle in electromagnetism that describes the relationship between a changing magnetic field and the induction of an electromotive force (EMF) or voltage in a conductor. This law is also known as Faraday’s First Law of Electromagnetic Induction. The law states that an emf is induced in a conductor when it cuts across a magnetic field, as shown below:These laws are fundamental to the operation of devices such as generators and transformers. When a coil is exposed to a changing magnetic field, the magnetic flux through the coil changes, inducing an EMF and causing a current to flow if the circuit is closed. The mathematical formula expressing the induced EMF in a coil due to a change in the magnetic field can be represented as:It’s important to note that the negative sign in the above equation indicates the direction of the induced current or voltage according to Lenz’s law, which states that the induced current will always oppose the change in magnetic flux that produced it. This conservation of energy principle ensures that the system resists changes in the magnetic field and maintains a stable state.This law pertains to the creation of force or torque. Whenever a conductor carrying an electric current is placed in a magnetic field, it produces a magnetic field. The interaction between the magnetic field produced by the current-carrying conductor and the main magnetic field causes a force to be exerted on the conductor, resulting in the production of torque, as shown in the figure below.The synchronous machine operates as a motor based on this principle. The formula for calculating the torque (T) in a synchronous motor is given by:Here are the main characteristics of synchronous machines, whether they are motors or generators:Synchronous motors do not have self-starting torque. They need an external prime mover to start as a motor.Synchronous machines are doubly-excited machines as they require two input supplies – one for the stator and another for the rotor.Synchronous machines maintain a constant speed, known as synchronous speed, during operation.Synchronous generators are capable of generating a voltage that remains constant in both magnitude and frequency.A synchronous machine can operate at lagging, leading, or unity power factor by adjusting the excitation.Compared to induction motors, synchronous motors possess a starting torque that is relatively higher.Synchronous motors are suitable for driving loads that require constant and slow speeds, usually less than 300 RPM.Synchronous machines are costlier. The article covers the construction and operation of synchronous machine, focusing on the rotor and stator components. It explains the use of electromagnets to create the field in synchronous machines, comparing salient-pole and round-rotor designs. Furthermore, it highlights the concept of synchronous speed and its relationship to the number of poles and electrical frequency. In the AC Machine article, we examined a simple permanent-magnet AC machine. That machine used a rotating armature coil, which means the power to run the motor or the power from the generator must be transmitted through the brushes and slip rings. For large machines, that is not very efficient, so AC synchronous machines are built with the armature on the stator and the field on the rotor. Construction of Synchronous Machine Rotor Figure 1 is a sketch of the rotor and stator of a synchronous machine. The rotor would be placed inside the stator. Instead of a permanent magnet, this machine (as do the overwhelming majority of synchronous machines) uses an electromagnet to create the field. A DC voltage is applied to the coils on the rotor, creating north and south poles. This particular rotor is called a salient-pole rotor because the rotor is not symmetric. In particular, the air gap between the pole faces and the stator is much smaller than that between the sides of the rotor and the stator. Some machines are built with a round rotor, which has slots in the side to hold the field coils. These are referred to as round-rotor synchronous machines. Round-rotor designs are typically limited to a maximum of four poles, whereas salient-pole machines have been built with over 50 poles. In either case, the rotor only sees a DC flux, so the rotor does not have to be laminated. Figure 1. Synchronous machine components labeled diagram Figure 2 shows a salient-pole rotor. This rotor is actually part of the excitation system for a very large (345 MVA) synchronous machine that was disassembled for maintenance. It operates on the same shaft as the larger unit, which is why the shaft diameter is so large. The front pole-face is marked “stator,” indicating the direction it faces when reassembled. The field coils are located directly behind the pole-faces. Figure 2. Salient-pole rotor diagram Figure 3 shows a round rotor for a synchronous generator. The pole-faces are at the top and bottom of the rotor as it is positioned in the picture. Note that putting more than two poles on the rotor in slots becomes very complicated. Figure 4 shows slip rings and brushes that are located on the end of the shaft of a 10 MW synchronous generator. This particular generator is a two-pole machine, which means it runs at 3600 RPM. Of course, the carbon in the brushes eventually wears down and the brushes have to be replaced. To keep from shutting the machine down, that has to be done while the machine is running. Figure 5 shows a cutaway view of a synchronous generator that is designed to be driven by a diesel engine. This machine has a salient-pole rotor, and an exciter machine is located at the left end of the shaft. This exciter is a permanent- magnet machine with the armature on the rotor. The AC is rectified by diodes on the rotor to provide DC for the main field winding. This is referred to as a rotating-rectifier exciter. Figure 3 Round rotor for a synchronous generator with wound field coils Stator The other half of the machine in Figure 1 is the stator, which contains the AC armature winding. Depending on the size of the machine, the armature winding consists of coils or copper bars laid into slots on the inside surface of the stator. Figure 6 shows the armature winding that surrounds the rotor of Figure 2. This winding consists of coils in slots, and the complete structure is approximately 4 feet in diameter. Figure 7 shows a lamination for the stator of a small AC machine (the lamination is about four inches wide). For machines like the one shown in Figure 6, the coils would be wound and then placed in the slots of the stator; for small machines like the one in Figure 7, the coils would be wound directly into the stator lamination stack. Because AC currents will flow through the stator winding, the stator must be constructed of laminations to reduce the eddy current losses. The slots shown in Figure 7 are designed to have coils wound into them since there are teeth at the openings of the slots. Finally, Figure 8 shows a close-up view of several slots of the armature winding of a 345 MVA machine. The inside diameter of this machine is about 9 feet. This winding is composed of copper bars laid into the slots, so essentially each coil contains one turn. Figure 4 Slip rings and brushes diagram in a synchronous generator Before we consider the motor and generator operation of the synchronous machine, we need to first consider how a three-phase armature winding creates a rotating magnetic field. Figure 5 Cutaway view of a synchronous machine labeled diagram Figure 6 Stator (armature) winding of a synchronous machine diagram Synchronous Machine Working Principle The rotating magnetic field Figure 9 shows two stator windings from AC machines. The stator on the left contains a complete winding, so the end turns are visible. The end turns were cut off