Synchronous generator

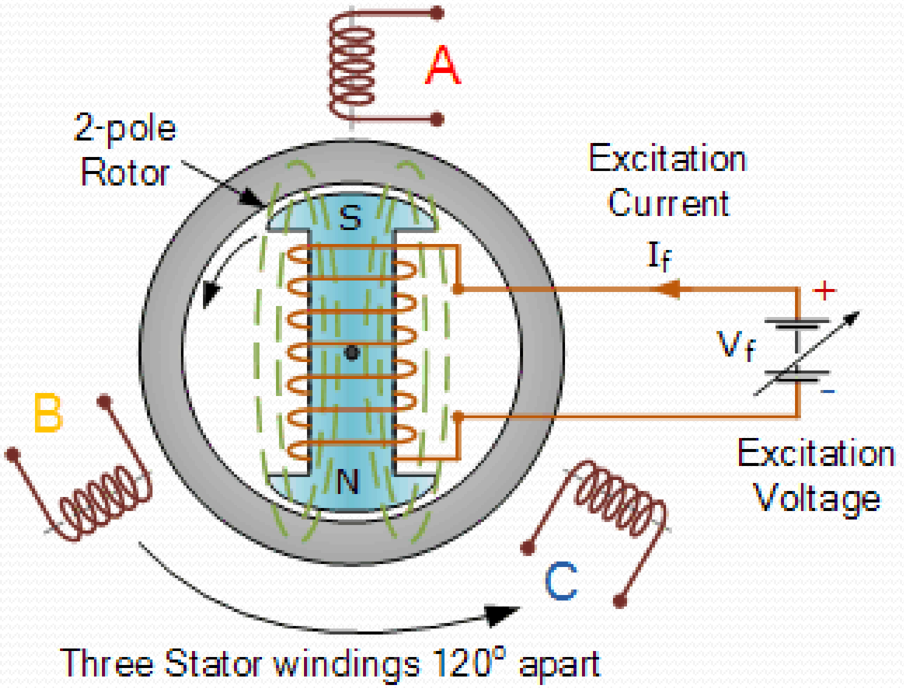
- Like the previous DC generator, the operation of the **Synchronous Generator** is also based on Faraday's law of electromagnetic induction and works in a similar way to the automotive alternator.
- The difference this time is that the synchronous generator produces a three-phase AC voltage output from its stator windings, unlike the DC generator which produces a single DC or direct current output.
- Single-phase synchronous generators are also available for low power domestic wind turbine synchronous generator system

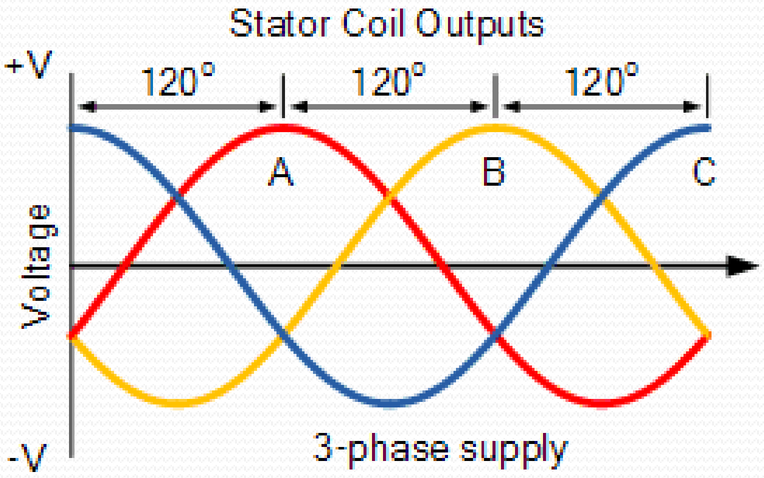
- Basically, the *synchronous generator* is a synchronous electro-mechanical machine used as a generator and consists of a magnetic field on the rotor that rotates and a stationary stator containing multiple windings that supplies the generated power.
- The rotors magnetic field system (excitation) is created by using either permanent magnets mounted directly onto the rotor or energized electromagnetically by an external DC current flowing in the rotor field windings.
- This DC field current is transmitted to the synchronous machine's rotor via slip rings and carbon or graphite brushes.
- Unlike the previous DC generator, synchronous generators do not require complex commutation allowing for a simpler construction.

