Alternator - principle - relation between poles, speed and frequency

Objectives: At the end of this lesson you shall be able to
- **explain the working principle of an alternator**
- **explain the method of production of sine wave voltage by a single loop alternator**
- **describe the relation between frequency, number of poles and synchronous speed.**

Principle of an alternator: An alternator works on the same principle of electromagnetic induction as a DC generator. That is, whenever a conductor moves in a magnetic field so as to cut the lines of force, an emf will be induced in that conductor. Alternatively whenever there is relative motion between the field and the conductor, then, the emf will be induced in the conductor. The amount of induced emf depends upon the rate of change of cutting or linkage of flux.

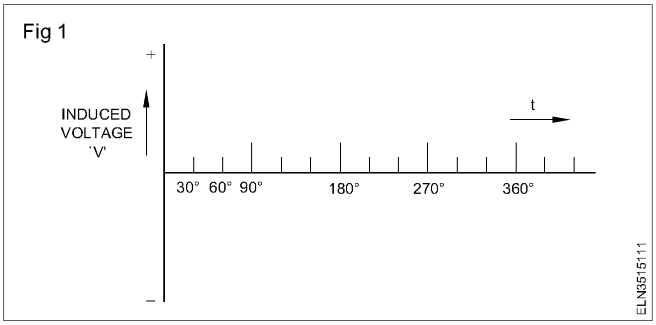
In the case of DC generators, we have seen that the alternating current produced inside the rotating armature coils has to be rectified to DC for the external circuit through the help of a commutator. But in the case of alternators, the alternating current produced in the armatrue coils can be brought out to the external circuit with the help of slip-rings. Alternatively the stationary conductors in the stator can produce alternating current when subjected to the rotating magnetic field in an alternator.

Production of sine wave voltage by single loop alternator: Fig 2a shows a single loop alternator. As it rotates in the magnetic field, the induced voltage in it varies in its direction and magnitude as follows.

To plot the magnitude and direction of the voltage induced in the wire loop of the AC generator in a graph, the electrical degrees of displacement of the loop are kept in the `X' axis as shown in Fig 1 through 30 electrical degrees. As shown in Fig 2c, three divisions on the `X' axis represent a quarter turn of the loop, and six divisions a half turn. The magnitude of the induced voltage is kept in the `Y' axis to a suitable scale.

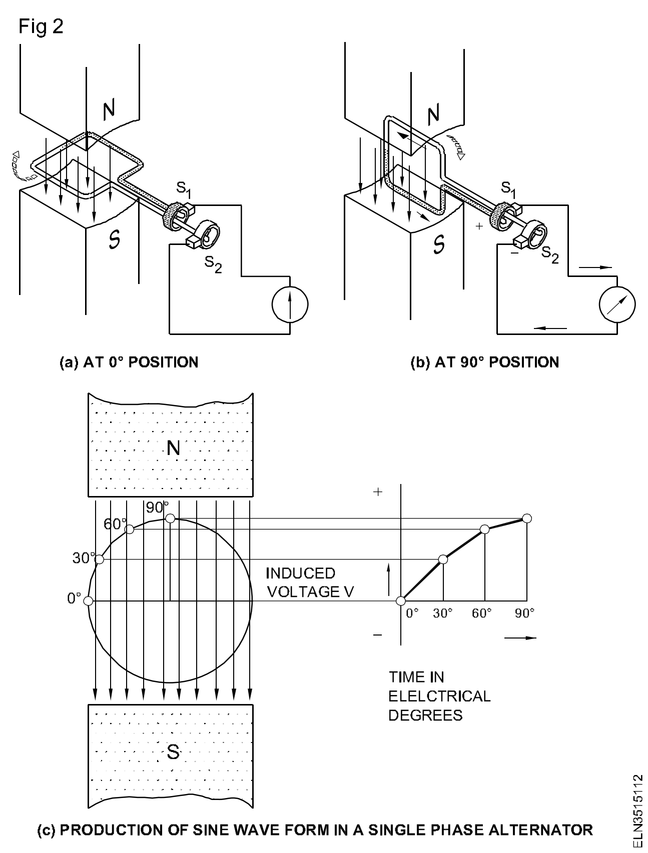
The part above the X-axis represents the positive voltage, and the part below it the negative voltage as shown in Fig 1.

Fig 1



The position of the loop at the time of starting is shown in Fig 2a and indicated in Fig 2c as `O' position. At this position, as the loop moves parallel to the main flux, the loop does not cut any lines of force, and hence, there will be no voltage induced. This zero voltage is represented in the graph as the starting point of the curve as shown in Fig 2c. The magnitude of the induced emf is given by the formula $Eo = BLV Sinq$

Fig 2



(a) AT 0° POSITION (b) AT 90° POSITION

(c) PRODUCTION OF SINE WAVE FORM IN A SINGLE PHASE ALTERNATOR

where

B is the flux density in weber per square metre,

L is the length of the conductors in metres,

V is the velocity of the loop rotation in metres per second and

q is the angle at which the conductor cuts the line of force.

As sin q = 0

E at 0 position is equal to zero. As the loop turns in a clockwise direction at position 30° as shown in Fig 2c, the loop cuts the lines of force and an emf is induced (E_{30}) in the loop whose magnitude will be equal to BLV Sinq where q is equal to 30°.

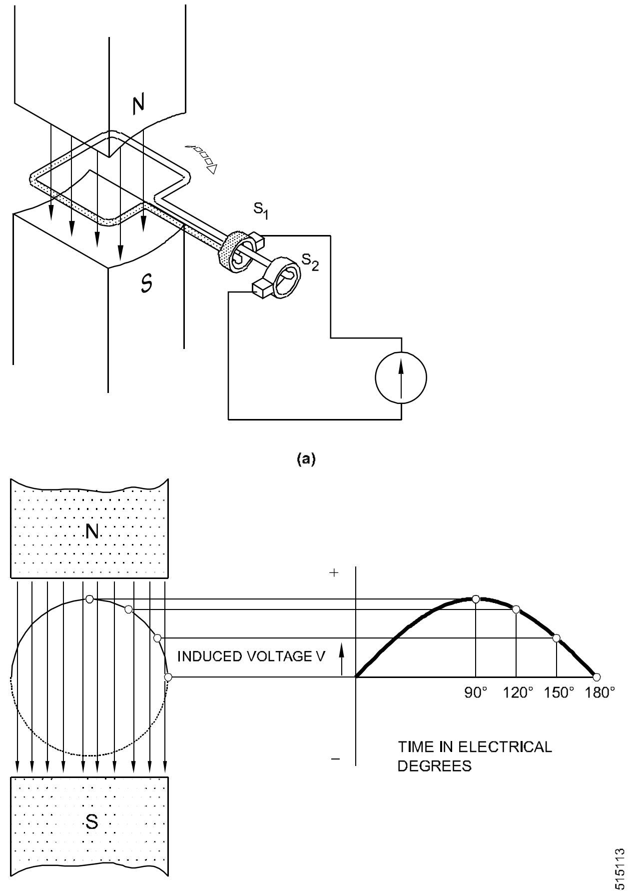
Applying the above formula, we find the emf induced in the loop at 90° position will be maximum as shown in Fig 2c.

As the loop turns further towards 180° it is found the number of lines of force which are cut will be reduced to zero value. If the quantity of emf induced at each position is marked by a point and a curve is drawn along the points, the curve will be having a shape as shown in Fig 3b.

During the turn of the loop, from 0 to 180°, the slip ring S_1 will be positive and S_2 will be negative.

However, at 180° position, the loop moves parallel to the lines of force, and hence there is no cutting of flux by the loop and there is no emf induced in the loop as shown in Fig 3b.

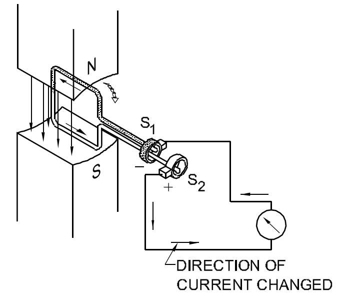
Fig 3



(b) VALUE OF INDUCED E.M.F. AT POSITION 180° FROM START

Further during the turn of the loop from the position 180° to 270°, the voltage increases again but the polarity is reversed as shown in Fig 4b. During the movement of the loop from 180 to 360°, the slip ring S_2 will be positive and S_1 will be negative as shown in Fig 4a. However, at 270° the voltage induced will be the maximum and will decrease to zero at 360°. Fig 5b shows the variation of the induced voltage in both magnitude and direction during one complete revolution of the loop. This is called a cycle.

Fig 4



(a) POSITION OF THE LOOP AT 270°

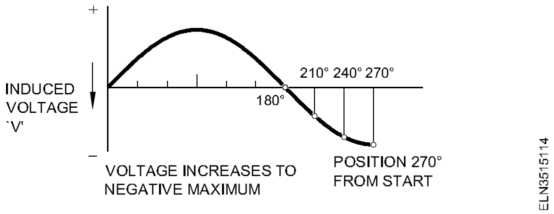
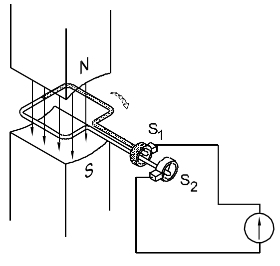
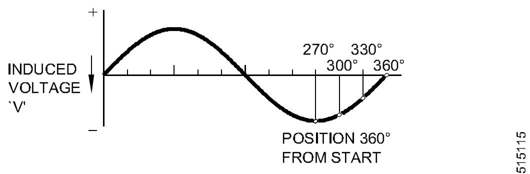


Fig 5



(a) POSITION OF THE LOOP AT 360°



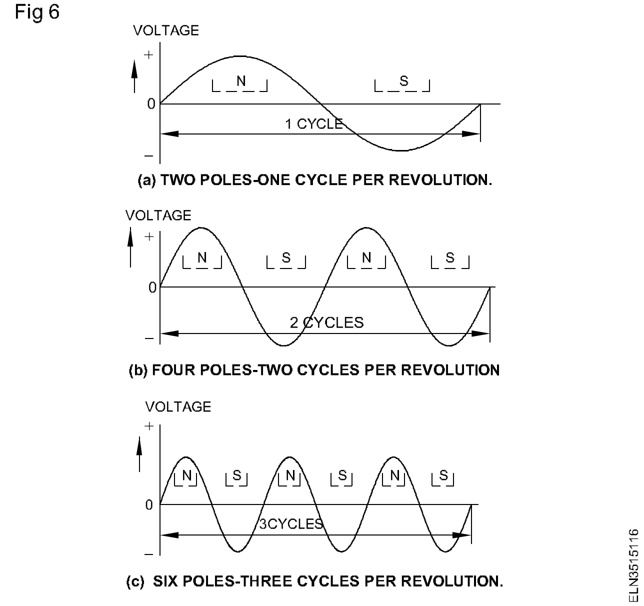
(b)

This type of wave-form is called a sine wave as the magnitude and direction of the induced emf, strictly follows the sine law. The number of cycles completed in one second is called a frequency. In our country, we use an AC supply having 50 cycles frequency which is denoted as 50 Hz.