the winding on the stator on the right side, exposing the coil turns in the slots of the stator. These stators contain a three-phase, six-pole winding so there are quite a few coils visible on the winding at the left. To consider the operation of a three-phase winding, we will start by looking at a single phase. Figure 7 Stator lamination of a small AC Synchronous machine Figure 10 (a) is a sketch of the cross-section of a stator with a single-phase coil. In order to produce the desired flux distribution in the air gap, the coil occupies several slots around the stator surface. This is referred to as a distributed winding. The other two phases would be centered 120° apart, and all of the stator circumference would contain slots. Consider what happens if an AC current, ${{I}_{m}}\cos \left(\omega t \right)$, is applied to the coil in the direction shown (X indicates current into the page and • indicates current out of the page). At time zero, the current will cause magnetic flux through the rotor in the down direction, as shown. Note that no matter what the magnitude of the current in coil a, the flux due to the current will always lie along the coil an axis. At Θ = 0° (the top), the flux is entering the air gap from the stator—define that to be positive. Figure 8 Armature winding and slots of 345 MVA synchronous machine At the opposite side (Θ = 180°), the flux enters the air gap from the rotor, so it is negative. By proper design of the winding, the flux can be made to be sinusoidally distributed in the air gap. Figure 9 Left: AC stator winding. Right: end turns cut off to expose coils in slots. Figure 10 Flux distribution in the air gap due to a single-phase coil in a synchronous machine Imagine that we could “unpeel” the air gap of the machine and view the flux distribution in the air- gap. At $\omega t=0$, the air gap and flux distribution might look like Figure 10(b). The dotted line indicates the center of the air gap, with the stator on top and the rotor on the bottom. At this instant in time, the current is constant, so B is a function only of Θ; i.e., $B\left(\theta \right)={{B}_{m}}\cos \theta $ where Bm is a function of the current, ${{I}_{m}}$. Likewise, when the current reverses, at $\omega t=\pi $, the B field will look like that shown in Figure 10(c), with the positive maximum at Θ = 180°. At other times, the flux wave will be somewhere between the extremes, as shown in 10(d). In other words, the flux density in the airgap is a standing wave. Thus, $B\left(\theta ,t \right)=B\left(\theta \right)\cos \omega t={{B}_{m}}\cos \omega t\cos \theta $ But by using trigonometric identities, $\cos \theta \cos \omega t=0.5\left[\cos \left(\theta -\omega t \right)+\cos \left(\theta +\omega t \right) \right]$ The first term on the right side, $\cos \left(\theta -\omega t \right)$ is the expression for a traveling wave in the forward direction. Since our airgap is actually circular, the wave is traveling around or rotating. Unfortunately, the second term on the right side represents a wave traveling backward around the air gap. Despite the presence of opposite traveling flux waves, single-phase motors will run once started. However, they have no starting torque because of the opposite traveling waves. A three-phase stator winding Figure 11 shows a three-phase stator winding. The phase windings would each occupy a number of slots as shown previously; however, each phase winding is represented by only one slot to keep the drawing legible. When the winding is shown in one slot, it is called a concentrated winding. Note that the windings of the three phases are physically 120° apart. Figure 11 Three-phase stator with the same current in all three phases in a synchronous machine In Figure 11, all three phases have the same current (represented by • and X). As a result, the flux distribution due to coil b is 120° behind coil a, and the flux due to coil c is 120° behind coil b, as shown. Since they have the same magnitude and are 120° apart, they will add to zero. Thus, if we apply a DC current or the same AC current to all three coils, the fluxes of the three phases would cancel. That obviously wouldn’t help much. Instead, consider what happens when a balanced three-phase set of currents is applied to the coils: $\begin{align} & {{i}_{a}}\left(t \right)={{I}_{m}}\cos \omega t \\ & {{i}_{b}}\left(t \right)={{I}_{m}}\cos \left(\omega t-{{120}^{o}} \right) \\ & {{i}_{c}}\left(t \right)={{I}_{m}}\cos \left(\omega t-{{240}^{o}} \right) \\\end{align}$ Figure 12 Balanced three-phase currents applied to the stator winding The balanced set of three-phase currents that are applied to the stator winding are shown in Figure 12. Each current will create a magnetic flux distribution, but the three phases are displaced both in time and in space. We could multiply the currents by the spacial distribution of the flux as was done previously and then add the three together. The result would be a traveling wave of constant magnitude. Rather than go through the algebra and trigonometric identities, we will instead consider a physical description of the machine. Figure 13 Rotating magnetic field created by a three-phase winding in a synchronous machine Figure 13 shows how the magnetic field of the stator varies with time as the currents in the three-phase coils change. At time zero, the current in phase a is at a positive maximum, while the other two phases have negative currents with an amplitude of 1/2 the current in phase a, as shown in Figure 12. For purposes of this discussion, let positive currents enter (designated by X) the coil side labeled by just a letter (e.g., a) and come out (designated by •) the side labeled by the letter and a prime symbol (a’). The large dot and thick X indicate a current with peak magnitude; the smaller d

of the flux has rotated by the same angle that the currents have moved through. The stator poles are rotating, one revolution per cycle of current since this is a two- pole machine. Mathematically, it can be shown that the peak of the flux wave is constant and rotating at a) radians per second. The direction of rotation was determined by the connections to the stator windings. By switching connections to any two phases, the direction of rotation could be reversed. The rotational speed of the stator field is called synchronous speed. For a two-pole machine, the speed of the stator field in RPM is 60 times the frequency, but for more than two poles, we must divide by the number of pole pairs (P/2). Repeating equation 1, synchronous speed is defined as $\begin{matrix} {{n}_{s}}=\frac{120\times f}{P}in\text{ }RPM & {} & \left(1 \right) \\\end{matrix}$ Where f is the electrical frequency, and P is the number of poles in the machine. There are 60 seconds per minute, so dividing equation 1 by 60 yields the synchronous speed in revolutions per second: $\begin{matrix} {{n}_{s}}=\frac{2\times f}{P}in & rev/s & \left(2 \right) \\\end{matrix}$ The electrical frequency determines the speed of the rotating magnetic field, which in turn determines how fast the motor will run. Synchronous Machine Key Takeaways Understanding the construction and operation of synchronous machines is essential due to their critical role in modern electrical and industrial applications. The use of electromagnets in rotors—whether in salient-pole or round-rotor configurations—offers design flexibility for machines of various sizes and speeds. The stator's distributed three-phase windings create a rotating magnetic field, a key principle that ensures efficient torque production and synchronous operation with the power supply. These machines are widely used in power generation (e.g., synchronous generators in power plants), industrial motor drives, and grid stability systems due to their constant-speed characteristics