- The synchronous generator operates in a similar way to the automotive car alternator and consists of the two following common parts:
  - The Stator: The stator carries three separate (3-phase) armature windings physically and electrically displaced from each other by 120 degrees producing an AC voltage output.
  - The Rotor: The rotor carries the magnetic field either as permanent magnets or wound field coils connected to an external DC power source via slip rings and carbon brushes.

- When talking about the "synchronous generator", the terminology used for the description of the machines parts is the reverse to that for the description of the DC generator.
- The field windings are the windings producing the main magnetic field which are the rotor windings for a synchronous machine, and the armature windings are the windings where the main voltage is induced usually called the stator windings.
- In other words, for a synchronous machine, **the rotor windings are the field windings** and **the stator windings are the armature windings** as shown.

Synchronous Generator Construction





- The example above shows the basic construction of a synchronous generator which has a wound salient two-pole rotor.
- This rotor winding is connected to a DC supply voltage producing a field current, I_f.
- The external DC excitation voltage which can be as high as 250 volts DC, produces an electromagnetic field around the coil with static North and South poles.
- When the generators rotor shaft is turned by the turbines blades (the prime mover), the rotor poles will also move producing a rotating magnetic field as the North and South poles rotate at the same angular velocity as the turbine blades, (assuming direct drive).
- As the rotor rotates, its magnetic flux cuts the individual stator coils one by one and by Faraday's law, an emf and therefore a current is induced in each stator coil.

- The magnitude of the voltage induced in the stator winding is, as shown above, a function of the magnetic field intensity which is determined by the field current, the rotating speed of the rotor, and the number of turns in the stator winding.
- As the synchronous machine has three stator coils, a 3-phase voltage supply corresponding to the windings, A, B and C which are electrically 120° apart is generated in the stator windings and this is shown above.
- This 3-phase stator winding is connected directly to the load, and as these coils are stationary they do not need to go through large unreliable slip-rings, commutator or carbon brushes.
- Also because the main current generating coils are stationary, it makes it easier to wind and insulate the windings because they are not subjected to rotational and centrifugal forces allowing for greater voltages to be generated.

Permanent Magnet Synchronous Generator

- As we have seen, wound-field synchronous machines require DC current excitation in the rotor winding.
- This excitation is done through the use of brushes and slip rings on the generator shaft.
- However, there are several disadvantages such as requiring regular maintenance, cleaning of the carbon dust, etc.
- An alternative approach is to use brushless excitation which uses permanent magnets instead of electromagnets.

- As its name implies, in a **permanent magnet synchronous generator** (PMSG), the excitation field is created using permanent magnets in the rotor.
- The permanent magnets can be mounted on the surface of the rotor, embedded into the surface or installed inside the rotor.
- The air gap between the stator and rotor is reduced for maximum efficiency and to minimize the amount of rare earth magnet material needed.
- Permanent magnets are typically used in low power, low cost synchronous generators.
- For low speed direct drive wind turbine generators the permanent magnet generator is more competitive because it can have higher pole number of 60 or more poles compared to a conventional wound rotor synchronous generator.
- Also, the excitation implementation with permanent magnets is simpler, more durable but does not allow control of excitation or reactive power.
- The one major disadvantage of permanent magnet wind turbine synchronous generators is that with no control of the rotor flux, they attain their peak efficiency only at one pre-defined wind speed.