Relation between frequency, speed and number of poles of alternator: If the alternator has got only two poles, the voltage induced in one revolution of the loop undergoes one cycle. If it has four poles, then one complete rotation of the coil produces two cycles because, whenever it crosses a set of north and south poles, it makes one cycle.

Fig 6 shows the number of cycles which are produced in each revolution of the coil, with 2 poles, 4 poles and 6 poles. It is clear from this that the number of cycles per revolution is directly proportional to the number of poles, `P' divided by two. Therefore the number of cycles produced per second depends on P/2, and the speed in revolutions per second.

Fig 6



(a) TWO POLES-ONE CYCLE PER REVOLUTION.

(b) FOUR POLES-TWO CYCLES PER REVOLUTION

(c) SIX POLES-THREE CYCLES PER REVOLUTION.

Therefore frequency $F = \frac{P}{2} \times 'n'$

where `n' is in r.p.s.

`P' is the number of poles.

Generally speed is represented in r.p.m.

Then we have requency $F = \frac{PN}{2 \times 60} = \frac{PN}{120}$

where P is number of poles and N is speed in r.p.m.

Accordingly we can state that the frequency of an alternator is directly porportional to the number of poles and speed.

Types and construction of alternators

Objective: At the end of this lesson you shall be able to

- **explain the construction, and the various types of alternators.**

Types of alternators: DC and AC generators are similar in one important respect, that is, they both generate alternating emf in the armature conductors. The AC generator sends out the electrical energy in the same form of alternating emf to the external load with the help of slip rings.

AC generators, named as alternators, must be driven at a very definite constant speed called synchronous speed, because the frequency of the generated emf is determined by the speed. Due to this reason these machines are called `synchronous alternators or synchronous generators'.

Classification according to the type of rotating part: One way of classifying the alternator is the way in which the rotating part is chosen. In the earlier lessons, we discussed how an alternator can have either stationary or rotating magnetic field poles. Accordingly an alternator having a stationary magnetic field and a moving armature is called a **rotating armature type,** and an alternator with a stationary armature and moving magnetic field is called a **rotating field type.** There are definite advantages in using rotating field type alternators.

Advantages of using rotating field type alternators

Only two slip rings are required for a rotating field type alternator whatsoever the number of phases may be.

As the main winding is placed over the stator, more conductors can be housed in the stator because of more internal peripheral area. More conductors result in higher voltage/current production.

As the winding in which the emf is induced is stationary, there is no possibility of breaking or loosening the winding and its joints, due to rotational forces.

There is no sliding contact between the stationary armature and the external (load) circuit, as the supply could be taken direct. Only two slip rings are provided in the rotor for low power low voltage field excitation. Thus less sparking and less possibility of faults.

The main winding being stationary, the conductors can be easily and effectively insulated, and the insulating cost also will be less for higher output voltage (less dielectric strength insulation will be sufficient).

Stationary main conductors need less maintenance.

As the rotar has a field winding which is lighter for the given capacity than in the rotating armature type, the alternator can be driven at a higher speed.

Classification according to the number of phases: Another way of classifying the alternators is based on production of single or 3-phase by the alternator. Accordingly the types are 1) single-phase alternators 2) three-phase alternators.

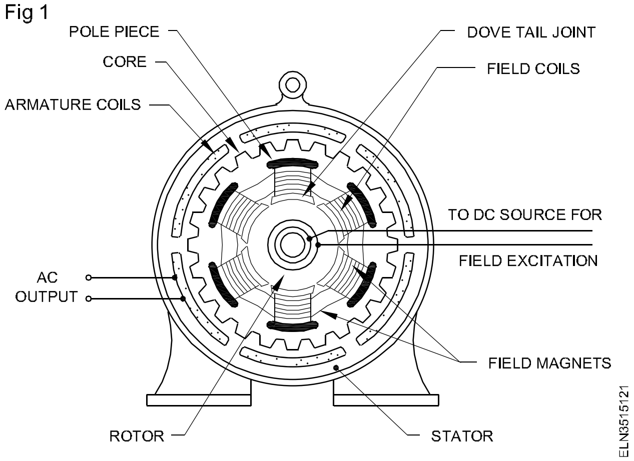
Single-phase alternators: A single-phase alternator is one that provides only one voltage. The armature coils are connected in `series additive'. In other words, the sum of the emf induced in each coil produces the total output voltage. Single phase alternators are usually constructed in small sizes only. They are used as a temporary standby power for construction sites and for permanent installation in remote locations.

Three-phase alternators: This alternator provides two different voltages, namely, phase and line voltages. It has 3 windings placed at 120° to each other, mostly connected in a star having three main terminals U,V,W and neutral `N'.

These alternators are driven by prime movers such as diesel engines, steam turbines, water wheels etc. depending upon the source available.

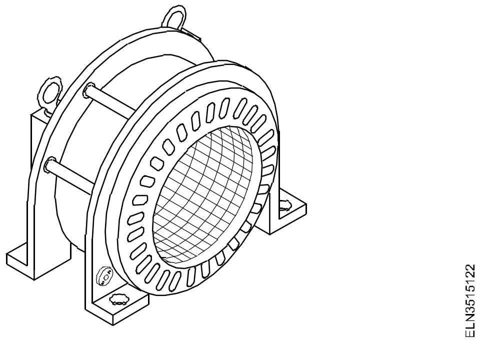
Construction of alternators: The main parts of a revolving field type alternator are shown in Fig 1.

Fig 1



Stator: It consists of mainly the armature core formed of laminations of steel alloy (silicon steel) having slots on its inner periphery to house the armature conductors. The armature core in the form of a ring is fitted to a frame which may be of cast iron or welded steel plate. The armature core is laminated to reduce the eddy current losses which occur in the stator core when subjected to the cutting of the flux produced by the rotating field poles. The laminations are stamped out in complete rings (for smaller machines) or in segments (for larger machines), and insulated from each other with paper or varnish. The stampings also have holes which make axial and radial ventilating ducts to provide efficient cooling. A general view of the stator with the frame is shown in Fig 2.

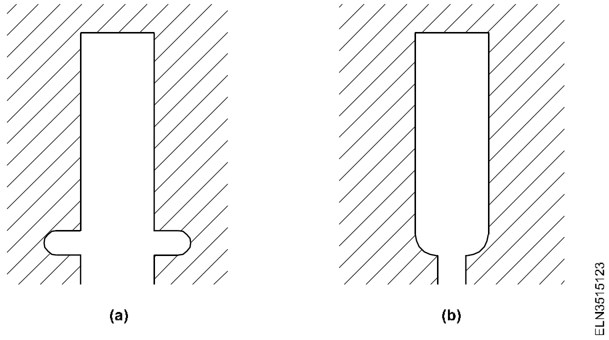
Fig 2



Slots provided on the stator core to house the armature coils are mainly of two types, (i) open and (ii) semi-closed slots, as shown in Fig 3a and b respectively.

The open slots are more commonly used because the coils can be form-wound and pre-insulated before placing in the slots resulting in fast work, less expenditure and good insulation. This type of slots also facilitates easy removal and replacement of defective coils. But this type of slots creates uneven distribution of the flux, thereby producing ripples in the emf wave. The semi-closed type slots are better in this respect but do not permit the use of form-wound coils, thereby complicating the process of winding. Totally closed slots are rarely used, but when used, they need bracing of the winding turns.

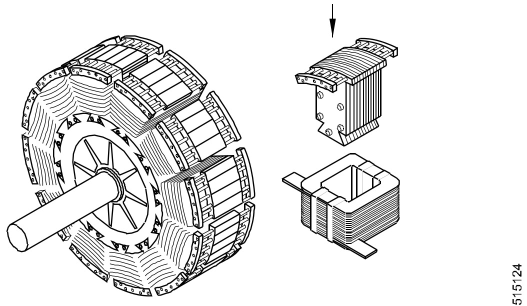
Fig 3



Rotor: This forms the field system, and is similar to DC generators. Normally the field system is excited from a separate source of low voltage DC supply. The excitation source is usually a DC shunt or compound generator, known as an exciter, mounted to the same alternator shaft. The exiting current is supplied to the rotor with the help of two slip- rings and brushes. The field poles created by the excitation are alternately north and south.

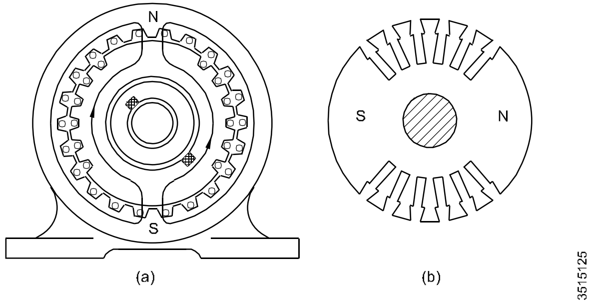
Rotating field rotors are of two types, namely (i) salient pole type as shown in Fig 4 and (ii) smooth cylindrical type or non-salient pole type, as shown in Fig 5.

Fig 4



SALIENT POLE FIELD STRUCTURE

Fig 5



NON-SALIENT POLE TYPE FIELD STRUCTURE

Salient pole type: This type of rotor is used only for slow and medium speed alternators. This type is less expensive, having more space for the field coils and vast heat dissipating area. This type is not suitable for high speed alternators as the salient poles create a lot of noise while running in addition to the difficulty of obtaining sufficient mechanical strength.

