DETAILS EXPLANATIONS

EE : Paper-1 (Paper-3) [Full Syllabus]

[PART : A]

1. *Active and Passive*

An active element is capable of generating energy while a passive element is not. A passive element either transform or stores electrical energy. Examples of passive elements are resistors, capacitors and inductors. Typical active elements include generators, batteries and operational amplifiers.

2. A node point is defined as an end point of a line segment and exists at the junction between two branches or at the ends of an isolated branch.

3. ***(i) Tree Branch :*** It is any branch of a tree. It is also named as twig.

(ii) Tree link (or chord) : It is that branch of the graph that does not belong to the particular tree. It is simply called a link.

(iii) Loop : This is the closed contour selected in a graph.

(iv) ***Degree of a Node :*** It is the number of branches incident to it.

4. These materials when placed in a magnetic field acquire a weak magnetization in the same direction as the applied field are called paramagnetic materials. The value of magnetic susceptibility for these materials is positive and very small.
Example: Phosphorus, O_2.

5. The degree of compensation or compensating factor in cross-field machines in defined as under:

$$\frac{\text{Effective Compensating Winding Turns}}{\text{Effective d-axis Ampere Turns}} = C$$

6.
- DC supplied at the armature terminals is convertes to AC in the armature winding by means of commutator.
- It renders the armature mmf stationary in space along the Q-axis even through the armature rotates.

7. (i) Direct-on line starter.

(ii) Stator-reactor starter

(iii) Auto-Transformer starter.

(iv) Star-delta starter

8. For free space

$$\sigma = 0$$
$$\rho_s = 0$$
$$\in = \in_0$$
$$\mu = \mu_0$$
$$\bar{\nabla} \times \bar{H}_s = \in_0 \frac{\partial E}{\partial t} \quad ...(1)$$
$$\bar{\nabla} \times \bar{E}_s = -\mu_0 \frac{\partial H}{\partial t} \quad ...(2)$$
$$\bar{\nabla}.\bar{E}_s = 0 \quad ...(3)$$
$$\bar{\nabla}.\bar{H} = 0 \quad ...(4)$$

9. $$e = -\frac{d\phi}{dt} = -(30t^2 + 50t)$$
$$e(t = 1) = -80 \text{ Volts}$$

10. Synchronous phase modifier differs from an ordinary synchronous motor in as much as they are built for the highest economical speeds, and provided with smaller shafts and bearings and special attention is paid for securing a high overall efficiency.

11. Feeder is a line which supplies a point of distribution network without being tapped at any intermediate point. In simple terms, the feeder may be defined as the line carrying current from the secondary substation to the distribution substations or as a primary distribution line.

12. Booster is a low voltage, high current series wound DC generator inserted into a DC circuit to add or inject a certain voltage proportional to circuit current.

13. Primary distribution system is that part of the distribution system which operates at voltages such as 3.3, 6.6 or 11 kV. The normal operation voltage of primary distribution is 11 kV.

14. The problems associated with EHV transmission are corona loss and radio interference, requirements of heavy supporting structures and erection difficulties and insulation requirements.

15. The most common and dangerous faults that occur in a power system are the short circuit or shunt faults such as L-G, L-L, L-L-G, L-L-L and L-L-L-G faults. The other type of faults that occur in a power system are series type such as one conductor open fault and two conductor open fault.

16. Protective relay is an electrical device designed to initiate isolation of a part of an electrical installation, or to operate an alarm signal, in the event of an abnormal condition or a fault.

17.
- The harmonic induced emf gets reduced significantly without much reduction in fundamental. So induced emf wave form is improved i.e. closer to sinusoidal.
- Slot depth is reduced hence there is reduction in slot harmonics.