The Generators Synchronous Speed

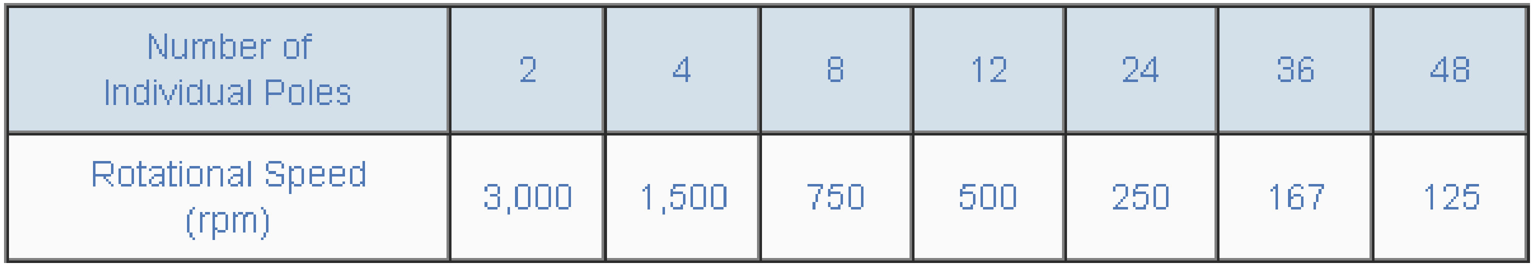
- The frequency of the output voltage depends upon the speed of rotation of the rotor, in other words its "angular velocity", as well as the number of individual magnetic poles on the rotor.
- In our simple example above, the synchronous machine has two-poles, one North pole and one South pole. In other words, the machine has two individual poles or *one pair of poles*, (North-South) also known as pole pairs.
- As the rotor rotates one complete revolution, 360°, one cycle of induced emf is generated, so the frequency will be one-cycle every full rotation or 360°.
- If we double the number of magnetic poles to four, (two pairs of poles), then for every revolution of the rotor, two cycles of induced emf will be generated and so on.
- Since one cycle of induced emf is produced with a single pair of poles, the number of cycles of emf produced in one revolution of the rotor will therefore be equal to the number of pole pairs, P.

- So if the number of cycles per revolution is given as: P/2 relative to the number of poles and the number of rotor revolutions N per second is given as: N/60, then the frequency, (*f*) of the induced ***emf*** will be defined as:

$$\text{Frequency}, (f) = \frac{P}{2} \times \frac{N}{60} = \frac{PN}{120}\,\text{Hz}$$

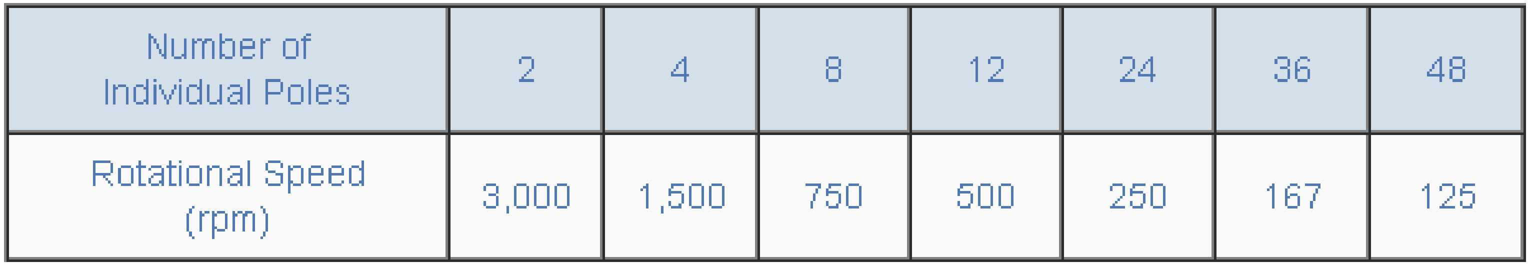
- In a synchronous motor, its angular velocity is fixed by the frequency of the supply voltage so N is commonly known as the synchronous speed.
- Then for a "P"-pole synchronous generator the speed of rotation of the prime mover (the turbine blades) in order to produce the required frequency output of either 50Hz or 60Hz of the induced emf will be:

1. at 50Hz



Number of Individual Poles	2	4	8	12	24	36	48
Rotational Speed (rpm)	3,000	1,500	750	500	250	167	125

