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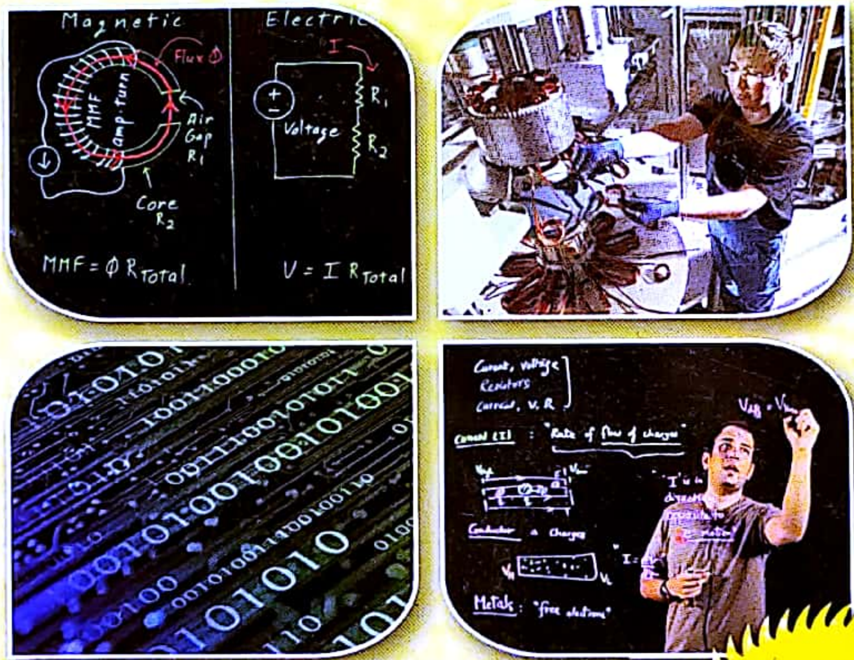
Semester - 4 Electrical & Electronics Engineering

Electrical Machines-I



Session 2019-20 Even Semester

- Topic-wise coverage of entire syllabus in Question-Answer form.
- Short Questions (2 Marks)

Includes solution of following AKTU Question Papers:
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KEE 403 : ELECTRICAL MACHINES - I

1 UNIT

Principles of Electromechanical Energy Conservation

CONTENTS

PART-1

Pre-Requisites : Magnetic Materials and BH Characteristics.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 1.1. **Write short notes on the following :**

A. Diamagnetic
B. Paramagnetic
C. Ferromagnetic
D. Antiferromagnetic
E. Ferrimagnetic

Answer

A. Diamagnetic : When a diamagnetic material is placed in a magnetic field, it becomes weakly magnetized in a direction opposite to the direction of external magnetic field. This property of material is known as diamagnetism.

B. Paramagnetic :

1. In paramagnetic materials the magnetic dipoles are already present. These materials are permanently magnetized but dipoles are randomly oriented and have a low net magnetism.
2. When these materials are placed in external magnetic field, the dipoles orient themselves in the direction of external magnetic field. This property is known as paramagnetism.

C. Ferromagnetic : When a ferromagnetic material is placed in external magnetic field, it strongly attracts the magnetic lines of force and the domains orient themselves in the direction of the field to increase the flux produced by the external field. This property is known as ferromagnetism.

D. Antiferromagnetic :

1. In antiferromagnetic material the atomic magnetic dipoles line up antiparallel to each other and cancel out exactly.
2. Therefore, these have no external magnetic field effects. This property is called antiferromagnetism.

E. Ferrimagnetic : In ferrimagnetic materials the atomic magnetic dipoles line up antiparallel to each other, but do not cancel out, because they have different magnetic dipole moments. The resultant magnetic moment may be quite large. This property is called ferrimagnetism.

Que 1.2. **Draw the *B-H* curve for a ferromagnetic material and identify the retentivity and the coercive field on the curve.**

Answer

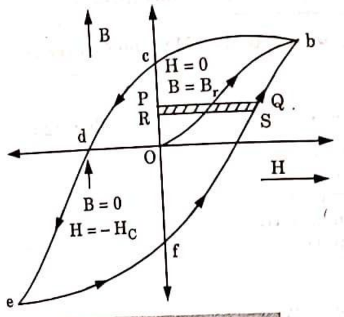


Fig. 1.2.1. Hysteresis loop.

i. Flux starts building up from the high as the value of magnetizing force *H* is increased from zero.

ii. In this range it is nearly proportional to *H* *i.e.*, the magnetic domains align themselves in direction of *H*.

iii. When *H* is further increased the rate of *B* falls and ultimately becomes zero and the flux density *B* reaches a maximum value or saturation.

iv. Now the maximum number of magnetic domains has aligned themselves in direction of *H* and no further alignment of domains is possible.

v. When the value of *H* reduced from saturation value to zero, the reduction of flux *B* does not follow the same path but is very slow.

vi. As *H* becomes zero there remains some amount of flux, *i.e.*, such domains orient themselves accordingly in the direction of *H* but some still remains in previous direction resulting in remanent flux density *B*. So the material remains magnetized even in absence of an external magnetic field *H*.

vii. **Residual magnetism :** It is defined as the magnetic flux density which still persists in magnetic material even when the magnetising force is completely removed.

viii. **Coercive force :** It is defined as demagnetizing force which is necessary to neutralize completely the magnetism in an electromagnet when the value of magnetizing force becomes zero.

PART-2

Introduction, Review of Magnetic System, Energy in Magnetic System, Force and Torque in Magnetic Field System, Energy Balance Equation, Energy Conversion via Electrical Field.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 1.3. **Explain how flow of energy takes place in electro-mechanical device ?**

AKTU 2014-15, Marks 05

OR

Explain the various phenomenon happening in electromechanical energy conversion in rotating electrical machines.

AKTU 2016-17, Marks 10

Answer

1. Electromechanical energy conversion is a reversible process.
2. This conversion process is not restricted to translatory devices but is equally applicable to rotatory devices.
3. Electrical and mechanical losses cause irreversible flow of energy out of a practical conversion device.
4. The flow of energy in electromechanical conversion in either direction along with irrecoverable energy losses is shown in Fig. 1.3.1.

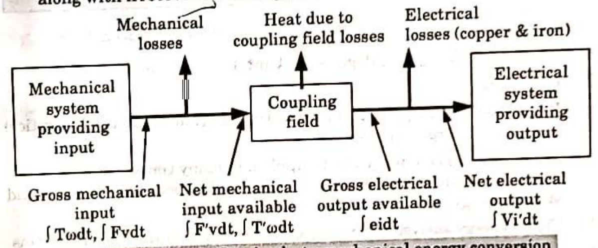


Fig. 1.3.1. Energy flow in electromechanical energy conversion device as a generator.

5. The energy balance equation for generator can be written as :

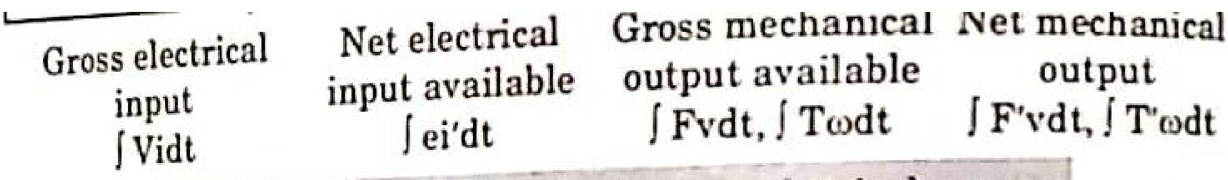


Fig. 1.3.2. Energy flow in electromechanical energy conversion device as a motor.

6. Energy balance equation for motor can be written as :
(Electrical energy input) = (Energy to electrical losses) + (Energy to field storage in the electrical system) + (Mechanical energy output)

Que 1.4. **What is energy ? Give its importance.**

Answer

A. Energy :

1. It is defined as the ability to perform work or cause change. The form of energy used in electrical machine is electricity.
2. **Importance of energy :** Energy (electricity) is the main input to the electrical machine which are the energy converting links between electrical and mechanical networks.

Que 1.5. **Define energy and co-energy.** **AKTU 2014-15, Marks 05**

Answer

A. Energy : Refer Q. 1.4, Page 1–5B, Unit-1.

B. Co-energy :

1. It is a non-physical quantity, measured in energy units, used in theoretical analysis of energy in physical systems.
2. The concept of co-energy can be applied to many conservative systems which can be described by a linear relationship between the input and stored energy.
3. The co-energy analysis techniques cannot be applied to non-linear systems.
4. $$W_f' + W_f = \lambda i$$

where W_f' = Co-energy

This expression gives the relation between energy and co-energy.

9. In the conversion, it is possible to apply the differential of $i\psi$

$$d(i\psi) = i d\psi + \psi\, di \quad ...(1.6.8)$$

Eq. (1.6.7) now yields

$$dW'_\phi(i, x) = d(i\,\psi) - dW_\phi(\psi, x) \quad ...(1.6.9)$$

10. By substituting equation (1.6.3) and (1.6.8) into (1.6.9) we obtain

$$dW'_\phi(i, x) = \psi\, di + F_\phi dx \quad ...(1.6.10)$$

11. The coenergy W'_ϕ is a function of two independent variables, i and x. This can be represented by partial derivatives

$$dW'_\phi(i, x) = \frac{\partial W'_\phi}{\partial i} di + \frac{\partial W'_\phi}{\partial x} dx \quad ...(1.6.11)$$

12. Eqs. (1.6.10) and (1.6.11) have to be equal at all values of di and dx. This gives us

$$\psi = \frac{\partial W'_\phi(i, x)}{\partial i}, \quad ...(1.6.12)$$

$$F_\phi = \frac{\partial W'_\phi(i, x)}{\partial x} \quad ...(1.6.13)$$

13. Eq. (1.6.13) gives a mechanical force directly from the current i and displacement x. The co-energy can be calculated with i and x

$$W'_\phi(i_0, x_0) = \int_0^i \psi(i, x_0)\, di$$

14. In a linear system, ψ and i are proportional, and the flux linkage can be represented by the inductance depending on the distance, as in eq. (1.6.1). The co-energy is

$$W'_\phi(i, x) = \int_0^i L(x)\, i di = \frac{1}{2} L(x) i^2 \quad ...(1.6.14)$$