and high efficiency. Figure 5.2 shows the simplified version of an ac Synchronous Machine Working Principle with a 2-pole field winding on the rotor and a single coil aa' on the stator. This type of rotor poles are known as salient (projecting) poles; and are excited by means of dc fed to the concentrated field winding. The current is fed to the rotor via two slip-rings and carbon brushes as shown already. Figure 5.2 also shows two mean paths of magnetic flux (shown dotted). The magnetic neutral regions are located in the interpolar gaps. Without any significant loss of accuracy, the reluctance of the iron path will be neglected. Assuming that the air-gap over the pole-shoes is uniform, the flux density in the gap over the pole-shoes is constant (as mmf acting along any flux path is constant for the concentrated field winding); the flux density in the air layer along the stator periphery gradually falls off to zero in the interpolar region. The result is a flat-topped flux density wave as shown in Fig. 5.3. Since the magnetic flux enters the stator normally, the relative movement between the stator conductors (coil-sides of the stator coil) and the air-gap flux density is mutually perpendicular. This results in the emf being induced along the stator conductors as per the Blv rule, with emf direction on being governed by v x B or the Fleming's right-hand rule. It is to be further observed that the magnetic field has symmetry along the axial length; the end effects (fringing) at either end of the cylindrical structure are neglected in this model. In ac machines it is desirable for the induced emfs to be sinusoidal in waveform, therefore, flux density wave in the machine air-gap must be sinusoidal. This is achieved in the salient pole construction (with concentrated field coils) by providing nonuniform air-gap above pole-shoes; minimum air-gap in the middle of the pole-shoe progressively increasing towards outer edges. Here it will be assumed the air-gap flux density wave is perfectly sinusoidal as shown in Fig. 5.4. Another method of obtaining a sinusoidal B-wave in air-gap is the use of the nonsalient pole structure, i.e. a cylindrical rotor with uniform air-gap but with a suitably distributed field winding along the rotor periphery as shown in Fig. 5.5. In this structure as one moves away from the pole-axis, the flux paths link progressively smaller number of field ampere-turns. The ampere-turns can be so distributed as to give a nearly sinusoidal B-wave in space as shown in Fig. 5.4. The armature coil in the elementary 2-pole machine of Fig. 5.2 is placed in two diametrically opposite slots notched out on the inside of the stator. The coil can have many turns. Various shapes of coils are employed; Fig. 5.6 shows a diamond-shaped coil. Each coil has two sides termed coil sides. The active length of coil-sides equals the magnetic length of the stator over which the B-wave acts to induce emf. No emf is produced in end connections which are suitably formed so as to be neatly accommodated on the stator ends away from the rotating parts. The two coil-sides of our elementary machine are shown in the cross-sectional developed diagram of Fig. 5.4. Since the coil-sides are 1/2 B-wave length (π radians) apart, the voltages induced in the two coil-sides (Blv, where v is the peripheral velocity of the pole-faces) are identical in value but opposite in sign so that the total coil voltage is double the coil-side voltage and has the same waveform as the B-wave and is shown in Fig. 5.7. One cycle of the alternating emf is generated in one revolution of the rotor. Consider now a machine with a 4-pole structure, as shown in Fig. 5.8, the poles being alternately north and south. The flux-density space wave of this structure is drawn in Fig. 5.9. It has two complete cycles in the total angle of 2π radians which will now be referred to as the mechanical angle. It is obvious from Figs. 5.8 and 5.9 that now two coils can be placed symmetrically—one coil under each pair of poles. Each coil has a span (pitch) of 1/2 B-wave length and the axes of the two coils are spaced one full B-wave length apart. It is immediately seen that magnetic and electrical conditions existing under one pair of poles are merely repeated under every other pole-pair. The emf's induced in coils a1a′1 and a2a′2 are both alternating, equal in magnitude and in time phase to each other. It is convenient to work in terms of one pole pair of a multi-polar machine (number of poles must obviously be even). The total angular span of one pole pair is therefore taken as 2π and is referred to as electrical angle as different from the actual mechanical angle. Let These angles are both shown in Fig. 5.9. Taking the ratio of total electrical and mechanical angles of a P-pole machine, The span of the coil, called the coil-pitch or coil-span, which was indicated to be 1/2 B-wavelength, will be π rad (180°) in electrical angle and is fixed irrespective of the number of machine poles. Such a coil is called full-pitched. For the time being, it will be assumed that all coils are full-pitched. Short-pitched (chorded) coils, i.e., coils with angular span less than 180° elect. are also employed. In a P-pole machine, one cycle of alternating emf is generated in each coil as one pole-pair of the rotor poles glides past the stator. Thus for one complete revolution of the rotor, P/2 cycles of emf are generated in the coil. Therefore, the frequency of the voltage wave (it is a time wave) is where n = speed of the rotor in revolution per minute (rpm) Differentiating each side of Eq. (5.1) with respect to time The two coils of the 4-pole generator Synchronous Machine Working Principle of Fig. 5.8 are seats of identical emfs and can be connected in series or parallel as shown in Fig. 5.10(a) and (b). The series connection gives double the voltage of one coil and can handle the same maximum current as any one coil. The parallel connection has the same voltage as that of each coil and has twice the maximum current-carrying capacity of one of the coils. The designer exploits the series-parallel arrangement of coil groups to build a machine of desired voltage and current rating. Like any other rotating electrical machine, a synchronous machine (generator or motor) has two essential parts namely, Stator − It is a stationary part of the machine and carries the armature winding. Rotor − It is the rotating part of the machine. The rotor of a synchronous machine produces the main field flux. In this chapter, let's discuss how the Stator and Rotor of a Synchronous Machine is constructed. Stator Construction The stator of a synchronous machine includes various parts like frame, stator core, stator windings and cooling mechanisms, etc. The frame is the outer part of the machine, and made up of cast iron for small-sized machines, and of welded steel for large-sized machines. The frame encloses the whole machine assembly and protects it from mechanical and environmental impacts. The stator core is a hollow cylinder which is made up of high-grade silicon steel laminations. The silicon steel laminations reduce the hysteresis and eddy-current losses in the machine. A number of evenly spaced slots are provided on the inner periphery of the stator core. A three-phase winding is put in these slots. When current flows through the stator winding, it produces a sinusoidal magnetic field and hence the EMF. In synchronous machines, there are two types of rotor constructions used namely, salient-pole rotor and cylindrical rotor. Salient-Pole Rotor The term salient means projecting. Hence, a salient-pole rotor is one that consists of field poles projecting out from the surface of the rotor core as shown in Figure-2. Since the rotor is subjected to a changing magnetic field, therefore it is made up