2. at 60Hz



Number of Individual Poles	2	4	8	12	24	36	48
Rotational Speed (rpm)	3,000	1,500	750	500	250	167	125

- So for a given synchronous generator designed with a fixed number of poles, the generator must be driven at a fixed synchronous speed to keep the frequency of the induced emf constant at the required value, either 50Hz or 60Hz to power mains appliances.
- In other words, the frequency of the emf produced is synchronized with the mechanical rotation of the rotor.
- Then from above, we can see that to generate 60 Hz using a 2-pole machine, the rotor must rotate at 3600 revs/min, or to generate 50 Hz using a 4-pole machine, rotor must rotate at 1500 revs/min.
- For a synchronous generator that is being driven by an electrical motor or steam generator, this synchronous speed may be easy to achieve however, when used as a wind turbine synchronous generator, this may not be possible as the velocity and power of the wind is constantly changing.

- We know from our previous wind turbine design tutorial, that all wind turbines benefit from the rotor operating at its optimal *tip speed ratio (TSR)*.
- But to obtain a TSR of between 6 to 8, the angular velocity of the blades is generally very low around 100 to 500 rpm, so looking at our tables above, we would require a synchronous generator with a high number of magnetic poles, eg, 12 or above, as well as some form of mechanical speed limiter such as a Continuously Variable Transmission, or CVT to keep the rotor blades rotating at a constant maximum speed for a direct drive wind turbine system.
- However, for a synchronous machine, the more poles it has the larger, heavier and more expensive becomes the machine which may or may not be acceptable.

- One solution is to use a synchronous machine with a low number of poles which can rotate at a higher speed of 1500 to 3600 rpm driven through a gearbox.
- The low rotational speed of the wind turbines rotor blades is increased through a gearbox which allows the generator speed to remain more constant when the turbines blade speed changes as a 10% change at 1500rpm is less of a problem than a 10% change at 100rpm.
- This gearbox can match the generators speed to variable rotational speeds of the blades allowing for variable speed operation over a wider range.

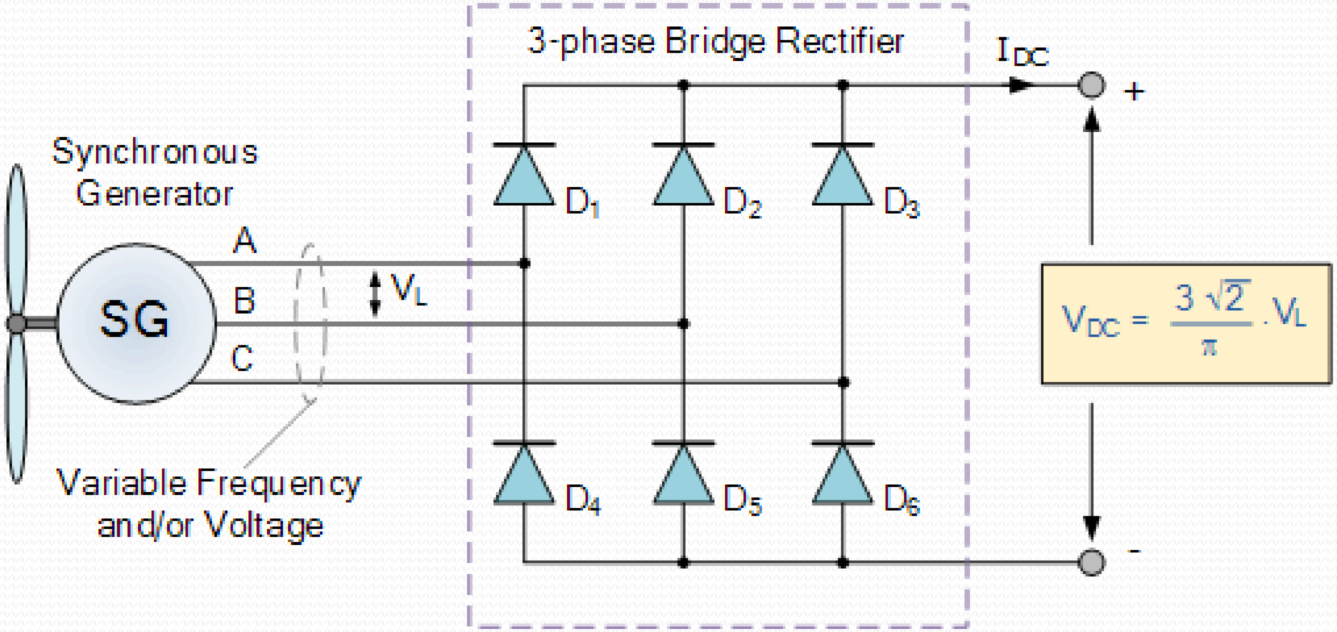
- The use of a gearbox or pulley system requires regular maintenance, increases the weight of the wind turbine, generates noise, increases power losses and reduces system efficiency.
- There are many advantages to using a direct drive system without a mechanical gearbox, but the omission of a gearbox means a larger synchronous machine with an increase in both size and cost of the generator, which then has to operate at a low speeds.