15. From eq. (1.6.6) and (1.6.14), it is clear that expression for energy and co-energy is same.

Que 1.7. **Define energy and co-energy. What is the significance of co-energy ? Show that the field energy in a linear magnetic system is given by $W_f = \frac{1}{2}Li^2 = \frac{1}{2}\psi i = \frac{1}{2L}\psi^2$.**

AKTU 2018-19, Marks 07

Answer

i. **Energy and co-energy :** Refer Q. 1.5, Page 1–5B, Unit-1.

ii. **Proof :**

1. For a linear system field-energy

$$W_f = \frac{1}{2} i\psi = \frac{1}{2} iN\phi \quad ...(1.7.1)$$

$$W_f = \frac{1}{2} F\phi \quad [\because Ni = F]$$

2. Also mmf $\quad F = S\phi$

where $\quad S$ = Reluctance of magnetic path

3. $$W_f = \frac{1}{2} S\phi^2 \quad ...(1.7.2)$$

4. Coil inductance, $\quad L = \frac{\psi}{i}$

$$\therefore \quad i = \frac{\psi}{L} \quad ...(1.7.3)$$

5. Substituting value of i in eq. (1.7.1), we get

Energy, $$W_f = \frac{1}{2}\frac{\psi^2}{L} = \frac{1}{2}Li^2 = \frac{1}{2}\psi i \quad \text{(using eq. (1.7.3))}$$

Que 1.8. **Derive an expression for reluctance torque in a rotating electrical machine.**

AKTU 2016-17, Marks 05

AKTU 2018-19, Marks 07

Answer

Expression for reluctance torque :

1. The complex power output per phase

$$S_{1\phi} = V I_a^* \quad ...(1.8.1)$$

Taking E_f as the reference phasor

$$V = V\angle{-\delta} = V\cos\delta - jV\sin\delta$$

$$I_a = I_q - jI_d$$

$$I_a^* = I_q + jI_d$$

$$\therefore \quad S_{1\phi} = VI_a^* = (V\cos\delta - jV\sin\delta)(I_q + jI_d) \quad ...(1.8.2)$$

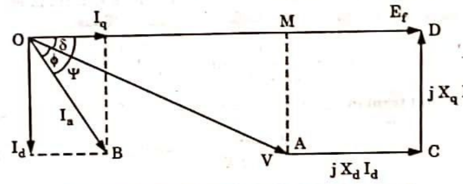


Fig. 1.8.1. Phasor diagram at lagging pf of a salient-pole generator, neglecting R_a.

2. From the phasor diagram of Fig. 1.8.1,

$$X_q I_q = CD = AM = V\sin\delta$$

$$\therefore \qquad I_q = \frac{V \sin \delta}{X_q}$$

3. $$X_d I_d = AC = MD = OD - OM = E_f - V \cos \delta \qquad ...(1.8.3)$$

$$\therefore \qquad I_d = \frac{E_f - V \cos \delta}{X_d} \qquad ...(1.8.4)$$

4. Substituting the values of I_q and I_d in eq. (1.8.2), we get

$$S_{1\phi} = (V \cos \delta - j V \sin \delta)\left(\frac{V \sin \delta}{X_q} + j \frac{E_f - V \cos \delta}{X_d}\right)$$

$$= \left[\frac{V E_f}{X_d} \sin \delta + \frac{V^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right) \sin 2\delta\right]$$

$$+ j\left[\frac{V E_f}{X_d} \cos \delta - \frac{V^2}{2 X_d X_q}\{(X_d + X_q) - (X_d - X_q) \cos 2\delta\}\right] \qquad ...(1.8.5)$$

5. Also, $$S_{1\phi} = P_{1\phi} + jQ_{1\phi} \qquad ...(1.8.6)$$

6. Therefore the real power per phase in watts is

$$P_{1\phi} = \frac{V E_f}{X_d} \sin \delta + \frac{V^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right) \sin 2\delta$$

7. Total real power in watts

$$P_{3\phi} = 3 P_{1\phi} = \frac{3 V E_f}{X_d} \sin \delta + \frac{3 V^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right) \sin 2\delta \qquad ...(1.8.7)$$

8. The electromagnetic torque or torque developed for a 3-phase synchronous machine is given by

$$\tau_{em} = \frac{3 P_{1\phi}}{\omega_m} = \frac{3}{2\pi n_s}\left(\frac{V E_f}{X_d} \sin \delta + \frac{X_d - X_q}{2 X_d X_q} \sin 2\delta\right) \qquad ...(1.8.8)$$

9. The resulting torque has two components. The first term in eq. (1.8.8) represents the torque τ_{exc} due to field excitation. Thus,

$$\tau_{exc} = \frac{3V E_f}{2\pi n_s X_d} \sin \delta \qquad ...(1.8.9)$$

10. The second term in eq. (1.8.8) is known as reluctance torque, τ_{rel}.

$$\therefore \qquad \tau_{rel} = \frac{3}{2 \pi n_s}\left(\frac{X_d - X_q}{2 X_d X_q}\right) \sin 2\delta \qquad ...(1.8.10)$$

PART-3

Energy in a Singly Excited System, Determination of the Force and Torque from Energy and Co-energy.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 1.9. **Explain magnetic field energy stored in singly excited magnetic system.**

OR

Describe in detail account on energy stored in magnetic system.

AKTU 2014-15, Marks 05

Answer

1. A considerable energy is stored in the magnetic field. This field acts as the energy-conversion medium and its energy is the reservoir between the electric and mechanical systems.
2. Consider the electromagnetic relay shown in Fig. 1.9.1. Initially the armature is in the open position. When switch 'S' is closed, current i is established in the N-turns coil.
3. The flux set up depends on mmf, Ni and the reluctance of the magnetic path.
4. The magnetic field thus produced, creates north and south poles as shown in Fig. 1.9.1 and as a result of it there establishes a magnetic force tending to shorten the air gap.
5. If the armature is not allowed to move, the mechanical work done, dW_{mech} is zero. Therefore

$$dW_{elec} = 0 + dW_{fld}$$

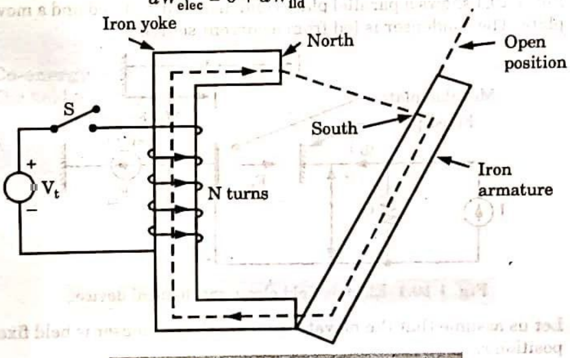


Fig. 1.9.1. Simple electromagnetic relay.

6. This shows that when the movable part of any physical system is kept fixed, the entire electrical energy input is stored in the magnetic field.

$$dW_{fld} = dW_{elec}$$

So, $dW_{fld} = dW_{elec} = id\lambda = Fd\phi$

7. If the initial flux is zero, then the magnetic field energy stored W_{fld} in establishing the flux or flux linkage λ is given by :

$$W_{fld} = \int_0^{\lambda} id\lambda = \int_0^{\phi} Fd\phi$$

8. The magnetic stored energy density w_{fld} is given by

$$w_{fld} = \frac{1}{2}HB = \frac{1}{2}\mu H^2 = \frac{1}{2}\frac{B^2}{\mu} \text{ joules/m}^3$$

where H = Magnetic-field intensity in ampere-turns per metre

μ = Permeability.

9. **Applications of singly excited system :**
   a. Used in electromagnets.
   b. Moving iron instruments in measurement of AC and DC.
   c. As reluctance motors.

Que 1.10. **Find an expression for the force per unit area between the plates of a parallel plate condenser in terms of the electric field intensity. Use both the energy and coenergy methods. Find the value of the force per unit area when $E = 3 \times 10^6$ V/m, the breakdown strength of air.**

AKTU 2017-18, Marks 07

Answer

A. **Energy method :**

1. Fig. 1.10.1 shows a parallel plate condenser with a fixed and a movable plate. The condenser is fed from a current source.

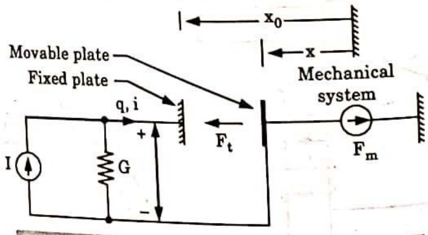


Fig. 1.10.1. Electric field electromechanical device.

2. Let us assume that the movable plate of the condenser is held fixed in position x.

3. The electric energy input to the condenser gets stored in the electric field so that

$$dW_e = vdq = dW_f \quad \text{...(1.10.1)}$$

The total field energy is

$$W_f = \int_0^q vdq$$

4. In a condenser v and q are linearly related as

$C = q/v$ = Capacitance of the device

$$\therefore \quad W_f = \frac{1}{2}\frac{q^2}{C} \quad \text{...(1.10.2)}$$

5. The capacitance C is a function of x (is the position of movable plate) and can be expressed as

$$C(x) = \frac{\varepsilon_0 A}{(x_0 - x)}$$

where A = Plate area

e_0 = Permittivity of free space.