18. Winding factor (k_w)

$$k_w = k_p.k_d$$

where, k_p = Pitch factor

k_d = distribution factor.

$$k_d = \frac{\sin\frac{Qr}{2}}{Q\sin\frac{r}{2}}$$

$$k_p = \cos\left(\frac{p}{2}\right)$$

where, $r = \frac{\pi}{(\text{slot / pole})}$

Q = Slot/pole/phase = $\frac{S}{MP}$

$Qr = \Psi =$ Phase spread or phase belt

p = Angle of short pitching or angle of cording

19. n^{th} harmonic pitch factor

$$k_{p_n} = \cos\frac{n\rho}{2}$$

To eliminate n^{th} harmonic

$$k_{p_n} = 0$$

$$\cos\frac{n\rho}{2} = 0$$

So, $\frac{n\rho}{2} = \frac{\pi}{2}$

$$S = \frac{\pi}{n} = \frac{1}{n} \times \text{pole pitch}$$

$$\text{Coil Span} = \pi - \rho = \pi - \frac{\pi}{n}$$

$$= \frac{n-1}{n} \times \pi = \frac{n-1}{n} \times \text{pole pitch.}$$

20. Following method to minimize slot harmonics.

- By increasing the air gap length.
- Using less slot opening.
- Using distributed and short pitch winding.
- Using fractional slot windings.
- Using skewed slot by one slot pitch.

[PART : B]

21. Selectivity is *absolute* if the protection responds only to the faults within its own zone, and *relative* if it is obtained by grading the settings of the protective relays of several zones all of which may respond to a given fault. Systems of protection which in principle are *absolutely selective* are called the *unit systems.* Systems in which selectivity is relative are *non-unit* systems. Differential protection and frame leakage protection fall in the former category while the current time graded protection and distance protection fall in the latter category.

22. Rated symmetrical breaking current

$$= \frac{\text{Rupturing capacity in MVA}}{\sqrt{3}\times\text{Operating voltage in kV}}\ \text{kA} = \frac{2000}{\sqrt{3}\times 33} = 35\ \text{kA}$$

Making current = 2.55 × Rated symmetrical breaking current

$$= 2.55 \times 35 = 89.25\ \text{kA}$$

23. In a three-phase system, there are two sets of voltages are. One is the set of phase voltages, and the other is the set of line voltages. In V_{RN} is the rms value of the voltage drop from R to N. That is, this is the phase voltage of phase R. Thus, V_{RN}, V_{YN} and V_{BN} denote the set of three phase voltages.

The term line voltage is used to denote the voltage between two lines. Thus, V_{RY} represents line voltage between the lines R and Y. The other line voltage are V_{YB} and V_{BN}.

24. We have $C = 200\ \mu F$

Current $i_1 = 0.5$ A

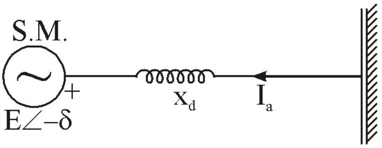
and voltage $v_1 = 8$

Capacitive reactance is

$$X_C = \frac{v_1}{i_1} = \frac{8}{0.5} = 16\ \Omega$$

$$X_C = \frac{1}{2\pi fC} = \frac{1}{2\pi\times 16\times 200\times 10^{-6}} = 49.74\ \text{Hz}$$

25. 3-ϕ synchronous motor is connected to an ∞ bus. Where armature current $\overline{I}_a$(i.e. $\overline{I}_d$) is drawn from ∞ bus. The armature current $\overline{I}_a$ varies with field current if (or field excitation) according to the V curve.



At normal excitation I_{f0}, at no load p = 0 the motor draws $I_{q0} \simeq 0$ at unity p.f. if field excitation is decreases i.e. $I_f < I_{f0}$, the armature current increases $I_a > I_{a0}$, when field current $I_f = 0$ the salient pole motor remains continuous to rotate at synchrnous speed due to reluctance torque.

When the I_f is increased ϕ again in the reverse direction, the position of field poles N_f, S_f is reversed and rotor slips by one pole pitch, again there will be locking between armature and field poles and finally motor cortinious to rotate in the same direction, if I_f is increased from zero the I_a decreases steeply.

With I_f = –ve, rotor slips by one pole pitch, i.e. N_f and S_f are interchanged and finally S_a and N_f and N_a and S_f are locked.

26.

$$\phi = BA\cos\theta$$

$$\phi(t) = BA\cos(\omega t)$$

$$e(t) = -\frac{d\phi}{dt}$$

$$e(t) = +B(\pi R^2)\omega\sin\omega t$$

$$e_{max} = (B\pi R^2\omega)\ \text{volts}$$

27. Magnetic bubble memory consists of magnetic bubbles used to store data bits. These bubbles move in thin films of magnetic material. The bubbles are cylindrical magnetic domains having polarization opposite to that of the thin film in which they are embedded.