Fig 4 shows the salient pole type rotor in which the riveted steel laminations are fitted to the shaft fitting with the help of a dovetailed joint. Pole faces are curved to have uniform distribution of the flux in the air gap leading to production of sinusoidal wave form of the generated emf. These pole faces are also provided with slots to carry the damper winding to prevent hunting. The field coils are connected in series in such a way as to produce alternate north and south poles, and the field winding ends are connected to the slip rings. The DC excitation source is connected to the brushes which are made to contact the slip rings with the required pressure.

Salient pole type alternators could be identified by their larger diameter, short axial length and low or medium speed of operation.

Smooth cylindrical or non-salient pole type rotor: This type is used in very high speed alternators, driven by steam turbines. To have good mechanical strength, the peripheral velocity is lowered by reducing the diameter of the rotor and alternatively with the increased axial length. Such rotors have either two or four poles but run at higher speeds.

To withstand such speeds, the rotor is made of solid steel forging with longitudinal slots cut as shown in Fig 5a which shows a two-pole rotor with six slots. The winding is in the form of insulated copper strips, held securely in the slots by proper wedges, and bound securely by steel bonds.

One part of the periphery of the rotor in which slots are not made is used as poles as shown in Fig 5b.

Smooth cylindrical pole type alternators could be identified by their shorter diameter, longer axial length and high speed of operation.

Rating of alternators

An electrical machines is usually rated at the load, which is can carry without over heating and damage to insulation. i.e the rating of electrical machine is governed by the temperature rise caused by internal losses of the machine. The copper loss in the armature (I2R) depends upon the strength of the armature current and is independent of power factor.

The output in kW is proportional to power factor for the alternator of a given kVA. For example output of 1000 kVA alternator on full load will be 200, 500, 800, 1000 kW at power factor 0.2, 0.5, 0.8 and unity respectively but copper losses in armature will remain the same regard less of power factor.

For the above reasons alternators are usually rated in kVA (kilo Volt Ampere).

Hunting

Hunting is a phenomenon in alternator which is caused by continuous fluctuation in load. When the load on the alternator is frequency changing, then the rotor of the alternator runs unsteadily making a noise of a whistle due to oscillations, or vibrations set up in the rotor. This phenomenon is called as hunting of alternators.

Hunting is prevented by the Damper Windings provided in the field pole core.

Generation of 3-phase voltage and general test on alternator

Objectives: At the end of this lesson you shall be able to

- **explain the method of generating 3-phase voltage wave-forms by a 3-phase alternator**
- **state the phase sequence of 3ϕ supply**
- **state the method of testing an alternator for continuity insulation and earth connection**
- **state e.m.f. equation of the alternator**
- **state the I.E.E. regulations and B.I.S. recommendations pertaining to earthing of the alternator.**

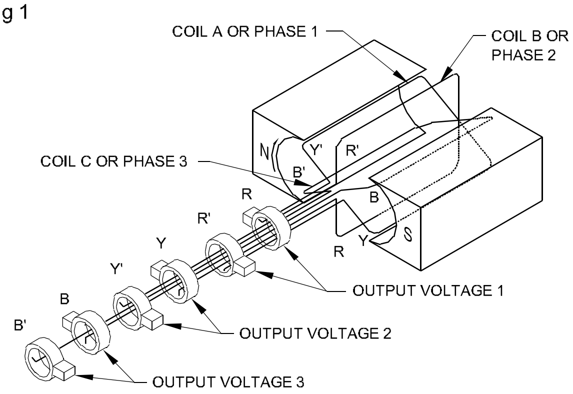
An AC three-phase system is the most common system used in the present world. It is because of its high efficiency, less cost of material required for the generation, transmission and distribution for a given capacity. The three-phase system supplies power to drive three-phase motors in industry as well as supplying power to single phase motors and lighting loads for both industrial and domestic purposes. Present day electricians may be employed in a generating station or may be employed in a standby power station where three-phase alternators are used. Hence a fairly good knowledge about production of 3-phase voltages, their phase sequence and general testing of alternators is essential.

Generation of three-phase voltage: Basically,the principle of a three-phase alternator (generator) is the same as that of a single phase alternator (generator), except that there are three equally spaced coils or windings which produce three output voltages which are out of phase by 120° with each other.

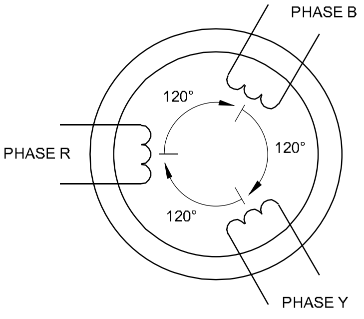
A simple rotating-loop, three-phase generator with its output voltage wave-forms is shown in Fig 1c.

As shown in Fig 1a, three independent loops spaced about 120° apart are made to rotate in a magnetic field with the assumption that the alternator shown is a rotating armature type. As shown in Fig 1a, the three loops are electrically isolated from each other and the ends of the loops are connected to individual slip rings. As the loops are rotating in a uniform magnetic field, they produce sine waves. In a practical alternator, these loops will be replaced by a multi-turn winding element and distributed throughout the rotor slots but spaced apart at 120° electrical degrees from each other. Further, in practice, there will not be six slip rings as shown in Fig 1a but will have either four or three slip rings depending upon whether the three windings are connected in a star or delta respectively.

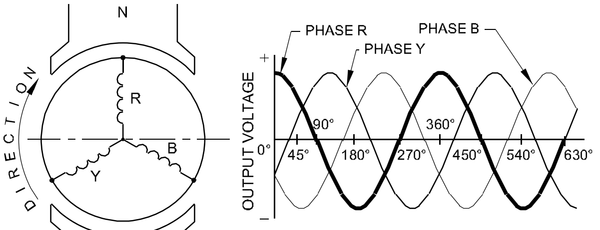
Fig 1



(a) ROTATING LOOP 3 –PHASE ALTERNATOR



(b) STATIONARY ARMATURE 3 –PHASE ALTERNATOR



3 PHASE WAVE FIRMS

(c)

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We also know, as discussed earlier, that the rotating magnetic field type alternators are mostly used. In such cases only two slip rings are required for exciting the field poles with DC supply. Fig 1b shows a stationary, 3-phase armature in which individual loops of each winding are replaced by coils spaced at 120 electrical degrees apart. However, the rotating part having the magnetic poles is not shown.

Fig 1c shows the rotating armature type alternator in which the 3 coils of the three-phases are connected in star which rotates in a two-pole magnetic field. According to Fig 1c, the coil `R' moves under the influence of the `N' pole cutting the flux at right angles, and produces the maximum induced voltage at position `O°' as shown in the graph as per Faraday's Laws of Electromagnetic induction. When the coil `R' moves in a clockwise direction, the emf induces falls to zero at 90 degrees, and then increases to -ve maximum under the influence of the south pole at 180 degrees. Likewise the emf induced in the `R' phase will become zero at 270 degrees and attain +ve maximum at 360 degrees. In the same manner the emf produced by coils `Y' and `B' could be plotted on the same graph. A study of the sine wave-forms produced by the three coils RYB shows that the voltage of coil `R' leads voltage of coil `Y' by 120°, and the voltage of coil `Y' leads voltage of coil `B' by 120°.

Phase sequence: The phase sequence is the order in which the voltages follow one another, i.e. reach their maximum value. The wave-form in Fig 1c shows that the voltage of coil R or phase R reaches its positive maximum value first, earlier than the voltage of coil Y or phase `Y', and after that the voltage of coil B or phase B reaches its positive maximum value. Hence the phase sequence is said to the RYB.

If the rotation of the alternator shown in Fig 1c is changed from clockwise to anticlockwise direction,the phase sequence will be changed as RBY. It is the most important factor for parallel connection of polyphase generators and in polyphase windings. Further the direction of rotation of a 3-phase induction motor depends upon the phase sequence of the 3-phase supply. If the phase sequence of the alternator is changed, all the 3-phase motors, connected to that alternator, will run in the reverse direction though it may not affect lighting and heating loads.

The only difference in the construction of a single phase alternator and that of a 3-phase alternator lies in the main winding. Otherwise both the types of alternators will have similar construction.

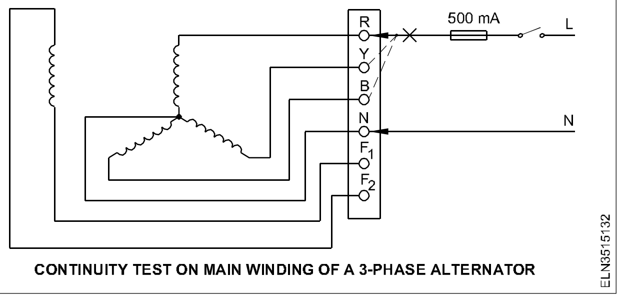
General testing of alternator: Alternators are to be periodically checked for their general condition as they will be in service continuously. This comes under preventive maintenance, and avoids unnecessary breakdowns or damage to the machine. The usual checks that are to be carried out on an altenator are:

- continuity check of the windings
- insulation resistance value between windings
- insulation resistance value of the windings to the body
- checking the earth connection of the machine.

Continuity test: The continuity of the windings is checked by the following method as shown in Fig 2.

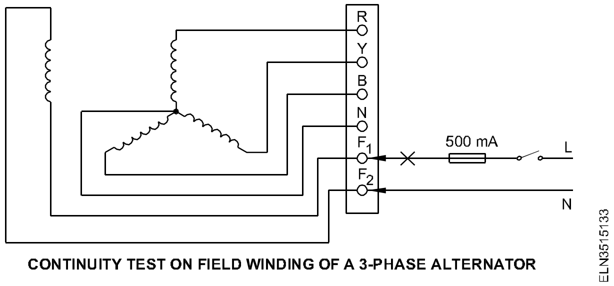
A test lamp is connected in series with one end to the neutral (star point) and the other end to one of the winding terminals (R Y B). If the test lamp glows equally bright on all the terminals RYB then the continuity of the winding is all right. In the same way, as shown in Fig 3, we can test the field leads F_1 and F_2 for field continuity.