6. Thus W_f, the field energy is a function of two independent variables q and x, *i.e.*,

$$W_f(q, x) = \frac{1}{2}\frac{q^2}{C(x)} \quad \text{...(1.10.3)}$$

$$= \frac{1}{2}\frac{q^2(x_0 - x)}{A\varepsilon_0}$$

7. $$F_f = -\frac{\partial W_f(q, x)}{\partial x} = \frac{1}{2}\frac{q^2}{A\varepsilon_0}$$

But $q = DA = \varepsilon_0 EA,$

$$F_f = \frac{1}{2}\varepsilon_0 E^2 A$$

$$\therefore \quad F_f/A = \frac{1}{2}\varepsilon_0 E^2 \quad \text{...(1.10.4)}$$

B. **Co-energy method :**

1. The field co-energy is

$$W'_f(v, x) = \frac{1}{2}Cv^2 = \frac{1}{2}v^2\frac{A\varepsilon_0}{(x_0 - x)}$$

2. Now, $$F_f = \frac{\partial W'_f(v, x)}{\partial x} = \frac{1}{2}v^2\frac{A\varepsilon_0}{(x_0 - x)^2}$$

But $v = E(x_0 - x)$

$$\therefore \quad F_f = \frac{1}{2}\varepsilon_0 E^2 A$$

$$\therefore \quad F_f/A = \frac{1}{2}\varepsilon_0 E^2 \quad \text{...(1.10.5)}$$

C. Numerical :

Given : $E = 3 \times 10^6$ V/m
To Find : F_f/A.

$$F_f/A = \frac{1}{2}\epsilon_0 E^2 = \frac{1}{2} \times (3 \times 10^6)^2 \times 8.85 \times 10^{-12}$$
$$= 39.8 \text{ N/m}^2$$

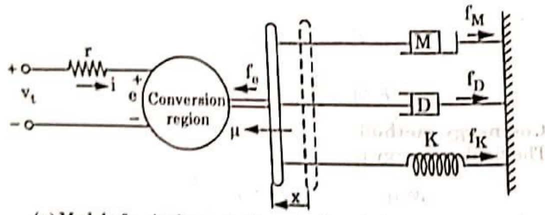
Que 1.11. **Derive an expression for dynamical equations of electromechanical systems.**

AKTU 2017-18, Marks 07

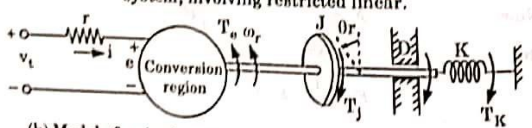
Answer

1. The electromechanical-energy-conversion devices operate with electrical system on one side and mechanical system on the other side.
2. Simple models of singly excited electro-mechanical systems are shown in Fig. 1.11.1(*a*) and (*b*).
3. **Voltage equations :** The voltage equation for the electrical system of both Fig. 1.11.1(*a*) and (*b*) is,

$$v_t = ir + \frac{d\phi}{dt} = ir + \frac{d}{dt}(Li)$$
$$= ir + L\frac{di}{dt} + i\left(\frac{dL}{d\theta_r}\right)\frac{d\theta_r}{dt}$$
$$= ir + L\frac{di}{dt} + i\left(\frac{dL}{d\theta_r}\right)\omega_r \quad ...(1.11.1)$$



(a) Model of a singly excited translational electromechanical system, involving restricted linear.



(b) Model of a singly excited rotational electromechanical system involving restricted rotary motion.

Fig. 1.11.1.

4. **Force equation :** In Fig. 1.11.1(*a*), the magnetic force f_e is opposed by inertia force f_M, damping force f_D and restraining spring force f_K. Therefore the force balance equation is

$$f_e = f_M + f_D + f_K = M\frac{du}{dt} + Du + K\int u\,dt$$

or
$$f_e = M\frac{d^2x}{dt^2} + D\frac{dx}{dt} + Kx \quad ...(1.11.2)$$

where, M = Mass in kgs
D = Coefficient of friction N/m/sec.
K = Linear spring constant in N/m
$u = \frac{dx}{dt}$, linear velocity in metres/sec.

5. **Torque equation :** In Fig. 1.11.1(*b*) the magnetic torque T_e is opposed by inertia torque T_J, damping torque T_D and restraining spring torque T_K. Therefore the torque-balance equation is

$$T_e = T_J + T_D + T_K = J\frac{d\omega_r}{dt} + D\omega_r + K\int \omega_r\,dt$$
$$T_e = J\frac{d^2\theta_r}{dt^2} + D\frac{d\theta_r}{dt} + K\theta_r \quad ...(1.11.3)$$

where, J = Moment of inertia in kg m^2
D = Damping constant in N-m per rad/sec.
K = Rotary spring constant in N-m per radian
$\omega_r = \frac{d\theta_r}{dt}$, angular velocity in rad/sec.

6. **Dynamic equation :** The dynamic equation for a rotating electric motor, from eq. (1.11.3) is

$$T_e = J\frac{d^2\theta_r}{dt^2} + D\frac{d\theta_r}{dt} + T_L$$

where T_L is the load torque opposing the magnetic torque T_e.

Que 1.12. **The magnetic flux density on the surface of an iron face is 1.6 T which is a typical saturation level value for ferromagnetic material. Find the force density on the iron face.**

AKTU 2014-15, Marks 05

AKTU 2017-18, Marks 07

Answer

Given : $B = 1.6$ T
To Find : Force per unit area, f_e/A (Force density).

1. The mechanical force due to field is

$$f_e = -\frac{\partial W_f(B,x)}{\partial x} = -\frac{1}{2}\frac{B^2 A}{\mu}$$

2. The force per unit area is

$$f_e/A = \frac{1}{2}\frac{B^2}{\mu} = \frac{1}{2} \times \frac{(1.6)^2}{4\pi \times 10^{-7}} = 1.02 \times 10^6 \text{ N/m}^2$$

PART-4

Generation of EMF in Machines, Torque in Machine with Cylindrical Air Gap.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 1.13. Write short notes on generated EMF in machines.

Answer

Generated EMF in machines :

1. In rotating electrical machines the generation of emf is due to relative motion between field and armature winding flux.
2. The flux linkage λ with the full-pitch N-turn armature coil, at any time t, are :

$$\lambda = N \text{ (flux passing through the coil at any time } t)$$
$$= N\phi \cos \omega_r t$$

3. By Faraday's law, the emf induced in N-turn armature coil is given by

$$e = \frac{d\lambda}{dt} = N\phi\omega_r \sin \omega_r t - N\frac{d\phi}{dt}\cos \omega_r t \quad ...(1.13.1)$$

4. In eq. (1.13.1), $N\phi\omega_r \sin \omega_r t$ is the speed-voltage term, because it contains speed ω_r in it. The second term $N\frac{d\phi}{dt}\cos \omega_r t$ is the transformer-voltage term, because it involves the time derivative of the flux ϕ.

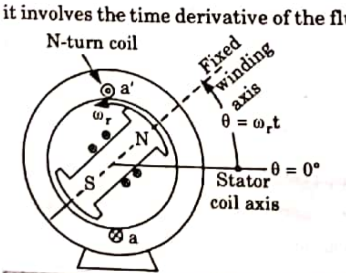


Fig. 1.13.1. Rotating electrical machine.

5. If the field flux ϕ is time-invariant, the transformer emf in eq. (1.13.1) reduces to zero and the generated emf is equal to the speed voltage alone.
6. Thus for electrical machines with time invariant flux, the generated emf is equal to the speed, rotational or motional emf alone and is given by

$$e = N\omega_r\phi \sin \omega_r t \quad ...(1.13.2)$$

where N = Number of turns in single full pitched coil
ϕ = Total flux per pole
ω_r = Relative velocity between field flux wave and armature coil.

7. If the single N-turn coil belongs to AC machines, then the maximum value of the speed or generated emf, E_{max} occurs when $\sin \omega_r t = 1$.

$$\therefore \quad E_{max} = \omega_r N\phi = 2\pi f_r N\phi$$

8. The rms value of the generated emf in a full pitched coil is

$$E = \frac{E_{max}}{\sqrt{2}} = \sqrt{2}\pi f_r N\phi = 4.44 f_r N\phi \quad ...(1.13.3)$$

where f_r = Rotational or speed frequency.

Que 1.14. An electrical machine has cylindrical stator and salient pole rotor. Justify the correctness of the following statement :

i. Reluctance torque is produced when exciting winding is on rotor.

ii. When stator and rotor both carry exciting winding, electromagnetic as well as reluctance torque are produced.

AKTU 2015-16, Marks 10

Answer

i.

1. The total torque developed by the doubly excited magnetic system is given by

$$T_e = \frac{1}{2}i_s^2\frac{dL_s}{d\theta_r} + \frac{1}{2}i_r^2\frac{dL_r}{d\theta_r} + i_s i_r\frac{dM_{sr}}{d\theta_r} \quad ...(1.14.1)$$

2. In Fig. 1.14.1, if $i_r = 0$, then from eq. (1.14.1)

$$T_e = \frac{1}{2}i_s^2\frac{dL_s}{d\theta_r}$$

3. The torque can be developed, because the reluctance seen by the stator-produced flux changes with rotor position. A change of reluctance varies the stator self-inductance L_s with θ_r.
4. If $\quad i_s = 0$, then $T_e = \frac{1}{2}i_r^2\frac{dL_r}{d\theta_r}$

5. The torque can be developed because L_r is a function of rotor position.
6. Hence, the reluctance torque is independent of excitation.

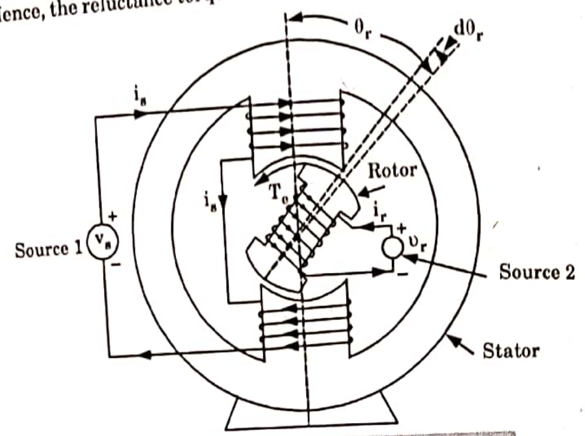


Fig. 1.14.1. Doubly-excited magnetic system.

ii. **Expression for magnetic torque for doubly excited system :**

1. Expression of torque, when both stator and rotor carry exciting winding, is given as :

$$T_e = \frac{1}{2} i_1^2 \frac{dL_1}{d\theta_m} + \frac{1}{2} i_2^2 \frac{dL_2}{d\theta_m} + i_1 i_2 \frac{dM}{d\theta_m} \quad ...(1.14.2)$$

2. The first two terms on the right-hand side of eq. (1.14.2) represent torques produced in the machine because of variation of self-inductance with rotor position. This component of torque is called the reluctance torque.
3. The third term represents torque produced by the variation of the mutual inductance between the stator and rotor windings. This component is called electromagnetic torque.

VERY IMPORTANT QUESTIONS

Following questions are very important. These questions may be asked in your SESSIONALS as well as UNIVERSITY EXAMINATION.

Q. 1. Explain how flow of energy takes place in electro-mechanical device ?

Ans. Refer Q. 1.3.

Q. 2. Define energy and co-energy.

Ans. Refer Q. 1.5.

Q. 3. Define energy and co-energy. What is the significance of co-energy ? Show that the field energy in a linear magnetic system is given by $W_f = \frac{1}{2}Li^2 = \frac{1}{2}\psi i = \frac{1}{2L}\psi^2$.