of thin steel lamination to reduce the eddy current loss. The field poles of same dimensions are constructed by stacking laminations of the required length and then riveted together. After wounding the field coils around each pole core, poles are fitted to a steel spider keyed to the rotor shaft. At the outer end of each pole, damper bars are provided to dame out the oscillations of rotor during sudden changes in the load. Though, the synchronous machines using the salient-pole rotor have a non-uniform air gap, where the air gap is minimum under the pole centers and it is maximum in between the field poles. The pole face (outer end of the pole) is so shaped that length of the radial air-gap increases from the pole center to the pole tip so it can result a sinusoidal distribution of flux in the air-gap. This will ensure the smooth operation of synchronous machine. In the salient-pole rotor, the individual field coils are connected in series so that they can give alternate north and south poles. The ends of the field coils are connected to a source of DC supply though brushes and slip-rings. The synchronous machines having salient-pole rotor usually have a large number of field poles, and operate at lower speeds. These machines have a larger diameter and a shorter axial-length. Cylindrical Rotor This type of synchronous machine rotor construction has a smooth cylindrical structure. In case of cylindrical rotor, there are no physical poles projecting outward. The cylindrical rotor is made from slid forgings of high-grade Ni-Cr-Mo steel. On the outer periphery of the rotor, evenly spaced slots are cut in about two-third part of the rotor and theses slots are parallel to the rotor shaft. The field windings are placed in these slots. The field windings are excited from a source of DC supply. The un-slotted part of the rotor forms pole-faces. The synchronous machines that use cylindrical rotor have a smaller diameter and longer axial length. The cylindrical rotor construction limits the effect of centrifugal forces. Consequently, the cylindrical rotor construction is mainly used in high-speed synchronous machines. Also, this rotor construction provides a greater mechanical strength and permits relatively more accurate dynamic balancing to the machine. The major advantage of having a synchronous machine using cylindrical rotor is that it makes less mechanical losses. Since the cylindrical rotor provides a uniform air-gap in the machine, hence their operation is less noisy. Synchronous Machine constitutes of both synchronous motors as well as synchronous generators. An AC system has some advantages over a DC system. Therefore, the AC system is exclusively used for the generation, transmission, and distribution of electric power. The machine which converts mechanical power into AC electrical power is called a Synchronous Generator or Alternator. However, if the same machine can be operated as a motor is known as Synchronous Motor. Synchronous machine is an AC machine whose satisfactory operation depends upon the maintenance of the following relationship. Where, Ns is the synchronous speed in revolution per minute (r.p.m) f is the supply frequency P is the number of poles of the machine. When connected to an electric power system, a synchronous machine always maintains the above relationship shown in equation (1). If the synchronous machine working as a motor fails to maintain the average speed (Ns) the machine will not develop sufficient torque to maintain its rotation and will stop. Then the motor is said to be Pulled Out of Step. In case, when the synchronous machine is operating as a generator, it has to run at a fixed speed called Synchronous speed to generate the power at a particular frequency. As all the appliances or machines are designed to operate at this frequency. In some countries, the value of the frequency is 50 hertz. Basic Principles of Synchronous Machine A synchronous machine is just an electromechanical transducer that converts mechanical energy into electrical energy or vice versa. The fundamental phenomenon or law which makes these conversions possible is known as the Law of Electromagnetic Induction and Law of interaction. The detailed description is explained below. Law of Electro-Magnetic Induction This law is also called Faraday's First Law of Electromagnetic Induction. This law relates to the production of emf, i.e.; emf is induced in a conductor whenever it cuts across the magnetic field as shown below: Law of Interaction This law relates to the production of force or torque, i.e., whenever a current-carrying conductor is placed in the magnetic field, by the interaction of the magnetic field produced by the current-carrying conductor and the main field, force is exerted on the conductor producing torque. The figure is shown below: Three-Phase Synchronous Machine The machine which is used in the household appliance such as the small machine used in air coolers, refrigeration, fans, air conditioners, etc. However, large AC machines are three-phase type synchronous machines because of the following reasons. For the same size of the frame, three-phase machines have nearly 1.5 times the output than that of the single-phase machine. Three-phase power is transmitted and distributed more economical than single-phase power. Three-phase motors are self-starting (except synchronous motors). Three-phase motors have an absolute uniform continuous torque, whereas, single-phase motors have pulsating torque. In a small synchronous machine, the fielding winding is placed on the stator, and the armature winding is placed on the rotor whereas for the large synchronous machine the field winding is placed on the rotor, and the armature winding is placed on the stator. Construction of a Synchronous Machine, i.e. alternator or motor consists of two main parts, namely the stator and the rotor. The stator is the stationary part of the machine. It carries the armature winding in which the voltage is generated. The output of the machine is taken from the stator. The rotor is the rotating part of the machine. The rotor produces the main field flux. The important parts of the Synchronous Machine are given below: Stator Rotor Miscellaneous Stator Construction The stationary part of the machine is called Stator. It includes various parts like stator frame, stator core, stator windings, and cooling arrangement. They are explained below in detail. Stator Frame It is the outer body of the machine made of cast iron, and it protects the inner parts of the machine. Stator Core The stator core is made of silicon steel material. It is made from a number of stamps that are insulated from each other. Its function is to provide an easy path for the magnetic lines of force and accommodate the stator winding. Stator Winding Slots are cut on the inner periphery of the stator core in which 3 phase or 1 phase winding is placed. Enameled copper is used as a winding material. The winding is star-connected. The winding of each phase is distributed over several slots. When the current flows in a distributed winding it produces an essentially sinusoidal space distribution of EMF. Rotor Construction The rotating part of the machine is called Rotor. There are two types of rotor construction, namely the salient pole type and the cylindrical rotor type. Salient Pole Rotor The term salient means projecting. Thus, a salient pole rotor consists of poles projecting out from the surface of the rotor core. The end view of a typical 6 pole salient pole rotor is shown below in the figure: Since the rotor is subjected to changing magnetic fields, it is made of steel laminations to reduce eddy current losses. Poles of identical dimensions are assembled by stacking laminations to the required length. A salient pole synchronous machine has