A thin film of magnetic garnet contains wavy strips of magnetic domains when an external magnetic field is applied perpendicular to the film and increased slowly, the wavy magnetization strips having magnetization opposite to the external field begin to narrow. At a certain value of field strength all these domains contract and look like small circular bubbles. These bubbles are tiny magnetic floating in an external field. These bubbles can be moved by applying a magnetic field parallel to the film. To control the direction of movement, special magnetic paths are created by depositing magnetically conductive material in specific pattern on the film.

The main components of magnetic bubble memory are thin film memory chip, drive coils, permanent magnetized control electronics. Logic 1s and Os are represented by presence or absence of bubbles respectively.

28. The operating voltage

$$V_1 = \sqrt{2}\pi f_1 B_{m1} A_i N$$

$$V_2 = \sqrt{2}\pi f_2 B_{m2} A_i N$$

$$\frac{V_1}{V_2} = \frac{f_1 B_{m1}}{f_2 B_{m2}}$$

or $$\frac{220}{230} = \left(\frac{60}{50}\right)\left(\frac{B_{m1}}{B_{m2}}\right)$$

$$\Rightarrow \quad B_{m2} = \frac{60(230)}{50(220)}$$

$$B_{m1} = 1.255\ B_{m1}$$

We know that

$$P_n = k_n f\, B_m^x$$

$$\therefore \quad \frac{P_{n2}}{P_{n1}} = \frac{f_2 B_{m2}^x}{f_1 B_{m1}^x} = \frac{50}{60}(1.255)^{1.6}$$

$$P_{n2} = 340\left(\frac{5}{6}\right)(1.255)^{1.6} = 408\ \text{W}$$

We know that

$$P_e = k_e\ f^2\ B^2_m$$

$$\therefore \quad \frac{P_{e2}}{P_{e1}} = \left(\frac{f_2}{f_1}\right)^2\left(\frac{B_{m2}}{B_{m1}}\right) = \left(\frac{50}{60}\right)^2 (1.255)^2$$

$$P_{e2} = (120)\left(\frac{5}{6}\right)^2 (1.255)^2 = 131.3\ \text{W}$$

Total core loss

$$P_{c2} = P_{n2} + P_{e2} = 408 + 131.3 = 539.3\ \text{W}$$

29. The field winding loss $V_f I_f$ and no-load rotational losses W_o remain approximately constant. The maximum efficiency as before, occurs when variable losses $I_a^2 r_a$ are equal to the Constant losses $V_f I_f + W_o$ this can be proved as follows:

We know that generator efficiency

$$\eta_g = \frac{V_t I_L}{V_t I_L + I_a^2 r_a + V_f I_f + W_o}$$

In shunt or compound machines, assume that the field current If is negligible as compared with the line current I_L with this assumption, $I_L = I_a$ and generator efficiency becomes.

$$\eta_g = \frac{V_t I_L}{V_t I_L + I_L^2 r_a + V_f I_f + W_o}$$

For a given value of V_t, the maximum efficiency occurs, when

$$\frac{d\eta_g}{dI_L} = \frac{\left[V_t I_L + I_L^2 r_a + V_f I_f + W_0\right] V_t - V_t V_L \left[V_t - 2I_L r_a\right]}{\left[\text{Denominator}\right]^2} = 0$$

or $\left[V_t I_L + I_L^2 r_a + V_f I_f + W_0\right] V_t = V_t V_L \left[V_t + 2I_L r_a\right]$

or $I_L^2 r_a = V_f I_f + W_0$

Variable armature circuit loss = Constant loss.

30. The shunt field current

$$I_f = \frac{220}{110} = 2A$$

At no load, armature current

$$I_{a1} = 5 - 2 = 3 \text{ A}$$

Counter emf

$$E_{a1} = 220 - 3 \times 0.2 = 219.4 \text{ Watts}$$

$\therefore$ Rotational Losses = $E_{a1} I_{a1}$ = 219.4 × 3 = 658.2 Watts

At full load, armature current

$$I_{a2} = I_L - I_f = 52 - 2 = 50A$$

$\therefore$ Counter emf $E_{a2} = 220 - 50 \times 0.2 = 210$ V

Here ϕ_1(No load flux) = ϕ_2(full load flux)

Because the field current is constant at 2A and effect of armature reaction is neglected.