Fig 2



CONTINUITY TEST ON MAIN WINDING OF A 3-PHASE ALTERNATOR

Fig 3



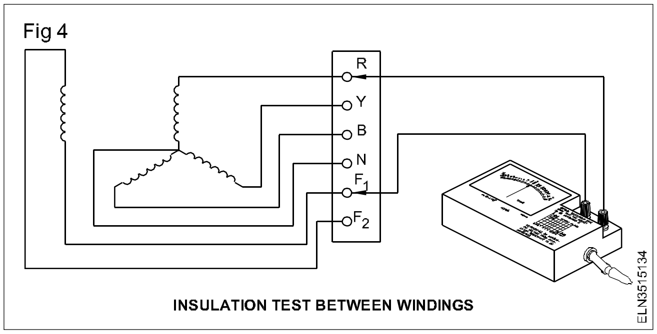
CONTINUITY TEST ON FIELD WINDING OF A 3-PHASE ALTERNATOR

Testing continuity with the test lamp only indicates the continuity in between two terminals but will not indicate any short between the same windings. A more reliable test will be to use an ohmmeter to check the individual resistances of the coils, and compare them to see that similar coils have the same resistance. The readings, when recorded, will be useful for future reference also.

For insulation resistance test

Between windings: As shown in Fig 4, one end of the Megger lead is connected to any one terminal of the RYB and the other is connected to F_1 or F_2 of the field winding. If the Megger reads one megohm or more, then the insulation resistance is accepted as okay.

Fig 4

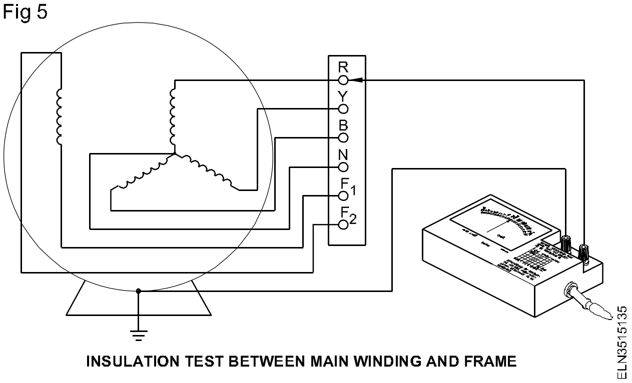


INSULATION TEST BETWEEN WINDINGS

If there is short, between the armature and field windings, the Megger reads zero ohms. If it is weak, it shows less than one megohm.

Testing insulation resistance between body and windings: As shown in Fig 5, one lead of the Megger is connected to one of the leads of the RYB, and the other lead of the Megger is connected to the body. If the insulation between the windings and the frame is all right, the Megger reads more than one megohm.

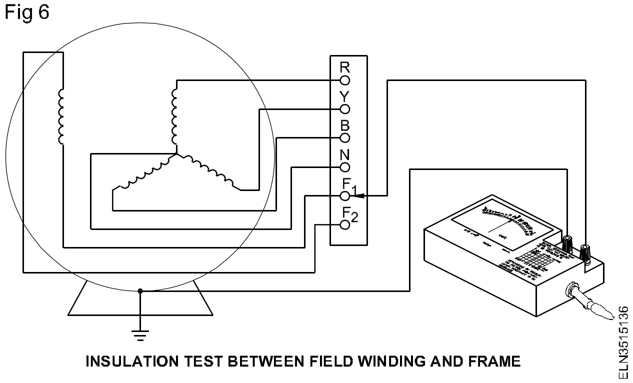
Fig 5



INSULATION TEST BETWEEN MAIN WINDING AND FRAME

The field is tested by connecting one terminal of the Megger to F_1 or F_2 of the field and the other terminal to the body as shown in Fig 6. If the insulation between the field and the frame is all right, the Megger reads more than one megohm. A lower reading than one megohm shows weak insulation and leakage to the ground.

Fig 6



INSULATION TEST BETWEEN FIELD WINDING AND FRAME

Caution

While conducting the insulation resistance test, if the Megger reads zero, then it should be concluded that the insulation of the winding has failed completely and needs thorough checking.

The permissible insulation resistance should not be less than 1 megohm.

Earthing of alternators: This consists of two equally important requirements as stated below.

- Earthing of the neutral of the alternator
- Earthing of the alternator frame.

Earthing of neutral: According to B.I.S. 3043-1966, it is recommended to use one of the following methods for earthing the neutral of the alternator.

- Solid earthing
- Resistance earthing
- Reactance earthing
- Arc-suppression coil earthing

The selection and the type of earthing depends to a large extent on the size of the unit, the system voltage protection scheme used, the manufacturer's recommendation and the approval of the electrical inspectorate authority. Trainees are advised to refer to B.I.S.3043-1966 for further details. As earthing of neutral is essential for the operation of protective relays, to maintain proper voltage in the system and for safety reasons, trainees are advised to identify the method of neutral earthing adopted in the available alternator, maintain the continuity of earth connections and keep the earth electrode resistance within the specified value.

Earthing alternator frame: This earthing is essential for the safety of the workers, and to keep the frame of the alternator at zero earth potential. Operation of the earth fault relays or fuses to open the electrical circuits in case of earth faults is fully dependent upon earthing of the frame.

As per I.E. rules No.61, all the electrical equipment/ machines are to be provided with double earthings for safe operation. The condition of earth must be checked periodically, and the earth electrode and the earth conductor resistance must also be measured and recorded at repeated intervals of time. The earth electrode and the earthing conductors should be maintained such that the resistance value is lower than the stipulated value according to the design of the system.

Emf equation of the alternator

Objective: At the end of this lesson you shall be able to
- **explain the emf equation to calculate the induced emf in an alternator.**

Equation of induced emf: The emf induced in an alternator depends upon the flux per pole, the number of conductors and speed. The magnitude of the induced emf could be derived as stated below

Let Z = No.of conductors or coil sides in series/ phase in an alternator

P = No.of poles

F = frequency of induced emf in Hz

Ø = flux per pole in webers

k_f = form factor = 1.11 - if emf is assumed to be sinusoidal

N = speed of the rotor in r.p.m.

According to Faraday's Law of Electromagnetic Induction we have the average emf induced in a conductor

= rate of change of flux linkage

$$= \frac{d\varnothing}{dt}$$

$$= \frac{\text{change of total flux}}{\text{time duration in which the flux change takes place}}$$

In one revolution of the rotor (ie in 60/N seconds), each stator conductor is cut by a flux equal to PØ webers.

Hence the change of total flux = dØ = PØ and the time duration in which the flux changes takes place

= dt = 60/N seconds.

Hence the average emf induced in a conductor

$$= \frac{d\varnothing}{dt} = \frac{P\varnothing}{\frac{60}{N}} \text{ volts} \qquad \text{-------- Eq 1}$$

Substituting the value for $N = \frac{120F}{P}$ in eqn 1

we have the average emf induced in a conductor =

$$= \frac{P\varnothing 120F}{P60} \text{ volts } = 2\varnothing F \text{ volts} \qquad \text{------ Eq. 2}$$

If there are Z conductors in series per phase we have the average emf per phase = 2ØFZ volts.

Then r.m.s. value of emf per phase = average value x form factor

$= V_{AV} \times K_F$

$= V_{AV} \times 1.11$

= 2ØFZ x 1.11

= 2.22ØFZ volts.

Alternatively r.m.s. value of emf per phase = 2.22ØF2T volts

= 4.44ØFT volts

where T is the number of coils or turns per phase and Z = 2T.

This would have been the actual value of the induced voltage if all the coils in a phase were (i)full pitched and (ii) concentrated or bunched in one slot. (In actual practice, the coils of each phase are distributed in several slots under all the poles.) This not being so, the actually available voltage is reduced in the ratio of these two factors which are explained below.

Pitch factor (K_p or K_c.): The voltage generated in a fractional pitch winding is less than the full pitch winding. The factor by which the full pitch voltage is multiplied to get voltage generated in fractional pitch is called pitch factor, and it is always less than one; and denoted as K_p or K_c. Normally this value is given in problems directly; occasionally this value needs to be calculated by a formula $K_p = K_c = \text{Cos } \alpha/2$

where α is the electrical angle by which the coil span falls short of full pitch.

Example: Calculate the pitch factor for a winding having 36 stator slots, 4 poles with a coil span of 1 to 8.

$$\text{For full pitch} = \frac{\text{Number of stator slots}}{\text{Number of slots}} = \frac{36}{4} = 9.$$

Hence winding should start at 1 and end at 10.

In actual practice the coil span is taken as 1 – 8.

Hence actual pitch = 8 – 1 = 7.

Hence the coil span is short pitched by = 9 – 7 = 2.

$$\text{The angle } \alpha = \frac{\text{difference in pitch}}{\text{full pitch}} \times 180^\circ$$

$$= \frac{2}{9} \times 180^\circ = 40^\circ$$

where 180° is the complete angle for full pitch.

$$\text{Pitch factor } K_c = \text{Cos } \frac{\alpha}{2} = \text{Cos } \frac{40}{2} = \text{Cos } 20 = 0.94.$$

Distribution factor (K_d): It is imperative that the conductors of the same phase need to be distributed in the slots instead of being concentrated at one slot. Because of this, the emf generated in different conductors will not be in phase with each other, and hence, cannot be added together to get the total induced emf per phase but to be added vectorially. This has to be taken into account while determining the induced voltage per phase.

Therefore, the factor by which the generated voltage must be multiplied to obtain the correct value is called a distribution factor, denoted by K_d and the value is always less than one. The formula for finding the value of K_d is given below.

$$K_d = \frac{\text{Sin m } \beta / 2}{\text{m Sin } \beta / 2}$$

where m is the number of slots per phase per pole

$$\beta = \frac{180^\circ}{\text{No. of slots per pole}}$$

Example: A six-pole alternator rotating at 1000 r.p.m. has a single-phase winding housed in three slots per pole; the slots in groups of three being 20° apart. Find the distribution factor.

$$K_d = \frac{\text{Sin m } \beta / 2}{\text{m Sin } \beta / 2}$$

where m = 3 slots per phase per pole

$\beta = 20^0$

$$K_d = \frac{\text{Sin } 3 \times 20 / 2}{3 \text{ Sin } 20 / 2} = \frac{\text{Sin } 30^\circ}{3 \text{ Sin } 10^\circ}$$

$$= \frac{0.5}{3 \times 0.1736} = 0.96$$

Example: A 3-phase, 12-pole, star-connected alternator has 180 slots with 10 conductors per slot, and the conductors of each phase are connected in series. The coil span is 144° (electrical). Find the distribution factor and the pitch factor K_p.

$$K_d = \frac{\text{Sin m } \beta/2}{\text{m Sin } \beta/2}$$

$$m = \frac{180}{3 \times 12} = 5 \text{ slots per phase per pole.}$$

$$\beta = \frac{180^\circ}{\frac{180}{12}} = 12^\circ$$

$$K_d = \frac{\text{Sin } 5 \times \frac{12}{2}}{5 \text{ Sin } \frac{12}{2}} = \frac{\text{Sin } 30^\circ}{5 \text{ Sin } 6^\circ} = \frac{0.5}{5 \times 0.1045} = 0.957$$

$$K_p = \text{Cos } \frac{\alpha}{2}$$

$$= \text{Cos } (180-144)/2 = \text{Cos } 36/2 = \text{Cos } 18^\circ = 0.95.$$

From the foregoing, it is found that the pitch factor and the distribution factor are to be used to multiply the induced emf to get the actual induced voltage. Thus emf induced in an alternator E_o per phase $= 4.44 \, K_p K_d F \text{Ø} T$ volts.