a non-uniform air gap. The air gap is minimized under the pole centers and it is maximum in between the poles. They are constructed for medium and low speeds as they have a large number of poles. A salient pole generator has a large diameter. The salient pole rotor has the following important parts. Spider: It is made of cast iron to provide an easy path for magnetic flux. It is keyed to the shaft and at the outer surface, pole core and pole shoe are keyed to it. Pole Core and Pole Shoe: It is made of laminated steel sheet material. The Pole core provides the least reluctance path for the magnetic field and the pole shoe distributes the field over the whole periphery uniformly to produce a sinusoidal wave. Field Winding or Exciting Winding: It is wound on the former and then placed around the pole core. DC supply is given to it through slip rings. When direct current flows through the field winding, it produces the required magnetic field. Damper Winding: At the outermost periphery, holes are provided in which copper bars are inserted and short-circuited at both sides by rings forming Damper winding. Non- Salient Pole Rotor or Cylindrical Rotor In this type of rotor, there are no projected poles, but the poles are formed by the current flowing through the rotor exciting winding. Cylindrical rotors are made from solid forgings of high-grade nickel chrome-molybdenum steel. It has a comparatively small diameter and long axial length. They are useful in high-speed machines. The cylindrical rotor type alternator has two or four poles on the rotor. Such a construction provides greater mechanical strength and permits more accurate dynamic balancing. The smooth rotor of the machine makes fewer windage losses and the operation is less noisy because of the uniform air gap. The figure below shows the end view of the 2 poles and 4 pole cylindrical rotors. They are driven by steam or gas turbines. Cylindrical synchronous rotor synchronous generators are called turbo-alternators and turbo generators. The machines are built in a number of ratings from 10 MVA to over 1500 MVA. The biggest size used in India has a rating of 500 MVA installed in the super thermal power plant. Non-salient pole-type rotors have the following parts. They are as follows: Rotor Core: The rotor core is made of silicon steel stampings. It is placed on the shaft. At the outer periphery, slots are cut in which exciting coils are placed. Rotor Winding or Exciting Winding: It is placed on the rotor slots, and the current is passed through the winding in such a way that the poles are formed according to the requirement. Slip Rings: Slip rings provide DC supply to the rotor windings. Miscellaneous Parts The miscellaneous parts are given below: Brushes: Brushes are made of carbon, and they slip over the slip rings. A DC supply is given to the brushes. Current flows from the brushes to the slip rings and then to the exciting windings. Bearings: Bearings are provided between the shaft and the outer stationary body to reduce the friction. They are made of high carbon steel. Shaft: The shaft is made of mild steel. Mechanical power is taken or given to the machine through the shaft. The article covers the construction and operation of synchronous machine, focusing on the rotor and stator components. It explains the use of electromagnets to create the field in synchronous machines, comparing salient-pole and round-rotor designs. Furthermore, it highlights the concept of synchronous speed and its relationship to the number of poles and electrical frequency. In the AC Machine article, we examined a simple permanent-magnet AC machine. That machine used a rotating armature coil, which means the power to run the motor or the power from the generator must be transmitted through the brushes and slip rings. For large machines, that is not very efficient, so AC synchronous machines are built with the armature on the stator and the field on the rotor. Construction of Synchronous Machine Rotor Figure 1 is a sketch of the rotor and stator of a synchronous machine. The rotor would be placed inside the stator. Instead of a permanent magnet, this machine (as do the overwhelming majority of synchronous machines) uses an electromagnet to create the field. A DC voltage is applied to the coils on the rotor, creating north and south poles. This particular rotor is called a salient-pole rotor because the rotor is not symmetric. In particular, the air gap between the pole faces and the stator is much smaller than that between the sides of the rotor and the stator. Some machines are built with a round rotor, which has slots in the side to hold the field coils. These are referred to as round-rotor synchronous machines. Round-rotor designs are typically limited to a maximum of four poles, whereas salient-pole machines have been built with over 50 poles. In either case, the rotor only sees a DC flux, so the rotor does not have to be laminated. Figure 1. Synchronous machine components labeled diagram Figure 2 shows a salient-pole rotor. This rotor is actually part of the excitation system for a very large (345 MVA) synchronous machine that was disassembled for maintenance. It operates on the same shaft as the larger unit, which is why the shaft diameter is so large. The front pole-face is marked "stator," indicating the direction it faces when reassembled. The field coils are located directly behind the pole-faces. Figure 2. Salient-pole rotor diagram Figure 3 shows a round rotor for a synchronous generator. The pole-faces are at the top and bottom of the rotor as it is positioned in the picture. Note that putting more than two poles on the rotor in slots becomes very complicated. Figure 4 shows slip rings and brushes that are located on the end of the shaft of a 10 MW synchronous generator. This particular generator is a two-pole machine, which means it runs at 3600 RPM. Of course, the carbon in the brushes eventually wears down and the brushes have to be replaced. To keep from shutting the machine down, that has to be done while the machine is running. Figure 5 shows a cutaway view of a synchronous generator that is designed to be driven by a diesel engine. This machine has a salient-pole rotor, and an exciter machine is located at the left end of the shaft. This exciter is a permanent- magnet machine with the armature on the rotor. The AC is rectified by diodes on the rotor to provide DC for the main field winding. This is referred to as a rotating-rectifier exciter. Figure 3 Round rotor for a synchronous generator with wound field coils Stator The other half of the machine in Figure 1 is the stator, which contains the AC armature winding. Depending on the size of the machine, the armature winding consists of coils or copper bars laid into slots on the inside surface of the stator. Figure 6 shows the armature winding that surrounds the rotor of Figure 2. This winding consists of coils in slots, and the complete structure is approximately 4 feet in diameter. Figure 7 shows a lamination for the stator of a small AC machine (the lamination is about four inches wide). For machines like the one shown in Figure 6, the coils would be wound and then placed in the slots of the stator; for small machines like the one in Figure 7, the coils would be wound directly into the stator lamination stack. Because AC currents will flow through the stator winding, the stator must be constructed of laminations to reduce the eddy current losses. The slots shown in Figure 7 are designed to have coils wound into them since there are teeth at the openings of the slots. Finally, Figure 8 shows a close-up view of several slots of the armature winding of a 345 MVA machine. The inside diameter of this machine is about 9 feet. This winding is composed of copper bars laid into the slots, so essentially