$$\therefore \quad \frac{E_{a1}}{E_{a1}} = \frac{n_1\phi_1}{n_2\phi_2}$$

$$\text{or} \quad n_2 = \frac{n_1\phi_1}{\phi_1} \times \frac{E_{a2}}{E_{a1}} = \frac{1500 \times 210}{219.4} = 1435 \text{ rpm}$$

Shaft power

$$P_{sh} = \text{Electromagentic power} - \text{Roational losses}$$
$$= 210 \times 50 - 658.2 = 9841.8 \text{ Watts}$$

$$\therefore \text{ Shaft torque} = \frac{P_{sh}}{W_m} = \frac{9841.8 \times 60}{2\pi \times 1435} = 65.4 \text{ Nm}$$

31. Line trap is an LC network inserted between the bus bar and connection of coupling capacitor to the line and tuned to resonance at the high frequency and are used to confine the carrier currents to the protected section so as to avoid interference with or from adjacent carrier current channels and also to avoid loss of the carrier current signal in adjoining power circuits for any reason.

The coupling capacitor is used to connect the high frequency (carrier) equipment to one of the line conductors and simultaneously serves to isolate the carrier equipment from the high power line voltage.

32. Resistance, $R = 5\ \Omega$

Base resistance,

$$R_B = \frac{(kV_B)^2 \times 1,000}{kVA_B} = \frac{(11)^2 \times 1000}{10} = 12100\ \Omega$$

Per unit resistance,

$$R_{pu} = \frac{R}{R_B} = \frac{5}{12100} = 0.000413\ \text{pu}$$

[PART : C]

33. Now $I_a = 0$

$$I_b = \frac{100 \times 1,000}{3.3 \times 1,000} = 30.3\ \text{A}$$

$$I_c = -I_b = -30.3\ \text{A}$$

Positive sequence component

$$I_{a1} = \frac{1}{3}\left(I_a + \alpha I_b + \alpha^2 I_c\right)$$

$$= \frac{1}{3} I_b(\alpha - \alpha^2) = \frac{1}{3} I_b \times 1.732 = \frac{30.3}{\sqrt{3}} = 17.5\ \text{A}$$

Negative sequence component

$$I_{a2} = \frac{1}{3}\left(I_a + \alpha^2 I_b + \alpha I_c\right)$$

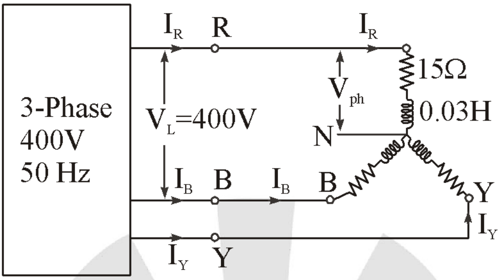
$$= \frac{1}{3}(0 + \alpha^2 I_b - \alpha I_b) = \frac{1}{3}(\alpha^2 - \alpha)$$

$$= \frac{30.3}{3} \times (-1.732) = 17.5\ \text{A}$$

Zero sequence component

$$I_{a0} = \frac{1}{3}\left(I_a + I_b + I_c\right) = \frac{1}{3}(0 + I_b - I_b) = 0 \text{ A}$$

34. The circuit is shown in figure.



(i) Phase current and line current

Line voltage

$$V_L = 400 \text{ V}$$

Phase voltage

$$V_{ph} = \frac{V_L}{\sqrt{3}} = \frac{400}{\sqrt{3}} = 231 \text{ V}$$

Impedance per phase

$$Z_{Ph} = R_{ph} + j2\pi fL = 15 + j2\pi 50 \times 0.03$$
$$= 15 + f9.42\ \Omega = 17.72\angle 32.14^\circ\ \Omega$$

We take the phase voltage as reference voltage. Thus Phase current

$$I_{ph} = \frac{V_{ph}}{Z_{ph}} = \frac{231\angle 0^\circ}{17.72\angle 32.14^\circ}$$
$$= 13.04\angle -32.140 \text{ A}$$

Line current

$$I_L = I_{ph} = 13.04\angle -32.140 \text{ A}$$

Thus each line current and phase current lags the respective phase voltage by 32.14°.