In the case of a star-connected alternator, the line voltage $= E_L = \sqrt{3}E_P = \sqrt{3}E_0$ and in the case of a delta-connected alternator the line voltage $E_L = E_p = E_o$. However, if the value of either Kd or K_p is not given in the problem it can be assumed to be one.

Example: Calculate the effective voltage in one phase of an alternator, given the following particulars. F=60 Hz, turns/phase T = 240, flux per pole Ø = 0.0208 webber.

Solution: As K_c/K_p and K_d values are not given, we can assume they are equal to one.

Voltage/phase E = 4.44 ØFT volts

= 4.44 x 60 x 0.0208 x 240 volts

= 1329.86 V or 1330 volts.

***Example*:** The following information is given in connection with a 3-phase alternator. Slots = 96, poles = 4, r.p.m. = 1500, turns/coil = 16 in single layer, Ø = 2.58 x 10^6 lines. Calculate the voltage generated/phase.

$$F = \frac{PN}{120} = \frac{4 \times 1500}{120} = 50 \text{ Hz.}$$

$$\text{Coils per phase} = \frac{\text{No. of slots}}{\text{No. of phases}} = \frac{96}{3} = 32.$$

Therefore turns/phase = 32 x 16 = 512

= 2.58 x 10^6 lines = 2.58 x 10^6 x 10^{-8} weber

V = 4.44 FØT

= 4.44 x 50 x 512 x 2.58 x 10^6 x 10^{-8} = 2932 volts.

Example: The stator of a 3-phase, 16-pole alternator has 144 slots, and there are 4 conductors per slot connected in two layers, and the conductors of each phase are connected in series. If the speed of the alternator is 375 r.p.m. calculate the emf induced per phase. The resultant flux in the air gap is 5 x 10^{-2} webers per pole, sinusoidally distributed. Assume the coil span as 150° electrical.

Sinusoidal distribution, hence the wave form is sine wave and the emf induced

E_o = E_p = 4.44 K_cK_dFØT volts

$$K_c = \text{Cos } \frac{\alpha}{2} = \text{Cos } (180\text{-}150)/2 = \text{Cos } \frac{30}{2}$$

= Cos 15 = 0.966

$$m = \frac{144}{3 \times 16} = 3$$

$$\beta = \frac{180^\circ}{\frac{144}{16}} = \frac{180}{9} = 20^\circ$$

$$K_d = \frac{\text{Sin } 3 \times \frac{20}{2}}{3 \text{ Sin } \frac{20}{2}} = 0.96.$$

$$\text{Number of slots/phase} = \frac{144}{3} = 48$$

Number of conductors/slots = 4

Number of conductors in series per phase = 48 x 4

$$\text{Number of turns in series per phase} = \frac{48 \times 4}{2} = 96.$$

$$\text{Frequency} = \frac{PN}{120} = \frac{16 \times 375}{120} = 50 \text{ Hz.}$$

E_{ph} = 4.44 K_cK_dFØT

= 4.44 x 0.966 x 0.96 x 50 x 5 x 10^{-2} x 96

= 988 volts.

Characteristic and voltage regulation of the alternator

Objectives: At the end of this lesson you shall be able to
- **explain the load characteristic of an alternator and the effect of the P.F. on terminal voltage**
- **explain the regulation of alternators and solve problems therein.**

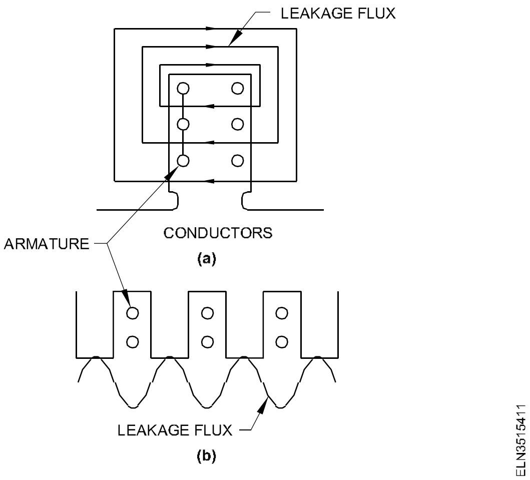
Load characteristic of an alternator: As the load on the alternator is changed, its terminal voltage is also found to change. The reason for this change is due to the voltage drop in the alternator because of

- armature resistance R_a
- armature leakage reactance X_L
- armature reaction which, in turn, depends upon the power factor of the load.

Voltage drop in armature resistance: Resistance of each phase winding of the alternator causes a voltage drop in the alternator, and it is equal to I_pR_a where I_p is the phase current and R_a is the resistance per phase.

Voltage drop in armature leakage reactance: When the flux is set up in the alternator due to the current flow in the armature conductors, some amount of flux strays out rather than crossing the air gap. These fluxes are known as leakage fluxes. Two types of leakage fluxes are shown in Figs 1a and b.

Fig 1



Though the leakage fluxes are independent of saturation, they do depend upon the current and the phase angle between the current and the terminal voltage `V'. These leakage fluxes induce a reactance voltage which is ahead of the current by 90°. Normally the effect of leakage flux is termed as inductive reactance X_L and as a variable quantity. Sometimes the value X_L is named as synchronous reactance to indicate that it refers to working conditions.

Voltage drop due to armature reaction: The armature reaction in an alternator is similar to DC generators. But the load power factor has considerable effect on the armature reaction in the alternators.

The effects of armature reaction have to be considered in three cases, i.e. when load power factor is

- unity
- zero lagging
- zero leading.

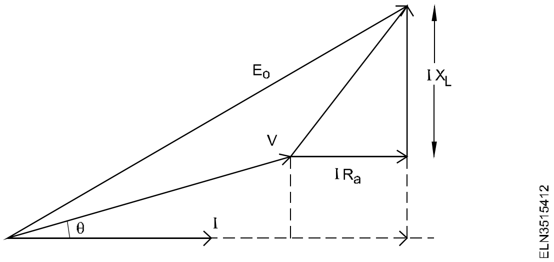
At unity P.F. the effect of armature reaction is only cross-magnetising. Hence there will be some distortion of the magnetic field.

But in the case of zero lagging P.F. the effect of armature reaction will be de-magnetising. To compensate this de-magnetising effect, the field excitation current needs to be increased.

On the other hand, the effect of armature reaction due to zero leading P.F. will be magnetising. To compensate the increased induced emf, and to keep the constant value of the terminal voltage due to this additional magnetising effect, the field excitation current has to be decreased.

Effect of armature resistance and reactance in the alternator: The induced emf per phase in an alternator is reduced by the effect of armature resistance, and reactance drops as shown vectorially in Fig 2 where

Fig 2



V is the terminal voltage per phase

I is the phase current

θ is the power factor angle between phase current and terminal voltage

E_o is the induced emf per phase

R_a is the armature resistance per phase

X_L is the armature reactance per phase.

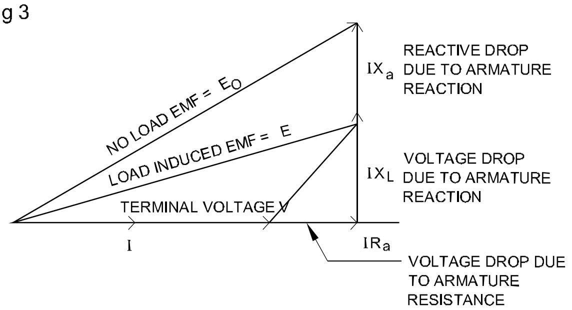
The induced emf can be calculated either vectorially or mathematically.

Mathematically the induced emf

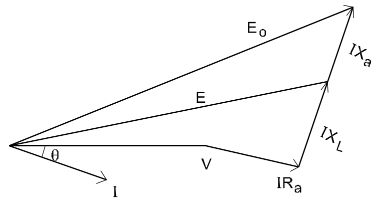
$$E = \sqrt{(V\mathrm{Cos}\theta + IR_a)^2 + (V\mathrm{Sin}\theta + IX_L)^2}$$

For any value of P.F. either lagging or leading, a combination of the effects of cross-magnetising, de-magnetising or magnetising takes place. In all the effects of armature reaction, it is shown vectorially as a force acting in line with the reactance drop as shown in Fig 3 by a vector IX_a. However this value is not measurable.

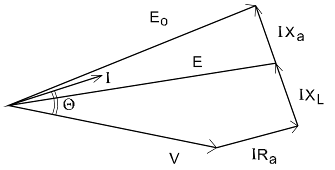
Fig 3



(a) UNITY POWER FACTOR



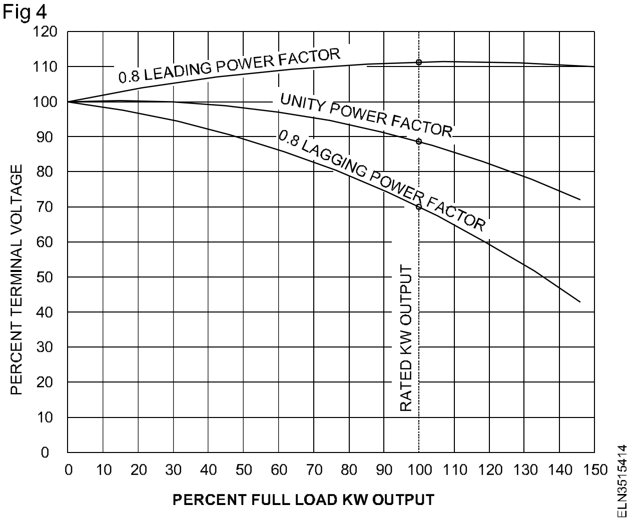
(b) LAGGING POWER FACTOR



(c) LEADING POWER FACTOR

On the basis of the above information, it is found that the terminal voltage of an alternator with unity power factor load will fall slightly on load as shown in Fig 4. Also it is found that the terminal voltage falls considerably for an alternator having lagging power factor. On the contrary, with leading P.F. the terminal voltage of the alternator on load increases even beyond the no-load terminal voltage as shown in Fig 4.