Ans. Refer Q. 1.7.

Q. 4. Derive an expression for reluctance torque in a rotating electrical machine.

Ans. Refer Q. 1.8.

Q. 5. Explain magnetic field energy stored in singly excited magnetic system.

Ans. Refer Q. 1.9.

Q. 6. Derive an expression for dynamical equations of electromechanical systems.

Ans. Refer Q. 1.11.

Q. 7. The magnetic flux density on the surface of an iron face is 1.6 T which is a typical saturation level value for ferromagnetic material. Find the force density on the iron face.

Ans. Refer Q. 1.12.

Q. 8. An electrical machine has cylindrical stator and salient pole rotor. Justify the correctness of the following statement :

i. Reluctance torque is produced when exciting winding is on rotor.

ii. When stator and rotor both carry exciting winding, electromagnetic as well as reluctance torque are produced.

Ans. Refer Q. 1.14.

☺☺☺

2 UNIT

DC Machines-I

CONTENTS

PART-1

Pre-Requisites : Principles and Construction, Classification and Circuit Model, EMF Equation of Generator and Torque Equation of Motor.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 2.1. Discuss the constructional details and working principles of DC machines.

Answer

A. **Constructional features :**

a. **Stator part :**

1. **Yoke :** For large DC machine, yoke is made by fabricated steel. Yoke has two functions :
   i. It provides path for the pole flux and carries half of it, *i.e.*, $\phi/2$.
   ii. It provides mechanical support to the whole machine.
2. **Field poles :** It consists of pole core and pole shoe. The pole core is made from thick (1.5 mm) cast steel but the pole shoe is laminated and fixed to the pole core appropriately. Pole shoes provide mechanical strength and support to the field winding.
3. **Field winding :** The pole is excited by a winding wound around the pole core, called field winding or exciting winding. It is prepared from copper.
4. **Interpole :** These are fixed to the yoke in between the main poles of a DC machine.
5. **Compensating winding :** To eliminate the effect of armature reaction compensating winding is used for only large DC machine.
6. **Brushes :** Brushes are made of carbon for small DC machine and electro-graphite brushes are used for all DC machine.

   These are housed in box type brush holder attached to the stator end covers or yoke. A small spring keeps the brushes pressed on the commutator surface.

b. **Rotor part :**

1. **Armature core :** It is made from 0.35 to 0.50 mm thick lamination of silicon steel to keep down the iron losses.

   It serves the two purposes :

i. Housing the armature coils in the slots.
ii. Providing the low reluctance path to the magnetic flux $\phi/2$.

2. **Armature winding :** The armature winding is made from copper. It consists of large number of insulated coils, each having one or more turns. There are basically two winding types :
   a. Lap winding
   b. Wave winding
3. **Commutator :**
   i. Alternating voltage is produced in a coil rotating in a magnetic field.
   ii. To obtain direct current in the external circuit a commutator is needed.
   iii. The commutator, which rotates with the armature, is made from a number of wedge-shaped hard-drawn copper bars or segments insulated from each other and from the shaft.
4. **Shaft :** Hub of commutator and spider in big machine or armature core in small machine and bearings are mounted on shaft. End covers are connected to the yoke on one side and to the bearings and shaft on the other side.

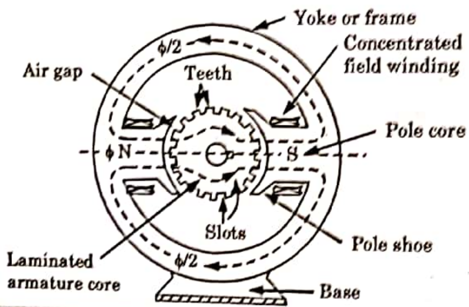


Fig. 2.1.1. Constructional features of a 2-pole DC machine.

B. Working principle of DC machine :

1. The stator has salient poles, excited by one or more field coils. The air gap flux distribution created by field windings is symmetric about field axis or direct axis.
2. When the armature conductors conduct current as shown in Fig. 2.1.2, a magnetic field is induced vertically upwards along the quadrature axis.
3. Thus the two fields interact to produce an electromagnetic torque in anticlockwise direction (as like poles repel and unlike poles attract).

4. In case of motor, the rotation direction is the same as that of electromagnetic torque *i.e.*, anticlockwise given by Fleming's left hand rule.

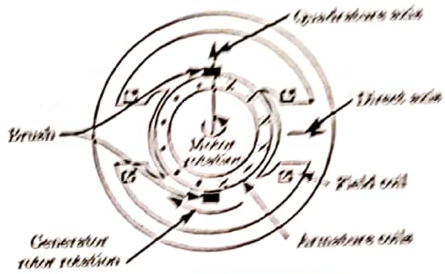


Fig. 2.1.2. DC machine.

5. Whereas, in case of generator, the turbine rotates against the electromagnetic torque *i.e.*, in clockwise direction given by Fleming's right hand rule.

Que 2.2. Discuss the constructional details and working principle of DC machines with interpole and compensating winding. Also mention the types of DC machines.

Answer

A. The constructional detail and working principle :
Refer Q. 2.1, Page 2–2B, Unit-2.

B. Types of DC machine : Depending on methods of excitation the DC machines are classified into two groups :

1. **Separately excited DC machine (generator/motor) :**

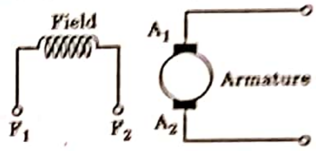


Fig. 2.2.1. Separate excitation.

2. **Self excited DC machine :** It can be further categorized as :
   a. **Shunt excitation of DC shunt machine :** If field winding and armature winding is connected in parallel, the machine is known as DC shunt machine.

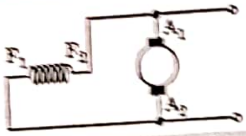


Fig. 2.2.2. DC shunt machine.

b. **Series excitation of DC series machine :** If field winding is connected in series with the armature winding, the DC machine is known as DC series machine.

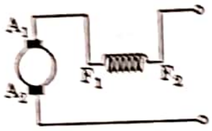


Fig. 2.2.3. DC series machine.

c. **Compound excitation or DC compound machine :** If both series and shunt field windings are present, along with the armature winding, the machine is known as DC compound machine.

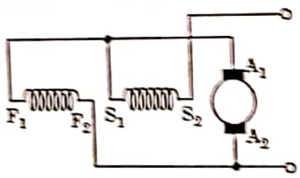


Fig. 2.2.4. DC compound machine.

Que 2.3. **Derive an expression for the emf generated in the armature winding of a DC machine.** **AKTU 2014-15, Marks 10**

OR

Derive the emf equation for a DC generator.

AKTU 2016-17, Marks 05

Answer

1. Let
   P = Number of poles
   ϕ = Flux per pole
   N = Speed of rotation
   Z = Number of conductors around the armature
   A = Number of parallel paths
2. The time taken by the armature for one revolution

$$= \frac{1}{N} \text{ min} = \frac{60}{N} \text{ sec}$$

3. Hence, time taken by each armature conductor to move through one pole pitch

$$t = \frac{60}{N} \times \frac{1}{P} \text{ sec}$$

4. During this period, the conductor cuts all the flux ϕ, produced by the pole and the average emf induced per conductor

$$= \phi \times \frac{NP}{60} = \frac{\phi NP}{60} \text{ volts/conductor}$$

5. The emf of a DC generator

$$E = \text{(emf induced per conductor)} \times \text{(number of conductors per parallel path)}$$

$$= \frac{\phi NP}{60}\left(\frac{Z}{A}\right) = \frac{\phi ZNP}{A \times 60} = \frac{\phi ZPn}{A} \text{ volts}$$

where n is rps.

6. For a given DC generator, P, Z and A are fixed and hence E is proportional to ϕ and n (*i.e.*, $E \propto \phi n$).

Que 2.4. **Derive an expression for the torque developed in the armature of a DC motor.** **AKTU 2014-15, Marks 10**

OR

Derive the EMF equation and torque equation for DC machines.

AKTU 2017-18, Marks 07

Answer

A. **EMF generation :** Refer Q. 2.3, Page 2–5B, Unit-2.

B. **Torque developed :**

1. Torque is the turning moment of a force about an axis.
   T = Force × Distance between force and axis about which rotor rotates.
   $T = F \times r$
2. Consider a pulley of radius 'r' meters acted upon by a circumferential force of 'F' Newton which causes it to rotate at N rpm.
3. Now work done by this force in one revolution
   = Force × Distance = $F \times 2\pi r$ joule
4. Power developed, $P = F \times 2\pi r \times N$ joule/sec or watts
   $= (F \times r) \times 2\pi N$ watts
   where $2\pi N$ = Angular velocity ω in radian/sec
5. ∴ Power developed, $P = T\omega$

Torque, $T = \left(\frac{P}{\omega}\right)$

6. Let T_a = Torque developed by armature of a motor running at N rpm.
Now power developed = $T_a \times 2\pi N$ watts

7. Electrical power converted into mechanical power in the armature $= E_b I_a$ watts

$$T_a \times 2\pi N = E_b I_a$$

$$E_b = \phi Z N \times \left(\frac{P}{A}\right) \text{ volts}$$

$$T_a \times 2\pi N = \phi Z N \left(\frac{P}{A}\right) I_a$$

$$T_a = \frac{1}{2\pi} \phi Z I_a \left(\frac{P}{A}\right)$$

$$= 0.159 \phi Z I_a \left(\frac{P}{A}\right) \text{ N-m} \qquad ...(2.4.1)$$

8. Also, $T_a = \frac{E_b I_a}{2\pi N}$

where N is in rpm. $T_a = \frac{E_b I_a}{2\pi \frac{N}{60}} = \frac{60}{2\pi} \frac{E_b I_a}{N}$

$$T_a = 9.55 \frac{E_b I_a}{N} \text{ N-m} \qquad ...(2.4.2)$$

Eq. (2.4.1) and (2.4.2) both represent torque equation for DC motor.

Que 2.5. **A 4-pole DC shunt generator with wave connected armature has field and armature resistance of 90 Ω and 0.15 Ω. It supplies power to 25 lamps rated at 100 V, 60 W each, calculate the armature current and emf generated neglecting brush drop.**

AKTU 2015-16, Marks 05

Answer

Given : Field resistance, R_{sh} = 90 Ω; Armature resistance, R_a = 0.15 Ω; V_t = 100 V; Power for each lamp, P = 60 W.
To Find : Armature current, I_a and emf generated, E_g.