(ii) Total power absorbed

$$P = 3I_{ph}^2 R_{ph}$$
$$= 3(13.04)^2 \times 15$$
$$= 7651.87 \text{ W}$$

35. A 3-phase winding carrying sinusoidal currents produces space harmonics of the order

$$n = 6k \pm 1$$

Where k is a positive integer (1, 2, 3,...) the synchronous speed of the nth harmonic is $\left(\frac{1}{n}\right)$ times the speed of the fundamental wave. The space harmonic waves rotate in the same direction as the fundamental wave if h = 6k + 1, and in the opposite direction if h = 6k − 1.

A space harmonic wave of order h is equivalent to a machine with number of poles equal to (h × Number of poles of the stator). Therefore, the synchronous speed of the nth space harmonic wave is

$$n_{S(h)} = \frac{n_S}{h} = \frac{120f}{h \times p}$$

p = Number of pole of stator

Thus, for k = 1, a 3phase winding will produce predominant backward rotating fifth harmonic rotating at a speed fo $\left(\frac{1}{5}\right)$ of synchronous speed and forward rotating 7th harmonic roating at a speed of $\left(\frac{1}{7}\right)$ of synchronous speed. These harmonics alone will have little effect on the operation of the motor. The torque-speed characteristics for the fundamental flux and fifth and seventh space harmonic flux are shown in figure. The 5th and 7th harmonic torques have the same general shape as that of the fundamental.

Since 5th harmonic flux rotates in the direction opposite to the rotation of the rotor, the torque oppose the fundamental component torque. Thus 5th harmonic flux produces a bracking torque. The 7th harmonic flux rotates in the same direction as the fundamental flux and torque aids the fundamental component torque. The resultant torque speed characteristic will be the combination of the fundamental, 5th and 7th harmonic characteristics as shown in figure, the resultant torque-speed characterstic has two dips. one near $\left(\frac{1}{5}\right)$ of synchronous speed and the other near $\left(\frac{1}{7}\right)$ of synchrnous speed figure also shows load torque characteristic. If the motor torque is developed due to the fundamental flux alone, the motor will accelerate to the point L which is the intersection of the load torque characterstic and the motor torque speed curve due to the presence of 7th harmonic flux torque, the load torque interesects the motor torque-speed characterstic at point A. Since the 7th harmonic flux torque curve has a negative slope at point A stable running condition over the torque range between the maximum and minimum points results. The motor torque falls below the load torque. At this stage the motor will not accelerate upto its normal speed, but will remain running at a speed which is nearly $\left(\frac{1}{7}\right)$ of its normal speed and being unable to pick up its normal speed is known as crawling of the motor.

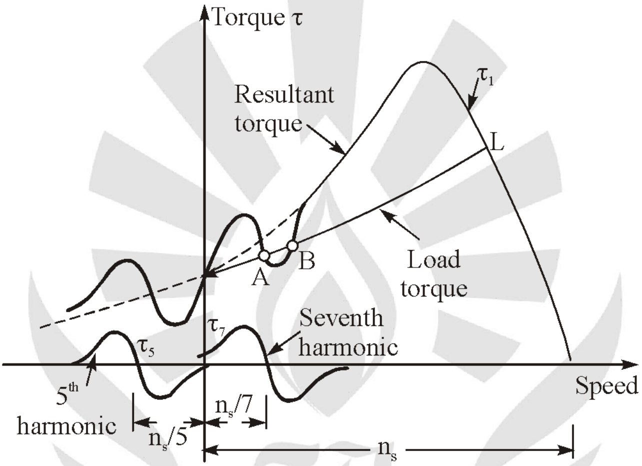


Figure : Torque-speed characteristics of a 3-phase induction motor showing the effect of space harmonic asynchronous (harmonic) torques.

When the number of stator and rotor slots are either equal or have an integer ratio. Then strong alignment force are produced between stator and rotor at the instant of starting. these forces may create an alignment torque greater than the accelerating torque with consequent failure of the motor to start. This phenomenon of magnetic locking between stator and rotor teeth is called cogging or teeth locking.

36. Open circuit and short circuit test are performed to determine the circuit constant, efficiency and regulation without actually loading the transformer.

Open Circuit Test :

Figure shows the connection diagram for the open circuit test. The high voltage (H.V.) side is left open.