Fig 4



Rating of alternators: As the power factor for a given capacity load determines the load current, and the alternator's capacity is decided on load current, the rating of the alternator is given in kVA or MVA rather than kW or MW in which case the power factor also is to be indicated along with the wattage rating.

Example: A 3-phase, star-connected alternator supplies a load of 5 MW at P.F. 0.85 lagging and at a voltage of 11 kV. Its resistance is 0.2 ohm per phase and the synchronous reactance is 0.4 ohm per phase. Calculate the line value of the emf generated.

Full load current = $I_L = \dfrac{P}{\sqrt{3}E_L \mathrm{Cos}\theta}$

$$\frac{5 \times 1000 \times 1000}{\sqrt{3} \times 11000 \times .85} = 309 \text{ Amps.}$$

In star $I_L = I_P$

IR_a drop = 309x0.2=61.8 V

Ix_L drop = 309 x 0.4 = 123.6 V

Terminal voltage (line)=11000 V

Terminal voltage(phase) $= \dfrac{11000}{\sqrt{3}} =$ 6350V

Power factor = 0.85

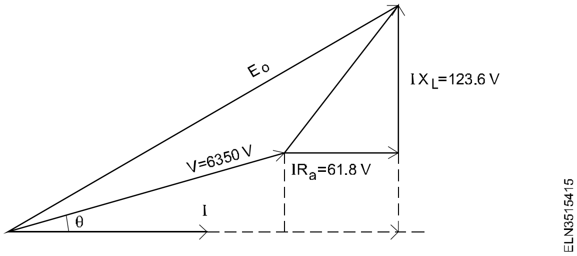
Power factor angle = $\theta = \mathrm{Cos}^{-1}(.85)$

= Cos 31.8°

Sin θ = 0.527.

Drawing the vector, as shown in Fig 5, with the above data, we have

Fig 5



$$E_o = \sqrt{(V\mathrm{Cos}\theta + IR_a)^2 + (V\mathrm{Sin}\theta + IX_L)^2}$$

$$= \sqrt{(6350 \times 0.85 + 61.8)^2 + (6350 \times 0.527 + 123.6)^2}$$

= 6468.787 volts.

Line voltage $= \sqrt{3}E_P = \sqrt{3} \times 6469 = 11204\text{V}$

The voltage regulation of an alternator: The voltage regulation of an alternator is defined as the rise in voltage when the load is reduced from the full rated value to zero, with the speed and field current remaining constant. It is normally expressed as a percentage of the full load voltage.

$$\% \text{ of voltage regulation} = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100$$

where V_{NL} - no load voltage of the alternator

V_{FL} - full load voltage of the alternator

The percentage regulation varies considerably, depending on the power factor of the load, and as we have seen for leading P.F. the terminal voltage increases with load, and for lagging P.F. the terminal voltage falls with the load.

Example: When the load is removed from an AC generator, its terminal voltage rises from 480V at full load to 660V at no load. Calculate the voltage regulation.

$$\% \text{ regulation} = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100$$

$$\frac{660 - 480}{480} \times 100 = 37.5\%$$

Parallel operation and synchronisation of three phase alternators - brushless alternator

Objectives: At the end of this lesson you shall be able to
- **state the necessity and conditions for paralleling of alternators**
- **explain the methods of paralleling two 3 phase alternators**
- **state the effect of changes in field excitation and speed on the division of load between parallel operation.**

Necessity for paralleling of two alternators

Whenever the power demand of the load circuit is greater than the power output of a single alternator, the two alternators to be connected in parallel

Conditions for paralleling (synchronising) of two 3 phase alternators

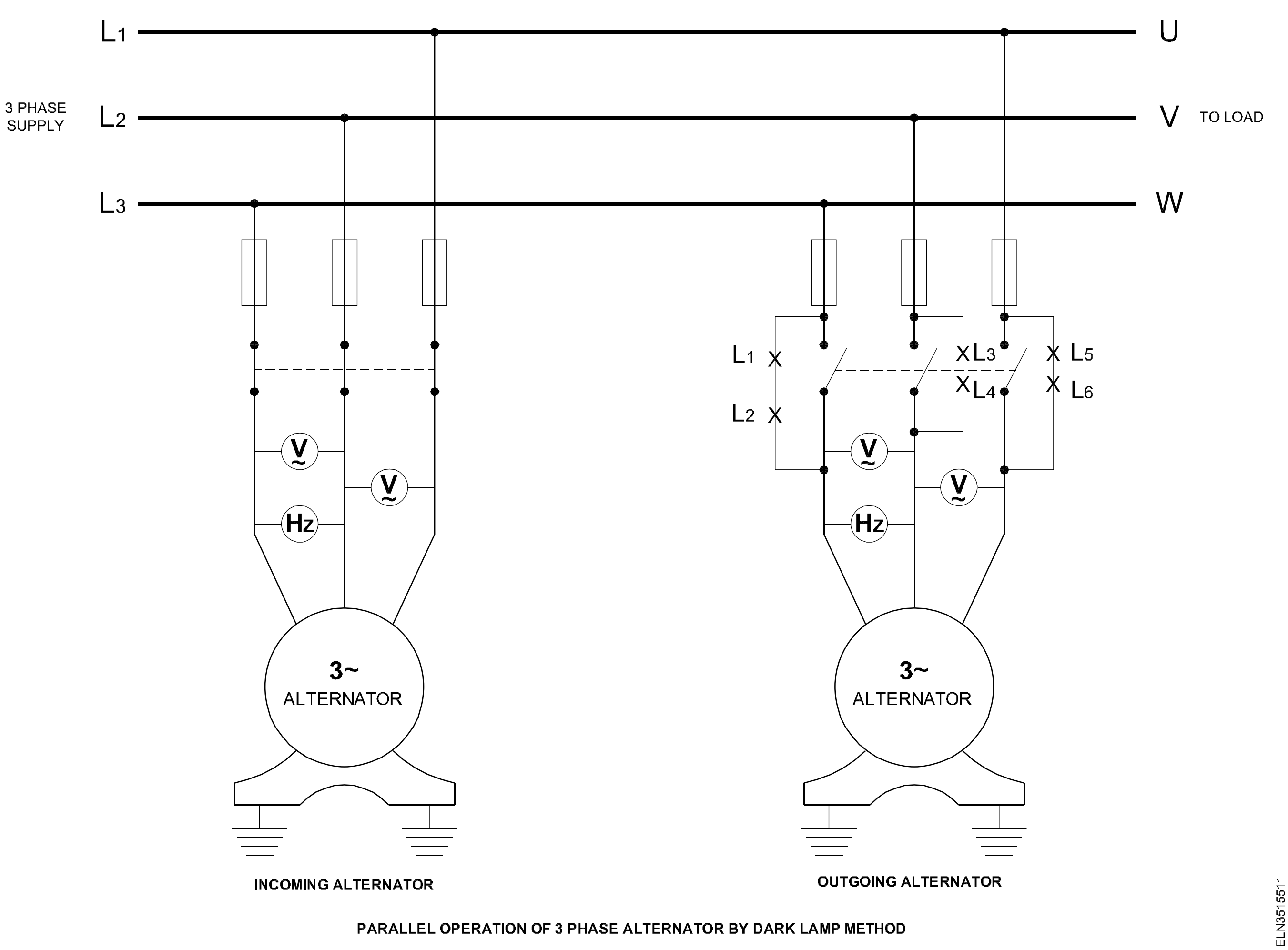
- The phase sequence of both 3 phase alternators must be same. It can be checked byusing phase sequence meters
- The output voltages of the two 3 phase alternators must be same.
- The frequency of both the alternators must be same

Dark lamp method

The following describes the method of synchronizing two alternators using the dark lamp method.

Fig 1 illustrates a circuit used to parallel two three-phase alternators. Alternator 2 is connected to the load circuit. Alternator 1 is to be paralleled with alternator 2 Three lamps rated at double the output voltage to the load are connected between alternator 2 and the load circuit as shown. When both machines are operating, one of two effects will be observed:

Fig 1



PARALLEL OPERATION OF 3 PHASE ALTERNATOR BY DARK LAMP METHOD

1 The three lamps will light and go out in unison at a rate which depends on the difference in frequency between the two alternators.

2 The three lamps will light and go out at a rate which depends on the difference in frequency between the two machines, but not in unison. In this case, the machines are not connected in the proper phase sequence and are said to be out of phase. To correct this, it's necessary to interchange any two leads to alternator 1. The machines are not paralleled until all lamps light and go out in unison. The lamp method is shown for greater simplicity of operation.