each coil contains one turn. Figure 4 Slip rings and brushes diagram in a synchronous generator Before we consider the motor and generator operation of the synchronous machine, we need to first consider how a three-phase armature winding creates a rotating magnetic field. Figure 5 Cutaway view of a synchronous machine labeled diagram Figure 6 Stator (armature) winding of a synchronous machine diagram Synchronous Machine Working Principle The rotating magnetic field Figure 9 shows two stator windings from AC machines. The stator on the left contains a complete winding, so the end turns are visible. The end turns were cut off the winding on the stator on the right side, exposing the coil turns in the slots of the stator. These stators contain a three-phase, six-pole winding so there are quite a few coils visible on the winding at the left. To consider the operation of a three-phase winding, we will start by looking at a single phase. Figure 7 Stator lamination of a small AC Synchronous machine Figure 10 (a) is a sketch of the cross-section of a stator with a single-phase coil. In order to produce the desired flux distribution in the air gap, the coil occupies several slots around the stator surface. This is referred to as a distributed winding. The other two phases would be centered 120° apart, and all of the stator circumference would contain slots. Consider what happens if an AC current, ${{I}_{m}}\cos \left(\omega t \right)$, is applied to the coil in the direction shown (X indicates current into the page and • indicates current out of the page). At time zero, the current will cause magnetic flux through the rotor in the down direction, as shown. Note that no matter what the magnitude of the current in coil a, the flux due to the current will always lie along the coil an axis. At Θ = 0° (the top), the flux is entering the air gap from the stator—define that to be positive. Figure 8 Armature winding and slots of 345 MVA synchronous machine At the opposite side (Θ = 180°), the flux enters the air gap from the rotor, so it is negative. By proper design of the winding, the flux can be made to be sinusoidally distributed in the air gap. Figure 9 Left: AC stator winding. Right: end turns cut off to expose coils in slots. Figure 10 Flux distribution in the air gap due to a single-phase coil in a synchronous machine Imagine that we could "unpeel" the air gap of the machine and view the flux distribution in the air- gap. At $\omega t=0$, the air gap and flux distribution might look like Figure 10(b). The dotted line indicates the center of the air gap, with the stator on top and the rotor on the bottom. At this instant in time, the current is constant, so B is a function only of Θ; i.e., $B\left(\theta \right)={{B}_{m}}\cos \theta $ where Bm is a function of the current, ${{I}_{m}}$. Likewise, when the current reverses, at $\omega t=\pi $, the B field will look like that shown in Figure 10(c), with the positive maximum at Θ = 180°. At other times, the flux wave will be somewhere between the extremes, as shown in 10(d). In other words, the flux density in the airgap is a standing wave. Thus, $B\left(\theta ,t \right)=B\left(\theta \right)\cos \omega t={{B}_{m}}\cos \omega t\cos \theta $ But by using trigonometric identities, $\cos \theta \cos \omega t=0.5\left[\cos \left(\theta -\omega t \right)+\cos \left(\theta +\omega t \right) \right]$ The first term on the right side, $\cos \left(\theta -\omega t \right)$ is the expression for a traveling wave in the forward direction. Since our airgap is actually circular, the wave is traveling around or rotating. Unfortunately, the second term on the right side represents a wave traveling backward around the air gap. Despite the presence of opposite traveling flux waves, single-phase motors will run once started. However, they have no starting torque because of the opposite traveling waves. A three-phase stator winding Figure 11 shows a three-phase stator winding. The phase windings would each occupy a number of slots as shown previously; however, each phase winding is represented by only one slot to keep the drawing legible. When the winding is shown in one slot, it is called a concentrated winding. Note that the windings of the three phases are physically 120° apart. Figure 11 Three-phase stator with the same current in all three phases in a synchronous machine In Figure 11, all three phases have the same current (represented by • and X). As a result, the flux distribution due to coil b is 120° behind coil a, and the flux due to coil c is 120° behind coil b, as shown. Since they have the same magnitude and are 120° apart, they will add to zero. Thus, if we apply a DC current or the same AC current to all three coils, the fluxes of the three phases would cancel. That obviously wouldn't help much. Instead, consider what happens when a balanced three-phase set of currents is applied to the coils: $\begin{align} & {{i}_{a}}\left(t \right)={{I}_{m}}\cos \omega t \\ & {{i}_{b}}\left(t \right)={{I}_{m}}\cos \left(\omega t-{{120}^{o}} \right) \\ & {{i}_{c}}\left(t \right)={{I}_{m}}\cos \left(\omega t-{{240}^{o}} \right) \\\end{align}$ Figure 12 Balanced three-phase currents applied to the stator winding The balanced set of three-phase currents that are applied to the stator winding are shown in Figure 12. Each current will create a magnetic flux distribution, but the three phases are displaced both in time and in space. We could multiply the currents by the spacial distribution of the flux as was done previously and then add the three together. The result would be a traveling wave of constant magnitude. Rather than go through the algebra and trigonometric identities, we will instead consider a physical description of the machine. Figure 13 Rotating magnetic field created by a three-phase winding in a synchronous machine Figure 13 shows how the magnetic field of the stator varies with time as the currents in the three-phase coils change. At time zero, the current in phase a is at a positive maximum, while the other two phases have negative currents with an amplitude of 1/2 the current in phase a, as shown in Figure 12. For purposes of this discussion, let positive currents enter (designated by X) the coil side labeled by just a letter (e.g., a) and come out (designated by •) the side labeled by the letter and a prime symbol (a'). The large dot and thick X indicate a current with peak magnitude; the smaller dot and thin X indicates a smaller magnitude. Based on this, at t = 0° in Figure 13, a large positive current enters side a, while smaller negative currents enter sides b' and c'. Conversely, the currents come out of sides a', b, and c. Notice the pattern that is formed—all of the currents enter the coils on the left side of the machine and come out on the right side. By the right-hand flux rule, the stator flux is directed in the downward direction, as shown by the arrow. As a result, the south (S) pole is at the bottom and the north (N) pole is at the top (θ = 0). Now consider what happens at ωt= 60°. Ic has reached its negative peak, while Ia and Ib are both at one-half of the positive peak. So now phase c has the large dot and thick X, while the other two phases have a small dot and thin X. Because 7b went from negative to positive, its dot and X have changed sides (X at b and • at b') Note that the pattern of dots and Xs has rotated. Again applying the right-hand flux rule, we find the direction of the stator flux has moved by 60°. Continuing every 60°, we find that each 60° increment in time causes a 60° rotation in the magnetic flux. We are not constrained to looking at 60° intervals; however, we could look at any instant in time and find that the direction of the flux has rotated by the same angle that the currents have moved through. The stator poles