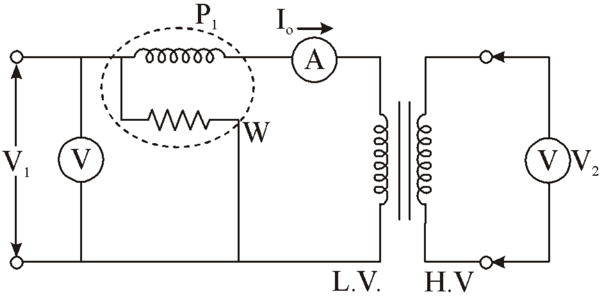


Figure : Open-Circuit Test on Transformer

There secondary is open-circuited, a very small current I_0, called the no-load current, flow in the primary. the ammeter A reads the no-load current I_0. The power loss in the transformer is due to core loss and a very small I^2R loss in the primary. There is no I^2R loss in the secondary since it is open and $I_2 = 0$ since the I_0 is very small (usually 2 to 5% of the full load primary current) the I^2R loss ln the primary winding can be neglected. The core loss depend upon the flux. Since the rated voltage V_1 is applied, the flux setup by it will have normal value so that normal core losses will occur. This core loss is the same at all loads. The no-load equivalent circuit can be determined

$$p_1 = V_1 I_0 \cos \phi_0$$

No load p.f.

$$\cos \phi_0 = \frac{P_i}{V_1 I_0}$$

$$I_w = I_0 \cos \phi_0$$

$$I_\mu = I_0 \sin \phi_0$$

$$R_0 = \frac{V_1}{I_w}$$

$$X_0 = \frac{V_1}{I_\mu}$$

Short Circuit Test :

Usually the LV side is short circuited by a thick conductor an ammeter, a voltmeter and a watt metter are connected on the H.V. side. The reasons for short circuiting the L.V. side and Taking measurement on the H.V. side are as follows:

- The rated current on H.V. side is lower than that on LV side this current can be safely measured with the available ammeter.
- Since the applied voltage is less than 5% of the rated voltage of the winding, greater accuracy in the reading of the voltmeter

is possible when the H.V. side is used as the primary. The H.V. winding is supplied at the reduced voltage from a variable voltage supply. The supply voltage is gradually increased untill full-load primary current flows. When the rated full-load current flow in the primary winding rated full-load current will flow in the secondary winding by transformer action.

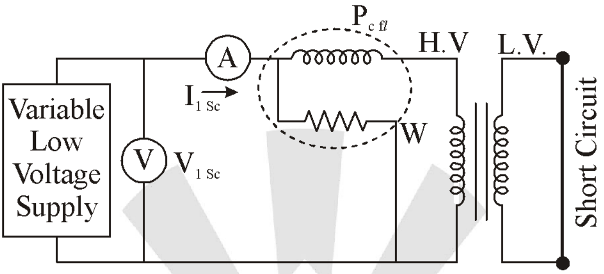


Figure : Short Circuit Test on a Transformer

Thus the wattmeter gives the full load copper losses p_{cfl}. The reading of the instrument on short-circuit test, the following calculations can be made :

Equivalent resistance of the transformer referred to primary

$$R_{e1} = \frac{P_{cfl}}{I_{1Sc}^2}$$

and equivalent inpedance refered to primary

$$Z_{C1} = \frac{V_{1Sc}}{I_{1Sc}}$$

Equation reactance referred to primary

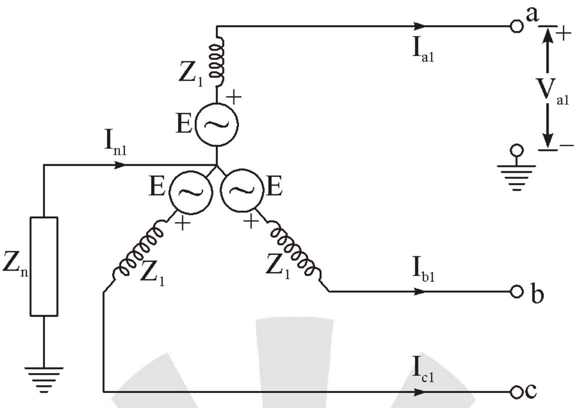
$$X_{e1} = \sqrt{Z_{e1}^2 - R_{e1}^2}$$

$$\cos\,\phi_{Sc} = \frac{R_{el}}{Z_{el}}$$

The full load p.f.