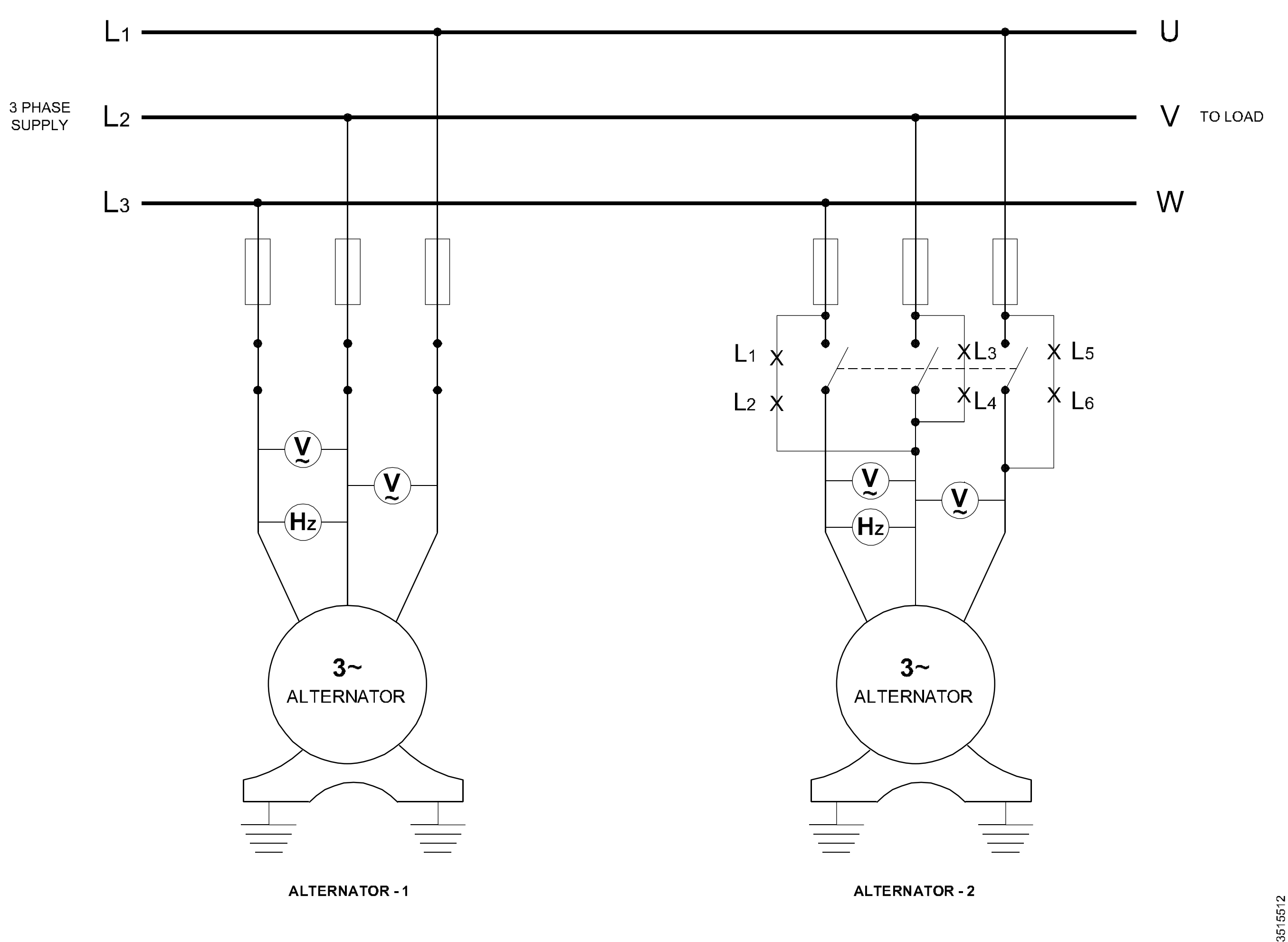
By making slight adjustments in the speed of alternator 1 the frequency of the machines can be equalized so that the synchronizing lamps will light and go out at the lowest possible rate. When the three lamps are out, the instantaneous electrical polarity of the three leads from 1 is the same as that of 2 At this instant, the voltage of 1 is equal to and in phase with that of 2 Now the paralleling switch can be closed at the middle period of the darkness of the lamps so that both alternators supply power to the load. The two alternators are in synchronism, according to the three dark method.

The three dark method has certain disadvantages and is seldom used. A large voltage may be present across an incandescent lamp even though it's dark (burned out). As a result, it's possible to close the paralleling connection while there is still a large voltage and phase difference between the machines. For small capacity machines operating at low speed, the phase difference may not affect the operation of the machines. However, when large capacity units having low armature reactance operate at high speed, a considerable amount of damage may result if there is a large phase difference and an attempt is made to parallel the units.

Two bright, one dark method (Dark and bright lamp method)

Another method of synchronizing alternators is the two bright, one dark method. In this method, any two connections from the synchronizing lamps are crossed after the alternators are connected and tested for the proper conditions for paralleling phase rotation. (The alternators are tested by the three dark method.) Fig 2 shows the connections for establishing the proper phase rotation by the three dark method. Fig 2 shows the lamp connections required to synchronize the alternator by the two bright, one dark method.

Fig 2



DARK & BRIGHT LAMP METHOD

When the alternators are synchronized, lamps 1 and 2 are bright and lamp 3 is dark. Since two of the lamps are becoming brighter as one is dimming, it's easier to determine the moment when the paralleling switch can be closed. Furthermore, by observing the sequence of lamp brightness, it's possible to tell whether the speed of the alternator being synchronized is too slow or too fast and can be connected it.

At the moment when the two lamps are full bright and one lamp is full dark, the synchronizing switch can be closed.

Now the both alternator are synchronized and share the load according to their ratings.

Synchroscope method

Objectives: At the end of this lesson you shall be able to
- **state the types of synchroscope**
- **explain the working principle of synchroscope.**

Synchroscope

A synchroscope is used to determine the correct instant for closing the switch which connects an alternator to the power station busbars. This process of connecting at the correct instant or synchronizing is necessary when an unloaded "incoming" machine is to be connected to the busbars in order to share the load.

The correct instant of synchronizing is when the busbar and the incoming machine voltages

a) are equal in magnitude,

b) are in phase and

c) have the same frequency.

For a 3-phase machine the phase sequence of the two should be the same. This condition is verified by a phase sequence indicator.

The voltages can be checked with the help of a voltmeter. The function of the synchroscope is to indicate the difference in phase and frequency of voltage of the busbar and the incoming machine.

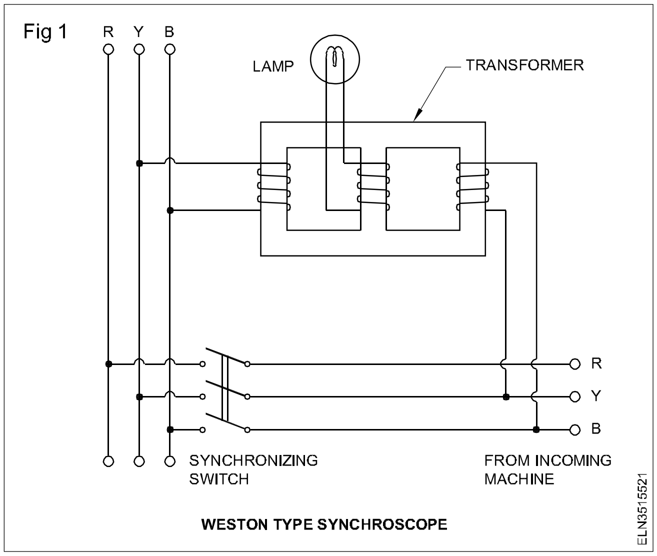
Synchroscopes may either be of **the electro-dynamometer type** or **the moving iron type**. Both types are special forms of respective power factor meters.

Electro dynamometer (Weston) type synchroscope

Fig 1 shows a simple circuit of Weston type synchroscope. it consists of three limbed transformer. The winding one of the outer limbs is excited from busbars and that on the other outer limb by the incoming machine. The winding on the central limb is connected to a lamp.

The windings on the outer limbs produce two fluxes which are forced through the central limb. The resultant flux through the central limb is equal to the phasor sum of these fluxes. This resultant flux induces an emf in the winding of the central limb. The two outer limb windings are so arranged that when the busbar and the incoming machine voltages are in phase, the two fluxes though the central limb are additive and thus emf induced in the central limb winding is maximum. Hence under these conditions the lamp glows with maximum brightness. When the two voltages are 180° out of phase with each other the resultant flux is zero and hence no emf is induced in the central limb winding, with the result the lamp does not glow at all and is dark. If the frequency of the incoming machine is different form that of the busbars, the lamp will be alternately bright and dark or in other words the lamp flickers. The frequency of flickering is equal to the difference in frequencies of the busbar and the incoming machine.

Fig 1



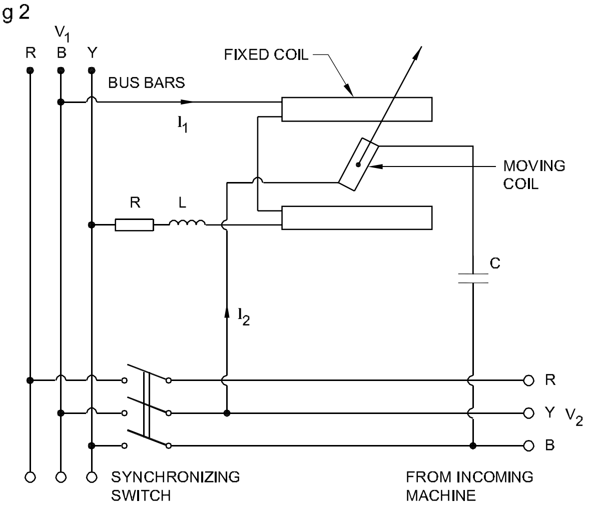
WESTON TYPE SYNCHROSCOPE

The correct instant of synchronizing is when the lamp is flickering at a very slow rate and is at its maximum brightness.

One of the defect of this simple circuit is that it does not indicate whether the incoming machine is too fast or too slow. This defect can be corrected by introducing an electrodynamometer type instrument into the circuit shown in Fig 2.

The electrodynamometer instrument consists of a fixed coil divided into two parts. The fixed coil is designed to carry a small current and is connected in series with a resistance across the busbars. The moving coil is connected in series with a capacitor across the terminals of the incoming machine. The instrument is provided with control springs which act as current leads for the moving coil. The shadow of the pointer is thrown on an opal glass.

Fig 2

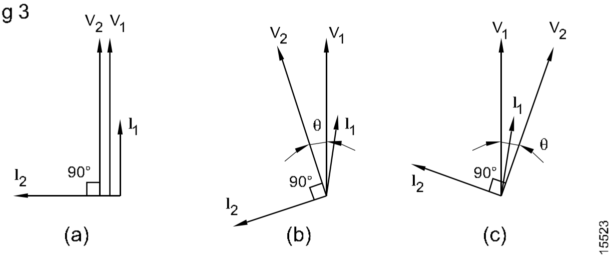


WESTON TYPE SYNCHROSCOPE

When the two voltages are in phase with each other, current I_1 and I_2 in fixed and moving coils respectively will be in quadrature with each other (Fig 3a) and therefore there will be no torque on the instrument. The control springs are so arranged that the pointer is in vertical position under this condition. Also the lamp is at its maximum brightness and the pointer is silhoueted against the opal glass.