1. $P = VI$

$\therefore$ $I = \frac{P}{V} = \frac{60}{100} = 0.6 \text{ A}$

2. Such 25 lamps are used as a load.

$$I_L = 25 \times I = 25 \times 0.6 = 15 \text{ A}$$

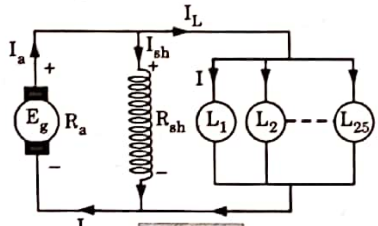


Fig. 2.5.1.

3. $I_{sh} = \frac{V}{R_{sh}} = \frac{100}{90} = 1.1 \text{ A}$

4. Armature current, $I_a = I_L + I_{sh} = 15 + 1.1 = 16.1 \text{ A}$

5. Emf, $E_g = V_t + I_a R_a = 100 + (16.1 \times 0.15)$
$= 100 + 2.415 = 102.415 \text{ V}$

PART-2

Armature Winding (Concentrated and Distributed), Winding Factor, Armature Reaction, Commutation, Interpoles and Compensating Windings.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 2.6. **Discuss about concentrated and distributed winding.**

Answer

A. Concentrated winding :

1. In AC machines there are certain number of slots per pole available to place to the place winding for each phase. But if the winding per phase is placed in a single slot per pole then it is called concentrated winding.
2. Depending upon the total number of slots and number of poles, certain no. of slots per phase available under each pole. This is denoted as 'm'.

m = Slots per pole per phase = n / number of phases
= n/3 (generally number of phases is 3)

3. In concentrated winding all conductors or coils belonging to a phase are placed in one slot under every pole.

B. Distributed winding :

1. In practice, an attempt is always made to use all the '*m*' slots per pole phase available for distribution of the winding.
2. If '*x*' conductors per phase are distributed amongst the 3-slots per phase available under every pole, the winding is called distributed winding.
3. In distributed type of winding all the coil belonging to a phase are well distributed over the '*m*' slots per phase, under every pole.

Que 2.7. **Explain the following terms in conjunction with electric machines :**

A. Pitch Factor (K_p)
B. Distribution Factor (K_d)
C. Winding Factor (K_w)

Answer

A. Pitch factor :

1. The coil span-factor or pitch-factor K_p is defined as the ratio of the voltage generated in the short-pitch coil to the voltage generated in the full-pitch coil. The coil span-factor is also called the chording factor.

$$K_p = \frac{\text{Actual voltage generated in the coil}}{\text{Voltage generated in the coil of span } 180° \text{ electrical}}$$

$$= \frac{\text{Phasor sum of the voltages of two coil sides}}{\text{Arithmetic sum of the voltage of two coil sides}}$$

$$= \frac{AC}{2AB} = \frac{2AD}{2AB} = \cos\frac{\alpha}{2}$$

$$\therefore \quad K_p = \cos\frac{\alpha}{2}$$

2. For full-pitch coil, $\alpha = 0°$, $\cos\frac{\alpha}{2} = 1$ and $K_p = 1$. For a short-pitch coil $K_p < 1$.

ii. Distribution factor :

1. The distribution factor or breadth factor is defined as the ratio of the actual voltage obtained to the possible voltage if all the coils of a polar group were concentrated in a single slot.

$$K_d = \frac{\text{Phasor sum of coil voltages per phase}}{\text{Arithmetic sum of coil voltage per phase}}$$

$$K_d = \frac{\sin m\beta/2}{m \sin \beta/2} \quad ...(2.7.1)$$

2. Let m = Slots per pole per phase

$$m = \frac{\text{Slots}}{\text{Poles} \times \text{Phases}}$$

β = Angular displacement between adjacent slots in electrical degrees

$$\beta = \frac{180°}{\text{Slots/ Pole}} = \frac{180° \times \text{Poles}}{\text{Slots}}$$

iii. Winding factor : The coil span factor and distributed factor of a winding are sometimes combined into a single winding factor K_w which is the product of K_p and K_d. That is,

$$K_w = K_p K_d$$

Que 2.8. **Calculate the number of conductor on each pole piece required in a compensating winding for a 4-pole, lap wound DC armature containing 136 conductors. The pole arc to pole pitch ratio is 0.9. The compensating winding carries full armature current.**

AKTU 2018-19, Marks 07

Answer

Given : Pole arc/pole pitch = 0.9, $P = 4$, $A = 4$, $Z = 136$
To Find : Z_{CW}

Compensating winding conductor

$$Z_{CW} = \frac{\text{Pole arc}}{\text{Pole pitch}} \times \frac{Z}{AP} = 0.9 \times \frac{136}{4 \times 4}$$

$$Z_{CW} = 7.65 \text{ or } 8$$

Que 2.9. **Discuss armature reaction in DC machine.**

Answer

1. Armature reaction is the effect of magnetic flux set up by armature current upon the distribution of flux under the main poles.
2. Fig. 2.9.1 shows a 2-pole DC generator. When there is no-load connected to the generator, the current in the armature conductors is zero.
3. Under these conditions there exists in it only the mmf of the main poles which produce the main flux ϕ. This flux is distributed symmetrically with respect to the polar axis, that is, the centre line of the north and the south poles.
4. Fig. 2.9.2 shows armature conductors carrying current with no current in field coils. The current flows in the same direction in all the conductors lying under one pole.

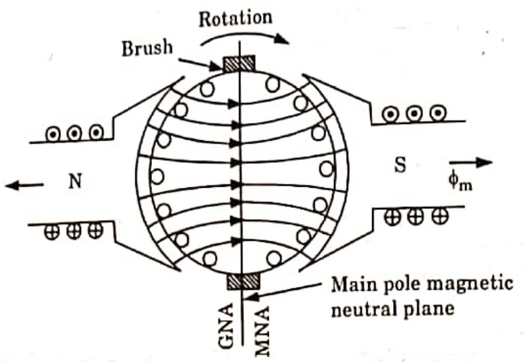


Fig. 2.9.1. Main pole magnetic flux distribution.

5. The conductors on the left-hand side of the armature carry current in the direction into the paper. The flux produced by current in these armature conductors is shown in Fig. 2.9.2. These conductors combine their mmfs to produce a flux through the armature in the downward direction.
6. Similarly, the conductors on the right-hand side of the armature carry current in the direction out of the paper. These conductors also combine their mmfs to produce a flux through the armature in the downward direction.
7. Thus, the conductors on both sides of the armature combine their mmfs in such a manner as to send a flux through the armature in the downward direction. This flux ϕ_A is represented by an arrow as shown in Fig. 2.9.2.

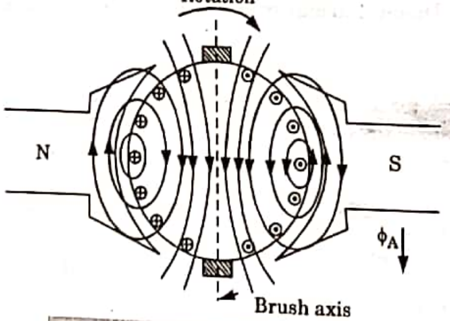


Fig. 2.9.2. Armature flux distribution.

8. Fig. 2.9.3 shows the condition when the field current and armature current are acting simultaneously. This occurs when the generator is on load.

9. Now there are two fluxes inside the machine, one produced by the main field poles of the generator and the other by the current in the armature conductors. These two fluxes now combine to form a resultant flux ϕ_R as shown in Fig. 2.9.3.
10. It is seen that the field flux entering the armature is not only shifted but also distorted. The distortion produces crowding of the flux (increase in the flux density) in the upper pole tip in the *N*-pole and in the lower pole tip in the *S*-pole.

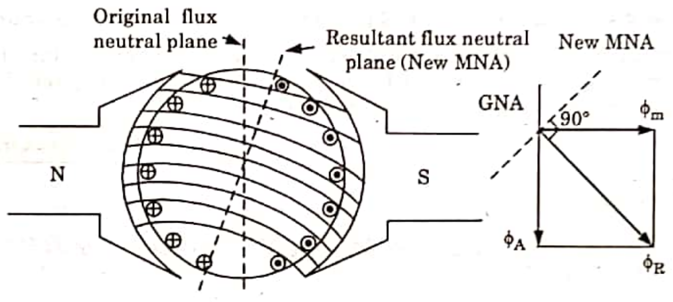


Fig. 2.9.3. Resultant flux distribution.

Similarly, there is a reduction of flux (decreased flux density) in the lower tip of the *N*-pole and in the upper pole tip of the *S*-pole.

11. The direction of the resultant flux has shifted in the direction of rotation of the generator. Since the MNA is always perpendicular to the axis of the resultant flux, the MNA is also shifted.

Que 2.10. **Explain the effects of armature reaction on the operation of a DC machine. How the effects of armature reactions can be minimized ?**

AKTU 2014-15, Marks 10

Answer

A. Effects of armature reactions :

i. The armature mmf produces two undesirable effects on the main field flux and these are :
1. Net reduction in the main field flux per pole.
2. Distortion of the main field flux wave along the air gap periphery.

ii. The net effect of armature flux on the main-field flux is :
1. Distort the main field flux thereby causing non-uniform distribution of flux under the main poles.
2. Shift the MNA in the direction of rotation for a generator and against the direction of rotation for a motor.

3. Reduce the main field flux from its no-load value due to magnetic saturation.

B. Methods of limiting the effects of armature reaction :

1. High-reluctance pole tips
2. Strong main-field flux
3. Interpoles
4. Compensating winding.

Que 2.11. **A 250 kW, 400 V, 6-pole DC generator has 720 lap wound conductors. It is given a brush lead of 2.5 angular degrees (mech.) from the geometric neutral. Calculate the cross and demagnetizing turns per pole. Neglect the shunt field current.**

AKTU 2017-18, Marks 07

Answer

Given : Power = 250 kW, $P = 6$, $V = 400$ V, $Z = 720$, $\theta_m = 2.5°$
To Find : AT_d/pole and AT_c/pole.