37.
- In synchronous generator armature winding always balanced due to equal number of turns and 120° space displacement between each phase winding. But due to unbalanced load the system will be unbalanced.
- In balanced condition only positive sequence current flows so there is induced emf. But for negative and zero sequence current there is no induced emf.

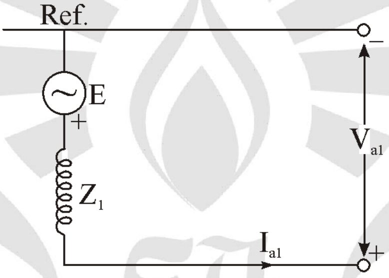
(i) Positive Sequence Network :



$\because \quad I_{n1} = I_{a1} + I_{b1} + I_{c1}$

$= I_{a1} + \alpha^2 I_{a1} + \alpha I_{a1}$

$= (1 + \alpha^2 + \alpha)I_{a1} = 0$

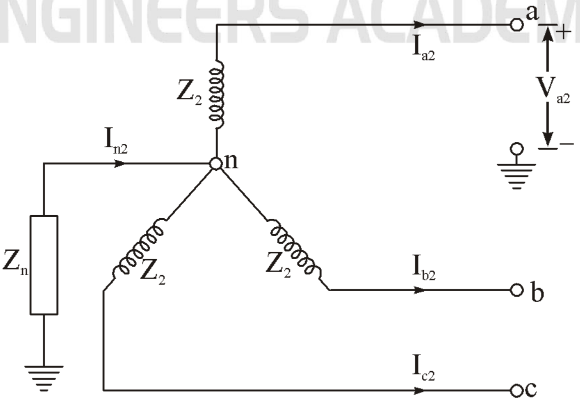


Applying KVL

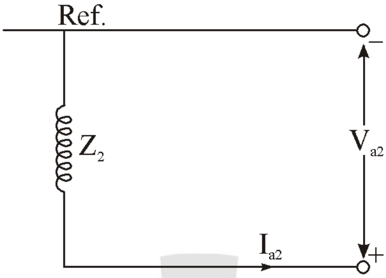
$+Z_n I_{n1} - E + Z_1 I_{a1} + V_{a1} = 0$

$\Rightarrow \quad V_{a1} = E - Z_1 I_{a1}$

(ii) Negative Sequence Network :



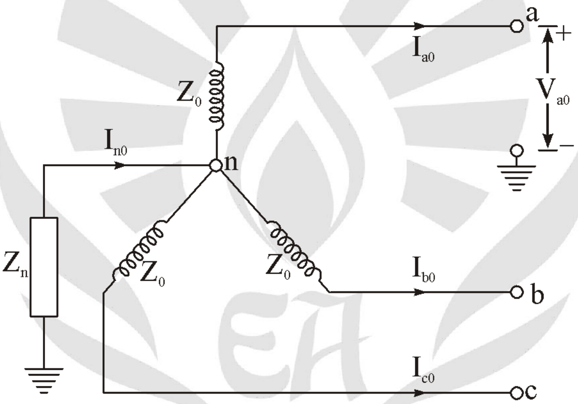
$$\because \quad I_{n2} = I_{a2} + I_{b2} + I_{c2}$$
$$= I_{a2} + \alpha I_{a2} + \alpha^2 I_{a2}$$
$$= (1 + \alpha + \alpha^2)I_{a2} = 0$$



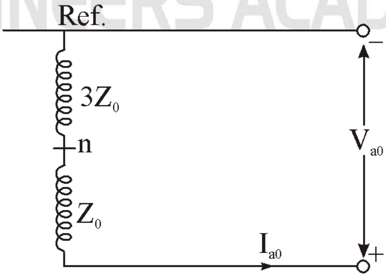
Applying KVL

$$+Z_nI_{n2} + Z_2I_{a2} + V_{a2} = 0$$
$$\Rightarrow \quad V_{a2} = Z_2I_{a2}$$

(iii) Zero Sequence Network :



$$\because \quad I_{n0} = I_{a0} + I_{b0} + I_{c0}$$
$$= I_{a0} + I_{a0} + I_{a0}$$
$$= 3I_{a0}$$



Applying KVL

$$+Z_nI_{n0} + Z_0I_{a0} + V_{a0} = 0$$
$$\Rightarrow \quad V_{a0} = -(Z_0 + 3Z_n)I_{a0}$$

38. Drawbacks of 3-point Starter.

The three-Point starter suffers from a serious draw back for motors with large variation of speed by adjustment of the field rheostat to increase the speed of the motor the field resistance should be increased therefore the current through the shunt field is reduced. The field current may may become very low because of the addition of high resistance to obtain a high speed. A very low field current will make the holding electromagnet too weak to overcome the force exerted by the spring. The holding magnet may release the arm of the starter during the normal operation of the motor and thus disconnected the motor from the line this is not desirable. A four point starter is used to overcome this difficulty.