Synchronous generator rectifiers

- Rectifiers are electronic devices used to convert AC (alternating current) into DC (direct current).
- By rectifying the power output from the synchronous generator into a DC supply, the wind turbine generator may be operated at different speeds and frequencies other than its fixed synchronous speed converting this variable frequency/variable amplitude AC output voltage of the generator to a DC voltage of a variable level.
- By rectifying the output from AC into DC, the generator can now be used as part of a battery-charging wind systems or as part of a variable-speed wind power system.
- Then the synchronous generator of an alternating current is transformed into a generator of a direct current.

Synchronous generator rectifier circuit

- The simplest type of rectifier circuit uses a diode bridge circuit to convert the AC generated by the generator into a fluctuating DC supply whose amplitude is determined by the generators speed of rotation. In this synchronous generator rectifier circuit shown below, the generator's 3-phase output is rectified to DC by a 3-phase rectifier.



- The circuit diagram of the full-bridge, three-phase, AC to DC rectifier is shown above. In this configuration, the wind turbine can operate the generator at a frequency independent of the synchronous frequency as changing the generator speed varies the generator frequency. Hence it is possible to vary the speed of the generator over a wider range and to run at the optimal speed to obtain the maximum power use depending on the actual wind speed.
- The output from the 3-phase bridge rectifier is not pure DC. The output voltage has a DC level together with a large AC variation. This waveform is generally known as "pulsating DC" which can be used to charge batteries but can not be used as a satisfactory DC supply. In order to remove this AC ripple content a filter or smoothing circuit is used. These smoothing circuits or ripple filter circuits use combinations of Inductors and Capacitors to produce a smooth DC voltage and current.

- When used as part of a grid-connected system, synchronous machines can only be connected to the mains grid, when their frequency, phase angle, and output voltage are the same as the grids, in other words they are rotating at their synchronous speed as we have seen above. But by rectifying their variable output voltage and frequency into a steady DC supply, we can now convert this DC voltage into an AC supply of the correct frequency and amplitude, matching that of the mains utility grid by using either a single-phase or 3-phase inverter.
- An *Inverter* is a device that converts direct current (DC) electricity to alternating current (AC) electricity which can be fed directly into the mains grid as grid-connected inverters operate in sync with the utility grid and produce electricity that's identical to utility grid power. Grid-connected sine-wave inverters for wind systems are selected with an input range that corresponds to the rectified output voltage of the turbine.

- Then the advantage of an indirect grid connection is that it is possible to run the wind turbine at variable speeds. Another advantage of rectifying the output from the generator is that wind turbines with synchronous generators which use electromagnets in their rotor design, can use this DC to supply the coil windings around the electromagnets in the rotor. However the disadvantage of indirect grid connection is the cost as the system needs an inverter and two rectifiers, one to control the stator current, and another to generate the output current as shown below.