1. Output current,

$$I_a = \frac{250000}{400} = 625 \text{ A}$$

2. And $I = \frac{625}{6} = 104.17$ A

3. De-magnetizing ampere turns/pole, $\frac{AT_d}{\text{Pole}}$

$$= \frac{\theta_m}{360} ZI = \frac{2.5}{360} \times 720 \times 104.17 = 520.85 \text{ AT}$$

4. Cross-magnetizing ampere turns per pole, $\frac{AT_c}{\text{Pole}}$

$$= ZI\left(\frac{1}{2P} - \frac{\theta_m}{360}\right) = 720 \times 104.17\left(\frac{1}{2 \times 6} - \frac{2.5}{360}\right) = 5729.35 \text{ AT}$$

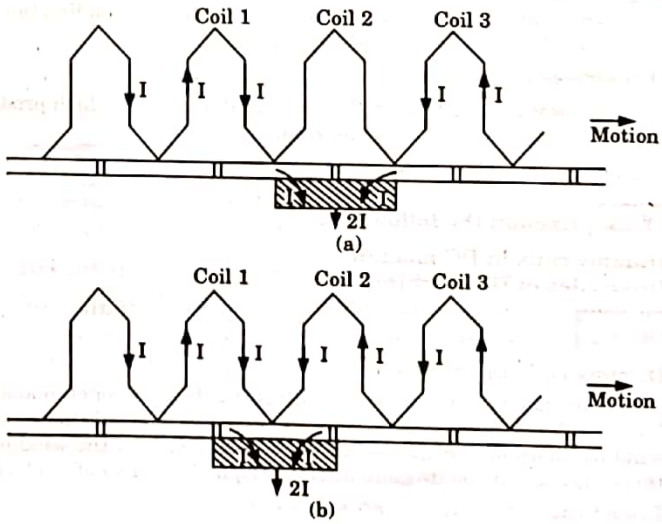
Que 2.12. **Explain the "Commutation Process" in DC machines. What are the significance and drawbacks of commutation process in DC machine ? Explain in brief.**

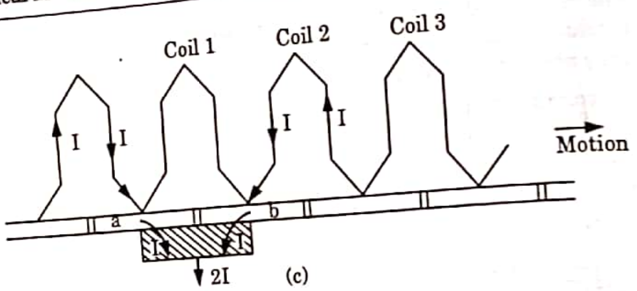
Answer

A. Working principle of commutator :

1. The currents induced in the armature conductors of a DC generator are alternating in nature. The commutation process involves the change from a generated alternating current to an externally applied direct current.

2. These induced currents flow in one direction when the armature conductors are under north pole. They are in opposite direction when they are under south pole.
3. As conductors pass out of the influence of north pole and enter the south pole, the current in them is reversed.
4. The reversal of current takes place along the MNA or brush axis. Whenever a brush spans two commutator segments, the winding element connected to those segments is short circuited.
5. By commutation we mean the change that take place in a winding element during the period of short circuit by a brush.
6. These changes are shown in Fig. 2.12.1. For simplicity, consider a simple ring winding.
7. In position shown in Fig. 2.12.1(*a*), the current *I* flowing towards the brush from the left-hand side pass round the coil in a clockwise direction.
8. In position shown in Fig. 2.12.1(*b*), this coil carries the same current in the same direction, but the coil is to short circuited by the brush.
9. In position shown in Fig. 2.12.1(*c*), the brush makes contact with bars *a* and *b*, thereby short circuiting coil 1. The current is still *I* from the left-hand side and *I* from the right-hand side.
10. Fig. 2.12.1(*d*) shows that bar *b* has just left the brush and the short circuit of coil 1 has ended. It is now necessary for the current *I* reaching the brush from the right-hand side in the anticlockwise direction.





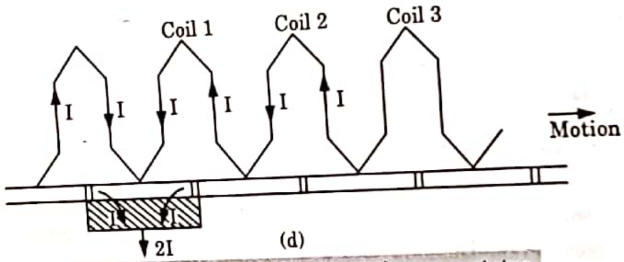


Fig. 2.12.1. Current collection at the commutator.

11. Hence, during period of short-circuit of armature coil by brush the current in that coil is reversed and also brought upto its full value in reverse direction.

B. **Significance :** The current induced in the armature conductor of DC machine are alternating in nature. To make their flow unidirectional in the external circuit, a commutator is required.

C. **Drawbacks :**

1. It produces wear and tear on the commutator surface which produces sparks due to uneven current distribution.
2. It produces high amount of losses.

Que 2.13. **Explain the following :**

i. **Dummy coils in DC machine.**
ii. **Interpoles in DC machine.**

Answer

i. **Dummy coils in DC machine :**

1. The wave winding is possible only with particular number of conductors but sometimes the standard armature punching available in armature winding shops do not meet with the requirements of the winding as these may accommodate more than the required number of conductors.
2. In such cases, dummy coils are employed.

3. These coils are placed in slots to preserve the balance of machine but not electrically connected to the rest of the winding. The ends of dummy coil are taped and are not connected to the commutator segment.

ii. **Interpoles in DC machine :**

1. Interpoles are placed in between the main poles in order to neutralize the effects of armature reaction in brush region and minimize sparking at brushes.
2. Interpoles generate voltage necessary to neutralize the emf of self-induction in the armature coils undergoing commutation.
3. Motor interpoles have a polarity opposite to that of the following main pole in the direction of rotation of armature.
4. Since the interpoles are connected in series with the armature, the change in direction of current in the armature changes the polarity of the interpole.
5. Thus, a DC machine that has correct interpole polarity when used as a generator will have the correct interpole polarity when used as a motor.

Que 2.14. **Discuss in detail the phenomenon of commutation in DC machine and also explain the methods adopted to improve commutation.**

AKTU 2014-15, Marks 10

OR

Explain the commutator action in DC machine. Also describe the ways for achieving good commutation.

AKTU 2015-16, Marks 05

OR

Explain commutator action in DC machines. Also describe two ways of achieving good commutation and compare them.

AKTU 2018-19, Marks 07

Answer

A. **Commutation in DC machine :** Refer Q. 2.12, Page 2–13B, Unit-2.

B. **Methods of improving commutation :**

1. **Resistance commutation :**

i. This method of improving commutation consists of using carbon brushes.
ii. This makes the contact resistance between commutator segments and brushes high.
iii. This high contact resistance has the tendency to force the current in the short-circuited coil to change according to the commutation requirements, to reverse and then build up in the reversed direction.

Voltage commutation :

In this method, arrangement is made to induce a voltage in the coil undergoing commutation, which will neutralize the reactance voltage.

i. This injected voltage is in opposition to the reactance voltage.

ii. If the value of the injected voltage is made equal to the reactance voltage, quick reversal of current in the short-circuited coil will take place and there will be sparkless commutation.

iv. Two methods may be used to produce the injected voltage in opposition to the reactance voltage :

a. Brush shift.

b. Commutating poles or interpoles.

3. **Compensating winding :**

i. Compensating windings are the most effective means for eliminating the problems of armature reaction and flashover by balancing the armature mmf.

ii. Compensating windings are placed in slots provided in pole faces parallel to the rotor (armature) conductors.

iii. These windings are connected in series with the armature windings.

iv. The direction of currents in the compensating winding must be opposite to that in the armature winding just below the pole faces. Thus, compensating winding produces an mmf that is equal and opposite to the armature mmf.

v. In effect the compensating winding demagnetizes or neutralizes the armature flux produced by the armature conductors lying just under the pole faces. The flux per pole is then undisturbed by the armature flux regardless of the load conditions.

C. **Comparison :**

S. No.	Resistance commutation	Voltage commutation
1.	This method consists of carbon brushes which makes the contact resistance high. This high contact resistance has the tendency to force the current in the short circuit coil to change according to commutation requirements.	In this method a voltage is induced which neutralizes the reactance voltage. This voltage is equal and opposite to the reactance voltage. This gives sparkless commutation.

PART-3

Performance Characteristics of DC Generators, Applications.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 2.15. **Explain the characteristics of a separately excited DC generator with its circuit diagram.**

Answer

1. In the separately excited DC generator, the field winding is connected to a separate source of DC power.
2. The circuit for a separately excited DC generator on load is shown in Fig. 2.15.1.

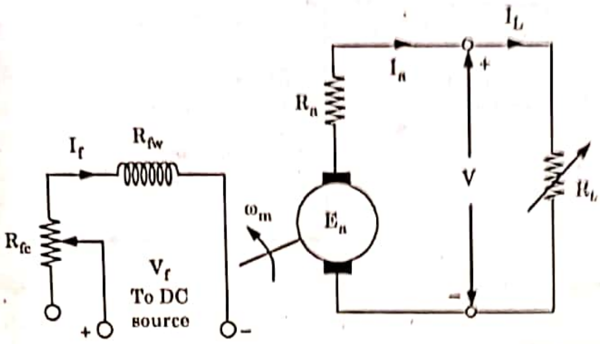


Fig. 2.15.1. Circuit model of a separately excited DC generator.

3. Let the generator be driven at a constant speed by a prime mover. The field excitation (I_f) is adjusted to give rated voltage at no-load. This value of voltage is kept constant throughout the operation considered.

4. Let R_{fw} = Resistance of the field winding

R_{fc} = Resistance of the field rheostat to control field current

R_f = Total field circuit resistance = $R_{fw} + R_{fc}$

R_a = Total resistance of the armature circuit

R_L = Load resistance

I_L = Load current

E_a = Internal generated voltage

V = Terminal voltage

I_a = Armature current

5. The defining equations for the separately excited DC generator are as follows :

$$V_f = R_f I_f$$
$$E_a = V + I_a R_a$$
$$E_a = K_a \phi \omega_m$$
$$V = I_L R_L$$
$$I_a = I_L$$

6. If there were no armature reaction, the generated voltage V_0 would be constant as shown by a straight line in Fig. 2.15.2. Because of the demagnetizing effect of armature reaction there is a voltage drop ΔV_{AR}. The internal characteristics ($E_a - I_L$) is shown in Fig. 2.15.2.