are rotating, one revolution per cycle of current since this is a two- pole machine. Mathematically, it can be shown that the peak of the flux wave is constant and rotating at a) radians per second. The direction of rotation was determined by the connections to the stator windings. By switching connections to any two phases, the direction of rotation could be reversed. The rotational speed of the stator field is called synchronous speed. For a two-pole machine, the speed of the stator field in RPM is 60 times the frequency, but for more than two poles, we must divide by the number of pole pairs (P/2). Repeating equation 1, synchronous speed is defined as $\begin{matrix} {{n}_{s}}=\frac{120\times f}{P}in\text{ }RPM & {} & \left(1 \right) \\\end{matrix}$ Where f is the electrical frequency, and P is the number of poles in the machine. There are 60 seconds per minute, so dividing equation 1 by 60 yields the synchronous speed in revolutions per second: $\begin{matrix} {{n}_{s}}=\frac{2\times f}{P}in & rev/s & \left(2 \right) \\\end{matrix}$ The electrical frequency determines the speed of the rotating magnetic field, which in turn determines how fast the motor will run. Synchronous Machine Key Takeaways Understanding the construction and operation of synchronous machines is essential due to their critical role in modern electrical and industrial applications. The use of electromagnets in rotors—whether in salient-pole or round-rotor configurations—offers design flexibility for machines of various sizes and speeds. The stator's distributed three-phase windings create a rotating magnetic field, a key principle that ensures efficient torque production and synchronous operation with the power supply. These machines are widely used in power generation (e.g., synchronous generators in power plants), industrial motor drives, and grid stability systems due to their constant-speed characteristics and high efficiency. An electrical machine is a general term used for an electromagnetic device that is used for conversion between electrical and mechanical energy. It can be used as a generator to develop electrical energy or as a motor to develop mechanism energy. A synchronous motor is a type of motor that is used in industries for its constant speed. Electric Motor An electric motor is a machine that converts electrical energy into mechanical energy. It has a stator (stationary part) and rotor (moving part). When electrical energy is supplied, the rotor rotates generating rotational mechanical energy. It works completely opposite to that of a generator. Electrical motors can be classified into AC and DC motors. While the AC motors are further classified into induction motors and synchronous motors. What is a Synchronous Motor? A synchronous motor is a type of AC motor whose rotor rotates at the same speed as the rotating magnetic field. The stator's magnetic field revolves at a speed that depends on the supply frequency known as synchronous speed. Hence the name synchronous motor. The rotor of the synchronous motor is synchronized with the frequency of the supplied current. When two synchronous generators are running in parallel operation and the prime mover of one generator is shut down. The generator will still run while taking power from the generator line. The alternator supplies the obtained power from the line to its losses. When a mechanical load is connected to it, the machine will run at constant speed. When a machine runs and operates the way mentioned above, it is known as a synchronous motor. Unlike the induction motor, the synchronous motor does not rely on the induced rotor current instead the rotor has either permanent magnets or field windings that are energized using an external source. In an induction motor, the stator windings generate a rotating magnetic field (RMF) that also induces a current in the rotor. In a synchronous motor, the stator only generates RMF. The rotor's magnetic field magnetically locks with the revolving RMF and rotates at the same speed known as synchronous speed. Click image to enlarge Good to Know: A synchronous motor is the same machine as Alternator or synchronous generator. For example, A synchronous motor can be operated as a synchronous generator (alternator) without changing the rating and design. i.e. When the machine converts the input electrical power into output mechanical power, it is known as a synchronous motor. When the same machine converts the input mechanical power into output electrical power, it is known to be a synchronous generator (alternator). The synchronous motor is structurally similar to an alternator. It operates at a constant speed called synchronous speed, NS. It depends on the supply frequency and the number of poles in the rotor. Synchronous speed is given by NS = 120f ÷ p Where NS = Synchronous speed (RPM) f = Frequency of supply current p = No. of poles The number of poles depends on the design of the motor and cannot be changed during operation. Therefore, the speed of the synchronous motor only varies with the supply frequency. Related Post: Three-Phase Induction Motor – Construction, Working, Types & Applications Construction of Synchronous Motors The construction of a synchronous motor is similar to an Alternator or Synchronous generator. it differs from an asynchronous or induction motor based on its rotor design. A Synchronous motor has two main parts The stator is the stationary part of the motor. Just like an induction motor, the stator core is made of thin laminated sheets of steel or cast iron of good magnetic quality to reduce hysteresis and Eddy current loss. The core has axial slots for holding the three-phase alternating stator field winding called armature winding. The stator's armature winding is supplied with 3-phase power through its input terminal. It is responsible for generating the rotating magnetic field (RMF). Rotor The rotor is the rotating part of a synchronous motor. It has a cylindrical shape and holds the field winding, which is responsible for generating the magnetic field or poles. The rotor is energized using slip rings and a brush assembly, typically with a DC source. Usually, a small DC generator connected to its shaft is used for excitation. The rotor of a synchronous motor can be designed in one of the following ways. Salient Pole Rotor The term 'salient' means 'pointing outward'. The salient Pole rotor has protruding or projecting poles toward the armature winding. The rotor core is made of a laminated steel sheet for reduction in hysteresis and Eddy current. The field windings are wounded around each pole. The salient Pole rotor has a large number of poles. It is not suitable for high-speed operation due to its high windage losses (at high speed). It is used in low and medium-speed synchronous motors. Physically, it has a large diameter and small axial length. Slip rings and brush assembly is used to provide electrical connection between the stationary circuit and rotating part of a machine. It is used to energize the field winding using a DC source. Related Post: Servo Motor – Types, Construction, Working, & Applications Non-Salient Pole or Cylindrical Rotor Such type of rotor has a cylindrical shape rotor made of laminated steel. The core has slots for field windings that are secured with the help of wedges to prevent by pulled out. While the unslotted portion of the core becomes magnetic poles. It has less number of poles, having smaller diameter and longer axial length. It is costlier than the salient pole rotor. However, the rotor design helps in uniform distribution of flux, mechanical strength, robustness, etc. Therefore such synchronous motors are used for high speed. Permanent Magnet Rotor Modern synchronous motors use a permanent magnet rotor where the rotor has permanent magnets