If the incoming machine voltage V_2 is leading the busbar voltage V_1 and the incoming machine slightly too slow, the conditions of the circuit will slowly change from those shown in Fig 3b to those shown in Fig 3c. Then the torque will change from $KI_1I^2 \cos (90° + \theta)$ i.e., from a negative value through zero to a positive value. And during this period lamp will be bright and the pointer will be seen to move from left hand side of dial through the vertical position to the right and side of dial. The dial can thus be marked with directions Fast and Slow as shown in Fig 4.

Fig 3



(a) (b) (c)

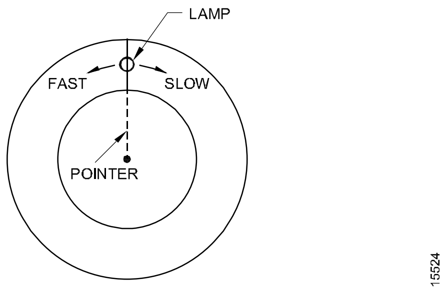
PHASOR DIAGRAMS

During this period when the voltages V_1 and V_2 are 180° out of phase the pointer will move back. But it will not be visible as under these conditions as the lamp is dark.

The visible movement of the pointer is therefore a series of traverses on the dial in one direction. If the incoming machine is too fast the visible traverses will be in the other direction. The correct instant of synchronizing is when the pointer is visible at its central position and is moving very slowly.

It may be observed that in order to have an exact quadrature relationship between currents I_1 and I_2 when voltages V_1 and V_2 are in phase, is obtained only if small inductance L is introduced in the fixed coil circuit.

Fig 4

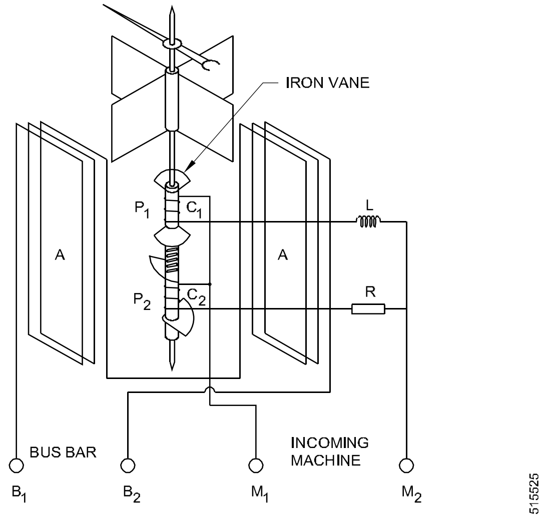


DIAL OF WESTON SYNCHROSCOPE

Moving Iron synchroscope

Fig 5 shows the construction of a moving iron synchroscope which is due to Lipman. It has a fixed coil divided into two parts. This fixed coil A is designed for a small value of current and is connected in series with a resistance across two phases of the busbar. There are two iron cylinders C_1 and C_2 mounted on the spindle. Each iron cylinder is provided with two iron vanes whose axes are 180° out with each other. The iron cylinders are excited by two pressure coils P_1 and P_2 which are connected to two phases of the incoming machine. One of the coils has a series resistance and the other has a series inductance. This is done in order to create an artificial phase difference of 90° between the currents of two pressure coils. There are no control springs. The instrument is provided with a pointer which moves over a dial marked Fast and Slow.

Fig 5



NALDER LIPMAN TYPE SYNCHROSCOPE

When the frequency of incoming machine is the same as that of busbars, the instrument behaves exactly like the corresponding form of the power factor meter. The deflection of the pointer from the plane of reference is equal to phase difference between the two voltages.

However if the frequencies of the two voltages are different, the pointer rotates continuously at a speed corresponding to difference in frequency of the two voltages. The direction of rotation depends whether the incoming machine is too fast or too slow.

Brushless alternator

Objectives: At the end of this lesson you shall be able to
- **state the principle and basic theory of brushless alternator**
- **explain the construction of brushless alternator**
- **describe the working of 3 phase brushless alternator.**

Principle of brushless alternator

In all alternators, voltage may be generated by rotating a coil in the magnetic field or by rotating a magnetic field within a stationary coil wire. To produce voltmeter either the coil is moving or the magnetic field is moving. Either configuration works equally well and both are used separately or in combination depending on mechanical, electrical and other objectives.

In the case of brushless alternator both combination is used together in one machine.

The stationary part of an alternator is called the stator and the roating part is called the rotor. The coils of wire used to produce a magnetic field are called the field winding and the coils that the power are called the armature winding. Here both armature and field winding used as rotor as well as stator.

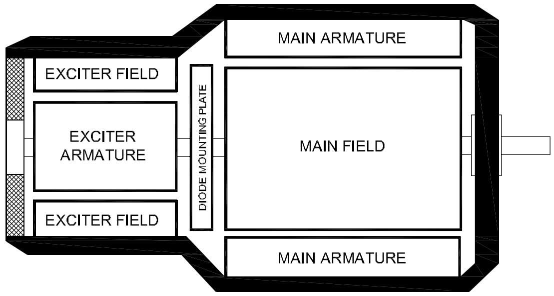
Working of brushless alternator

Brushless alternators having two part one is excitation alternator part and another is main alternator part (Fig 1)

Excitation alternator

The armature is rotor and field winding is stator. When it starts rotating a voltage is generatred in Exciter armature which gives current the main field to produce magnetic field in main alternator.

Fig 1



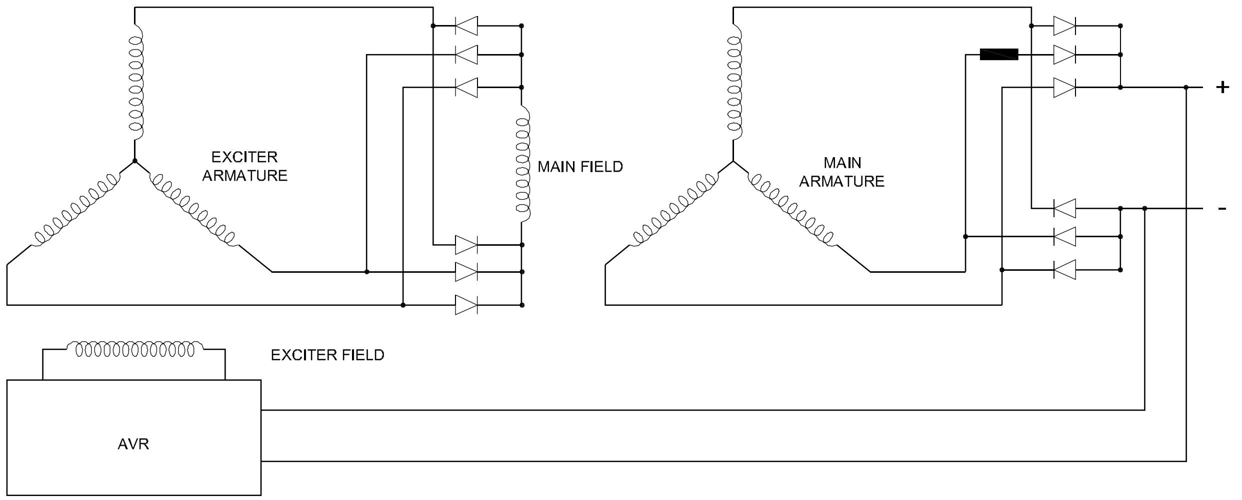
Main alternator

Here main field is rotor and armature is stator so the supply can be taken out directly. No brushes required. Voltage produced in the exciter armature produce a magnetic field on the main alternator rotor. When this magnetic field cuts the main armature, a potential difference produced. Here the voltage produced can be regulated by exciter field current (Fig 2).

Basic theory

When an electric current is passed through a coil of wire, a magnetic field is produced (an electromagnet). Conversely, when a magnetic field is moved through a coil of wire, a voltage is induced in the wire. The induced voltage becomes a current when the electrons have some place to go such as into a battery or other load. Both of these actions take place in alternators, motors and generators or dynamos.

Fig 2



3 PHASE BRUSHLESS ALTERNATOR CIRCUIT DIAGRAM

Construction

A brushless alternator is composed of two alternators built end-to-end on one shaft. Smaller brushless alternators may look like one unit but the two parts are readily identifiable on the large versions. The larger of the two sections is the main alternator and the smaller one is the exciter. The exciter has stationary field coils and a rotating armature (power coils). The main alternator uses the opposite configuration with a rotating field and stationary armature

Exciter

The exciter field coils are on the stator and its armature is on the rotor. The AC output from the exciter armature is fed through a set of diodes that are also mounted on the rotor to produce a DC voltage. This is fed directly to the field coils of the main alternator, which are also located on the rotor. With this arrangement, brushes and slip rings are not required to feed current to the rotating field coils. This can be contrasted with a simple automotive alternator where brushes and slip rings are used to supply current to the rotating field

Main alternator

The main alternator has a rotating field as described above and a stationary armature (power generation windings). This is the part that can be confusing so take note that in this case, the armature is the stator, not the rotor.

With the armature in the stationary portion of the alternator, the high current output does not have to go through brushes and slip rings. Although the electrical design is more complex, it results in a very reliable alternator because the only parts subjects to wear are the bearings.

Three-phase brushless alternator

A three phase alternator has a minimum of 3 sets of windings spaced 120^0 apart around the stationary armature (stator). As a result, there are 3 outputs from the alternator and they are electrically spaced 120^0 out of phase with each other. A multi-pole design will have multiple sets of 3 windings. These sets of windings (poles) are spaced evenly around the circumference of the machine. The more poles there are , the slower the alternator turns for a given voltage and frequency. More poles increase the complexity of the alternator and that in part accounts for the higher price of slower speed versions.

Other than in single-phase power plants, most alternators, including the automotive type, generate 3-phase power. A three-phase AC alternator will not have any diodes in it. If the output is DC, it will probably have 6 diodes to convert the output from the main alternator to DC. This is the configuration used in automotive alternators. A 3-phase brushless alternator may have 4 or 6 diodes on the rotor for the exciter output in addition to the diodes that may be on the stator

There are two ways that 3-phase machines can be wired. One is the delta (triangle) configuration with one wire coming off each "point of triangle". The other is the wye (Y) or star configuration. They have one wire from each branch of the "Y" and in some cases a 4" common wire is added from the centre/centre point of the "Y" (the common connection point between the windings)

Multiple voltage machines will have additional wires to allow them to be configured for the desired system voltage.