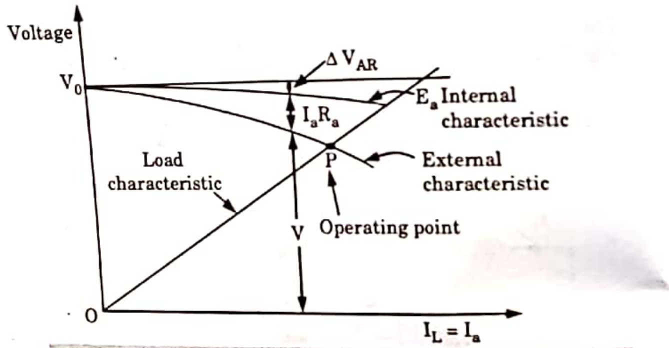


Fig. 2.15.2. Characteristics of a separately excited DC generator.

7. There is a voltage drop I_aR_a across R_a. The generator external characteristic ($V - I_L$) is defined by the relation

$$V = E_a - I_a R_a$$

8. The operating point gives the operating values of terminal voltage V and terminal (load) current I_L.

Que 2.16. **Draw the characteristics of compound DC generator.**

Answer

1. Depending upon the number of series field turns, the cumulatively compound generators may be over compounded, flat compounded, and under compounded. For an over compounded generator, full-load terminal voltage is higher than the no-load terminal voltage.
2. For a flat compounded (or level compounded) generator the terminal voltage at full-load is equal to the no-load terminal voltage.
3. In an under compounded generator the terminal voltage at full-load is less than the no-load terminal voltage.

4. In differential compounded generators, the terminal voltage drops very quickly with increasing armature current.

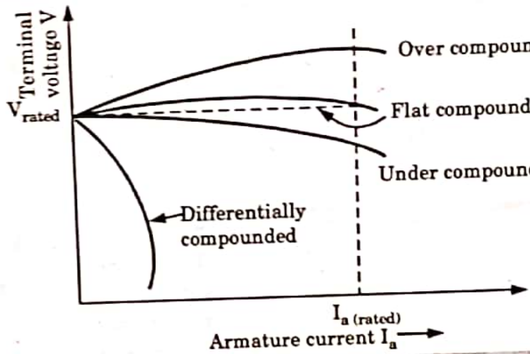


Fig. 2.16.1. Voltage-current characteristics of compound DC generator.

Que 2.17. **Discuss the internal and external characteristics of the DC shunt generator. Also explain why the load characteristics of DC shunt generator have drooping more than that of separately excited generator ?**

AKTU 2015-16, Marks 10

AKTU 2018-19, Marks 07

Answer

A. Internal characteristics :

1. The internal characteristic curve represents the relation between the generated voltage E_g and the load current I_L as shown in Fig. 2.17.1.
2. When the generator is loaded then the generated voltage is decreased due to armature reaction.
3. So, generated voltage will be lower than the emf generated at no-load.

B. External characteristics :

1. It shows the variation of terminal voltage with the load current.
2. Ohmic drop due to armature resistance gives lesser terminal voltage than the generated voltage. That is why the curve lies below the internal characteristic curve.
3. Terminal voltage $V = (E_g - I_aR_a) = E_g - (I_{sh} + I_L) R_a$. The terminal voltage can always be maintained constant by adjusting the resistance of the load terminal.
4. When the load resistance of a shunt wound DC generator is decreased, then load current of the generator is increased. But the load current

Que 2.19. **Give the application of DC machines.**

Answer

Applications of DC machines :

S. No.	Types of DC Machines	Applications
1.	DC shunt generator	a. For electroplating b. Battery charging c. For excitation of alternators
2.	Series generators	a. Used as boosters b. Used for supply to arc lamps
3.	Compound generator	a. To supply power DC welding machines. b. To supply power for offices, hostels and lodges etc. c. To compensate the voltage drop in feeders.
4.	Separately excited generator	For the testing purposes.
5.	DC shunt motors	a. Lathes b. Drills c. Boring mills d. Shapers e. Spinning and weaving machines
6.	DC series motor	a. Electric traction b. Cranes c. Elevators d. Air compressor e. Vacuum cleaner f. Hair drier g. Sewing machine
7.	DC compound motor	a. Presses shears b. Reciprocating machine

VERY IMPORTANT QUESTIONS

Following questions are very important. These questions may be asked in your SESSIONALS as well as UNIVERSITY EXAMINATION.

Q. 1. Discuss the constructional details and working principle of DC machines with interpole and compensating winding. Also mention the types of DC machines.

Ans. Refer Q. 2.2.

Q. 2. Derive an expression for the emf generated in the armature winding of a DC machine.

Ans. Refer Q. 2.3.

Q. 3. Derive an expression for the torque developed in the armature of a DC motor.

Ans. Refer Q. 2.4.

Q. 4. Discuss about concentrated and distributed winding.

Ans. Refer Q. 2.6.

Q. 5. Discuss armature reaction in DC machine.

Ans. Refer Q. 2.9.

Q. 6. Explain the effects of armature reaction on the operation of a DC machine. How the effects of armature reactions can be minimized ?

Ans. Refer Q. 2.10.

Q. 7. Discuss in detail the phenomenon of commutation in DC machine and also explain the methods adopted to improve commutation.

Ans. Refer Q. 2.14.

Q. 8. Discuss the internal and external characteristics of the DC shunt generator. Also explain why the load characteristics of DC shunt generator have drooping more than that of separately excited generator ?

Ans. Refer Q. 2.17.

☺☺☺

3

UNIT

DC Machines-II

CONTENTS

PART-1

Performance Characteristics of DC Motors, Starting of DC Motors, 3 Point and 4 Point Starters.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 3.1. **Describe performance characteristic of shunt motor (DC). Also describe torque versus current plot.**

Answer

A. Speed-armature current characteristic :

1. In a shunt motor, $I_{sh} = V/R_{sh}$. If V is constant, I_{sh} will also be a constant. Hence the flux is constant at no-load.
2. The flux decreases slightly due to armature reaction.
3. If the effect of armature reaction is neglected, the flux ϕ will remain constant.
4. The motor speed is given by

$$N \propto \frac{V - I_a R_a}{\phi} \qquad ...(3.1.1)$$

5. If ϕ is constant, the speed can be written as

$$N \propto V - I_a R_a \qquad ...(3.1.2)$$

6. Eq. (3.1.2) is the equation of a straight line with a negative slope. That is, the speed N of the motor decreases linearly with the increase in armature current as shown in Fig. 3.1.1.

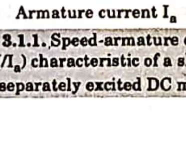


Fig. 3.1.1. Speed-armature current (N/I_a) characteristic of a shunt or separately excited DC motor.

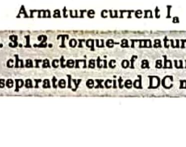


Fig. 3.1.2. Torque-armature current characteristic of a shunt or separately excited DC motor.

B. ***Torque-armature current characteristic :***

1. *If the effect of armature reaction is neglected, ϕ is nearly constant and*

$$\tau_g \propto I_a \quad ...(3.1.3)$$

2. *Eq. (3.1.3) shows that the graph between τ_g and I_a is a straight line passing through the origin as shown in Fig. 3.1.2.*
3. *If the effect of armature reaction is taken into account, the value of ϕ decreases slightly with the increase in armature current.*
4. *Hence at higher values of I_a the gross or total torque τ_g decreases slightly.*
5. The relation between various torques is given by the relation

$$\tau_n = \tau_g - (\tau_f + \tau_w)$$

where τ_n = Net torque of useful torque or load torque at the output shaft

τ_g = Gross or total torque

τ_f = Frictional torque

τ_w = Windage torque

Que 3.2. **Describe performance characteristic of series motor.**

Answer

A. **Speed-armature current characteristic :**

1. The motor speed N is given by

$$N \propto \frac{V - I_a(R_a + R_{se})}{\phi} \quad ...(3.2.1)$$

2. At low values of I_a, the voltage drop $I_a(R_a + R_{se})$ is negligibly small in comparison with V. Therefore

$$N \propto \frac{V}{\phi} \quad ...(3.2.2)$$

3. Since V is constant,

$$N \propto \frac{1}{\phi} \quad ...(3.2.3)$$

4. In a series motor, the flux ϕ is produced by the armature current flowing in the field winding so that $\phi \propto I_a$. Hence the series motor is a variable flux machine. Eq. (3.2.3) becomes

$$N \propto \frac{1}{I_a} \quad ...(3.2.4)$$

5. Thus, for the series motor, the speed is inversely proportional to the armature (load) current. The speed-load characteristic hyperbola is shown in Fig. 3.2.1.

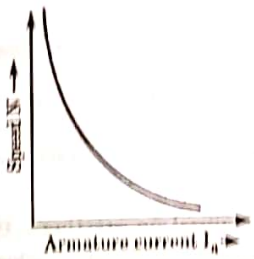


Fig. 3.2.1. Speed-armature current characteristic of a DC series motor.

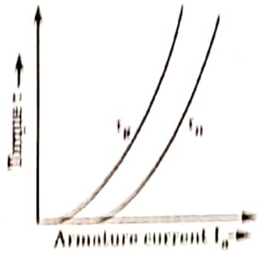


Fig. 3.2.2. Torque-armature current characteristic of a DC series motor.

B. **Torque-armature current characteristic :**

1. $$\tau_g \propto \phi I_a \quad ...(3.2.5)$$
2. Before saturation, $\phi \propto I_a$ and hence at light loads

$$\tau_g \propto I_a^2 \quad ...(3.2.6)$$

3. Eq. (3.2.6) shows that the torque-armature current (τ/I_a) curve will be parabolic.
4. When the iron becomes magnetically saturated, ϕ becomes almost constant, so that at heavy loads

$$\tau_g \propto I_a \quad ...(3.2.7)$$

5. Eq. (3.2.7) shows that the τ/I_a characteristic is a straight line. Thus, the torque-current characteristic of a DC series motor is initially parabolic and finally becomes linear when the load current becomes large.
6. The characteristic changes smoothly from one curve to another. This characteristic is shown in Fig. 3.2.2.

Que 3.3. **Compare the speed-torque characteristics of DC shunt, series and compound motor. Which machine is most suitable for traction purpose ?**

AKTU 2015-16, Marks 05

Answer

1. From the Fig. 3.3.1, it is found that the speed of a series motor is inversely proportional to the torque.

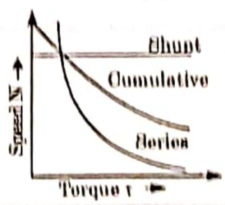


Fig. 3.3.1. Speed-torque characteristics of DC motor.