mounted on its surface. There are no field windings. These magnets generate the necessary field without the requirement of an excitation source. The permanent magnet is made of neodymium-boron-iron since they are easily available and cost-effective. Such rotor does not have a slip ring or brush assembly. The disadvantage of a permanent magnet rotor is that the motor is not self-starting due to the rotor's inertia, it can't follow the fast revolving RMF right at the startup. Therefore VFD (variable frequency drive) is necessary for its operation. Working Principle of Synchronous Motor Synchronous motor works on the principle of magnetic locking between the stator RMF (rotating magnetic field) and the rotor magnetic field. As we know, opposite poles attract each other, therefore the RMF poles attract the opposite rotor poles generating a rotating motion. A synchronous motor is a doubly excited machine i.e. it requires AC and DC supply for both parts stator as well as rotor to achieve synchronism. A three-phase AC is supplied to the stator's windings to generate RMF. The stator is designed to have the same number of poles as the rotor. These poles rotate at the speed that is in sync with the input frequency f is called synchronous speed. It is given by NS = 120f / p A DC supply is provided to the rotor's windings to generate a fixed magnetic field. As the DC source supplies constant current, the rotor's magnetic field does not vary. Magnetic poles are generated at the opposite ends of the rotor. The rotor's poles interact with the RMF of the stator and rotate at the same speed as it attains the synchronous speed. If the rotor rotates at the same speed as the stator RMF, there is no load torque. The rotor and stator poles align with each other. If a mechanical load is applied, the rotor starts oscillating about its new equilibrium position, this phenomenon is known as 'hunting'. The rotor lags a few degrees behind the stator RMF and starts developing torque. As the load is increased the angle between them is increased until the rotor field lags by 90° behind RMF. At this point, the motor provides the maximum available torque called breakdown torque. If the load exceeds this limit, the motor stalls. Related Post: Linear Induction Motor – Working Principle and Applications Features of Synchronous Motor The synchronous motor is inherently not self-starting. The rotor needs to be brought up to the synchronous speed by any means to synchronize with the supply frequency. Its speed only varies with the frequency of the input supply. VFD is used to control the speed of the synchronous motor. Its speed is independent of the load. Therefore synchronous motor is not affected by any variation in the load. The Increase in load increase the torque. A synchronous motor will stall if the torque increase beyond the breakdown torque. Synchronous motor either run at synchronous speed or does not run at all. Synchronous motor can run in both leading as well as lagging power factors. Therefore they are used for power factor Improvement in industries. Starting Methods of Synchronous Motors A synchronous motor isn't inherently Self-starting due to the rotor's inertia. When power is applied, the stator RMF instantly starts revolving with synchronous speed. However, the rotor cannot keep up. To provide the necessary speed for the rotor to synchronize, the following methods are used. A damper winding is used in the salient pole rotor. It is a short-circuited winding just like in an induction motor. The RMF induces a current in this winding and generates its own magnetic field that interacts with the RMF and produces the required starting torque. When the rotor reaches near synchronous speed, the DC excitation is applied to the rotor field winding and the motor locks into synchronism. In this method, the motor initially starts as an induction motor using the damper winding. This winding also helps in damping the oscillations due to sudden changes in load. Pony Motor Method A pony motor is a small induction motor or DC shunt motor that is connected with the shaft of a synchronous motor. It helps in providing the necessary starting torque. The DC excitation is not applied until the rotor attains speed near synchronous speed. The rotor magnetically locks with RMF and the power supply to the pony motor is cut off. Variable Frequency Method VFD or variable frequency drive is a device that provides power with adjustable frequency. As we know, synchronous speed depends on the supply frequency. Initially, the frequency is set to a minimum to reduce the synchronous speed. The speed is gradually increased to the desired value or normal speed. Related Post: DC Machine – Construction, Working, Types and Applications Types of Synchronous Motors The synchronous motor is mainly classified into two categories based on rotor magnetization. DC Excited Motor In such synchronous motor, a DC source is used to excite its rotor through a slip ring. The rotor includes field winding that is magnetized to generate a constant magnetic field that interacts with the stator RMF. Non Excited Motor The rotor of such a synchronous motor does not require external excitation to generate the magnetic field. Instead, it is made of material that generates its own field such as in a permanent magnet or with the help of the stator field. Cobalt steel is usually used due to its high retentivity (material that stores magnetic properties). Non Excited Motor can be further classified into the types Permanent Magnet Synchronous Motor Hysteresis Synchronous Motor Reluctance Synchronous Motor Permanent Magnet Synchronous Motor As the name suggests, the rotor is made of a permanent magnet that generates a constant magnetic field. There are no windings, slip rings and brushes. The rotor field locks with the stator RMF and rotates at synchronous speed. Since they are not self-starting and there are no windings in the rotor, it requires VFD to provide gradual increases in starting speed. Hysteresis Synchronous Motor The rotor of such synchronous motor is made of a material having high hysteresis loss such as chrome, and cobalt steel. It is a self-starting single-phase motor that runs at synchronous speed. It has two stator windings i.e. 'main winding' and 'auxiliary winding' to generate the stator RMF. The cylindrical rotor starts rotation due to induced Eddy current, thus it starts like an induction motor. Once it achieves near synchronous speed, the stator RMF locks the rotor into synchronism. Reluctance Synchronous Motor Such synchronous motor works on the principle of reluctance. Under the influence of a magnetic field, a ferromagnetic material will move to complete the magnetic circuit where there is minimum reluctance. Magnetic field lines follow a low reluctance path just like current follows a low resistance path. Therefore, a squirrel cage type rotor is used with some teeth removed to form a salient pole as well as less reluctance path. The stator is similar to the hysteresis motor having main and auxiliary windings to generate RMF. At startup, the rotor tries to align with RMF and starts revolving in its direction. But due to rotor inertia, RMF passes the alignment position and tries again during the next revolution. Thus the speed gradually increases and eventually reaches the synchronous speed and magnetically locks with the RMF. Advantages & Disadvantages of Synchronous Motor Advantages Here are some advantages of synchronous motor It has a constant operating speed called synchronous speed that only depends on supply frequency and does not vary with any change in load. It can operate in lagging, unity and leading power factor by increasing the field excitation. Thus making it useful for power factor improvement. It has a relatively higher efficiency above 90