Four Point Starter :

The schematic connection diagram of four point starter is shown in figure.

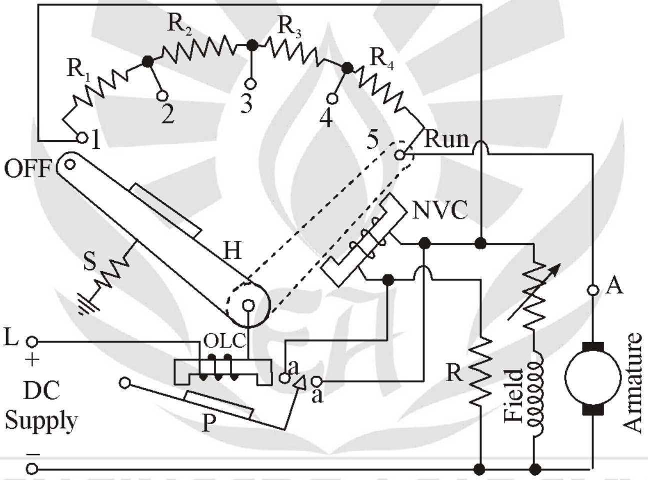


Figure : 4-Point DC Shunt Motor Starter

The basic difference in the circuit of a 4-point starter as compared to a 3-point starter is that, the holding coil is removed from the shunt field circuit and is connected directly across the line with a current limiting resistance R in series. Such an arrangement from three parallel circuits:

- Armature, starting resistance and overload release.
- A variable resistance and shunt field winding.
- Holding coil and current limiting resistance.

With this arrangement, a change in field current for variation of speed for the motor, does not affect the current through the holding coil, because the two circuits are independent of each other.

Now a days automatic push button starters are also used in such starter the ON push button is pressed to connected the current limiting starting resistor in series with the armature circuit. These resistor are gradually disconnected by an automatic ocontrolling arrangement until full line voltage is available to the armature circuit with pressing the off button. The circuit is disconnected Automatic starter circuits have been developed using electromagnetic contactors and time delay relays. The automatic starters enable even an inexperienced operator to start and stop the motor without any difficulty.

39. Conductor radius = $\frac{1.9}{2}$ cm = 0.95 cm

Spacing of conductors,

$$d = 3.81 \text{ m} = 381 \text{ cm}$$

Dielectric strength of air,

g_0 = 21.1 kV/cm (rms) as assumed

Air density factor,

$$\delta = \frac{3.92b}{273+t} = \frac{3.92\times73.7}{273+44} = 0.91$$

Irregularity factor, m_0 = 0.85 (assumed)

Critical disruptive voltage to neutral,

$$V_{d0} = g_0\delta m_0 r \log_e\frac{d}{r}$$

$$= 21.1 \times 0.91 \times 0.85 \times 0.95 \log_e\frac{381}{0.95} = 92.94 \text{ kV (rms)}$$

Line-to-line disruptive critical voltage

$$= \sqrt{3} \times 92.94 = 160.97 \text{ kV}$$

Visual critical voltage to neutral (fine weather)

$$V_{v0} = g_0\delta m_v r\left[1+\frac{0.3}{\sqrt{\delta r}}\right]\log_e\frac{d}{r}$$

$$= 21.1\times0.91\times0.8\times 0.95\left(1+\frac{0.3}{\sqrt{0.91\times0.95}}\right)\log_e\frac{381}{0.95}$$

$$= 115.7 \text{ kV}$$

Line-to-line visual critical voltage (fine weather)

$$= \sqrt{3} \times 115.7 = 200 \text{ kV}$$

Line-to-line visual critical voltage (rough weather)

$$= \frac{0.66}{0.8}\times200 = 165 \text{ kV}$$

OOO