2. In shunt motor, the speed of the motor remains constant.
3. The speed-torque characteristic of the compound motor has a high starting torque together with a safe no-load speed.
4. The characteristic shows that the DC series motor has a high torque at a low speed and a low torque at a high speed.
5. Hence the speed of the DC series motor changes considerably with increasing loads. Thus it is more suitable for traction purpose.

Que 3.4. **Explain why a starter is required for starting a DC motor. Describe a 3-point starter, having no-volt and over-load protections for a DC shunt motor.**

Answer

A. Starting of DC motor :

1. At the time of starting, the motor speed is zero, therefore, counter emf $E_a (= K_a \phi \omega_n)$ is also zero.
2. Consequently, for the armature circuit, the voltage equation is $V_t = 0 + I_a r_a$ for shunt motor and $V_t = 0 + I_a (r_a + r_s)$ for both series and compound motors.
3. With rated applied voltage the starting armature current is, therefore, $\frac{V_t}{r_a}$ for shunt motor and $\frac{V_t}{r_s + r_a}$ for both series and compound motors.
4. Since the resistance r_a and $(r_a + r_s)$ are much smaller, the motor draws large starting armature current from the supply mains.
5. Due to heavy inrush of starting current taken by the motor, it may result in :
   i. Detrimental sparking at the commutator.
   ii. Damage the armature winding and deterioration of the insulation due to overheating.
   iii. High starting torque and quick acceleration which may damage the rotating parts of the motor and the load.
   iv. Large dips in the supply voltage.
6. In order to limit starting current, starters are necessary for suitable operation of DC machines.
7. To limit the starting current, an external resistance should be inserted into armature circuit, which is removed gradually as motor fix-up the speed. On the basis of the these points following two types of starters are used :
   i. Three-point starter
   ii. Four-point starter

B. Three-point DC shunt motor starter :

1. Fig. 3.4.1 shows a three-point DC shunt motor starter. It consists of a graded resistance R to limit the starting current.
2. Prior to starting, the handle H is kept in the OFF position by a spring S.
3. For starting the motor, the handle H is moved manually and when it makes contact with the resistance, stud 1 is in the START position.
4. In this position the field winding receives the full supply voltage, but the armature current is limited by the graded resistance $R (= R_1 + R_2 + R_3 + R_4)$.
5. The starter handle is then gradually moved from stud to stud, allowing the speed of the motor to build up until it reaches the RUN position.
6. In this position,
   a. The motor attains full speed,
   b. The supply is directly across both the windings of the motor, and
   c. The resistance R is completely cut out.
7. The handle H is held in RUN position by an electromagnet energized by a no-volt trip coil NVC. The no-volt trip coil is connected in series with field winding of the motor.
8. In the event of switching off, or when the supply voltage falls below a predetermined value or the complete failure of supply while the motor is running, NVC is de-energized.
9. This results in release of the handle, which is then pulled back to OFF position by the action of the spring.
10. The NVC also provides protection against an open-circuit in the field winding. The NVC is called no-volt or undervoltage protection of the motor.
11. Without this protection, the supply voltage might be restored with the handle in the RUN position. Consequently, full line voltage may be applied directly to the armature resulting in a very large current.
12. The other protective device incorporated in the starter is the overload protection. Overload protection is provided by the overload trip coil OLC and the NVC.
13. The overload coil is a small electromagnet. It carries the armature current, and for normal values of armature current the magnetic pull of OLC is insufficient to attract the strip P.
14. When the armature current exceeds the normal rated value (that is, when the motor is overloaded), P is attracted by the electromagnet of OLC and closes the contacts aa. Thus, NVC is short-circuited.
15. This results in the release of the handle H, which returns to the OFF position and the motor supply is cut off.

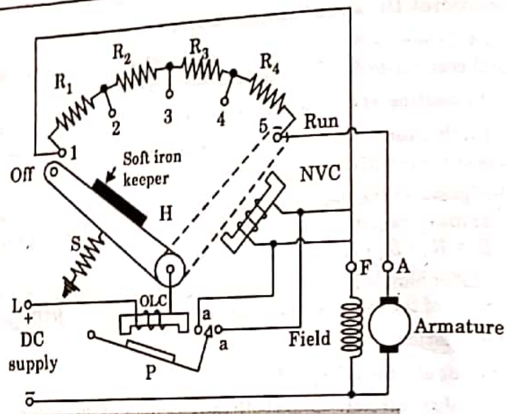


Fig. 3.4.1. Three-point DC shunt motor starter.

16. Merits :

i. It limits the high starting current into armature by having the resistance high at the time of starting and reducing it during running condition.

ii. It also protects the motor from overload and under voltage conditions.

Que 3.5. **Describe a 3-point starter using a neat diagram. Compare and distinguish it with a four point starter.**

AKTU 2018-19, Marks 07

OR

Discuss about four-point starter.

Answer

i. **Three-Point DC shunt motor starter** : Refer Q. 3.4, Page 3–5B, Unit-3.

ii. **Four-point starter :**

1. The schematic connection diagram of four-point starter is shown in Fig. 3.5.1.
2. 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.
3. Such an arrangement forms three parallel circuits :
   i. Armature, starting resistance and overload release.
   ii. A variable resistance and shunt field winding.
   iii. Holding coil and current limiting resistance.

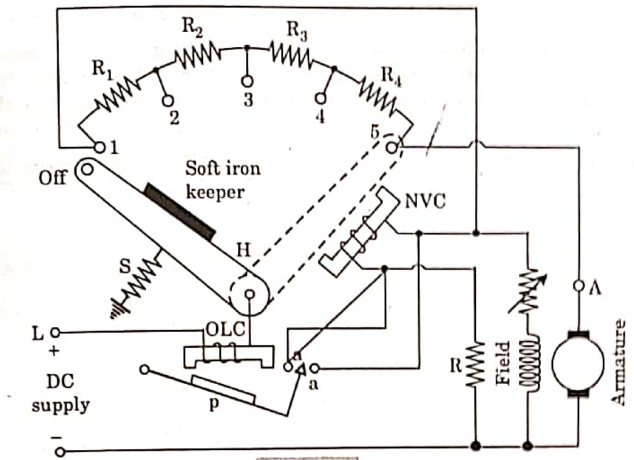


Fig. 3.5.1.

4. With this arrangement, a change in field current for variation of speed of the motor does not affect the current through the holding coil because the two circuits are independent of each other.
5. **Merits :** Speed control above rated speed is possible.

iii. Difference :

Basis for comparison	Three-point starter	Four-point starter
Definition	The starter which uses the three terminals for starting the motor.	The four-point starter uses the four terminals for acceleration of motor.
Terminals	Armature terminal, field terminal and the line terminal.	Armature terminal, field terminal, line terminal and the additional terminal that directly connects the supply to the no voltage coil (NVC).
No Volts Coil (NVC)	Connects in series with the field coil.	Connects in parallel with the field coil.

Que 3.6. A 250 V DC shunt motor has a shunt field resistance of 200 Ω and an armature resistance of 0.3 Ω. For given load, motor runs at 1500 rpm drawing a current of 22 A from the supply. If a resistance of 150 Ω is added in series with the field winding, find the new armature current and the speed. Assume load torque constant and magnetization curve to be linear. **AKTU 2014-15, Marks 10**

Answer

Given : $V = 250$ V, $R_{sh} = 200\ \Omega$, $R_a = 0.3\ \Omega$, $N_1 = 1500$ rpm, $I_L = 22$ A

To Find : New armature current, I_{a2} and new speed, N_2.

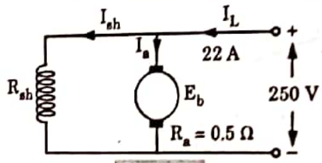


Fig. 3.6.1.

1. $$I_{sh1} = \frac{V}{R_{sh}} = \frac{250}{200} = 1.25 \text{ A}$$
$$I_{a1} = 22 - 1.25 = 20.75 \text{ A}$$
$$E_{b1} = V - I_{a1}R_a$$
$$E_{b1} = 250 - 20.75 \times 0.3 = 243.77 \text{ V}$$
2. When a resistance of 150 Ω is inserted in field circuit
$$I_{sh2} = \frac{V}{R_{sh} + R} = \frac{250}{200 + 150} = 0.7142 \text{ A}$$
3. Neglect the magnetic saturation,
$$\phi \propto I_{sh}$$
$$\frac{\phi_1}{\phi_2} = \frac{I_{sh1}}{I_{sh2}} = \frac{1.25}{0.7142} = 1.75$$
4. For constant torque,
$$T_{e1} = T_{e2}$$
$$K\phi_1 I_{a1} = K\phi_2 I_{a2}$$
5. $$I_{a2} = I_{a1} \times \frac{\phi_1}{\phi_2} = I_{a1} \times \frac{I_{sh1}}{I_{sh2}} = 20.75 \times 1.75 = 36.312 \text{ A}$$
6. $$E_{b2} = 250 - 36.312 \times 0.3 = 239.11 \text{ V}$$
$$E_b \propto N\phi$$
$$\frac{E_{b1}}{E_{b2}} = \frac{N_1\phi_1}{N_2\phi_2}$$

$$\frac{243.77}{239.11} = \frac{1500}{N_2} \times \frac{I_{sh1}}{I_{sh2}}$$
$$1.02 = \frac{1500}{N_2} \times 1.75$$
$$\therefore \quad N_2 = 2574 \text{ rpm}$$

PART-2

Speed Control of DC Motors : Field Control, Armature Control and Voltage Control (Ward Leonard Method).

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 3.7. Write short note on field flux control in speed control of DC motor.

Answer

1. Since the flux is produced by the field current, control of speed by this method is obtained by control of the field current.
2. In the shunt motor, this is done by connecting a variable resistor R_c in series with the shunt field winding as shown in Fig. 3.7.1. The resistor R_c is shunt field regulator.
3. The shunt field current is given by $I_{sh} = \dfrac{V}{R_{sh} + R_c}$.
4. The connection of R_c in the field reduces the field current and hence the flux ϕ is also reduced.
5. The reduction in flux will result in an increase in the speed.
6. Consequently, the motor runs at a speed higher than normal speed.

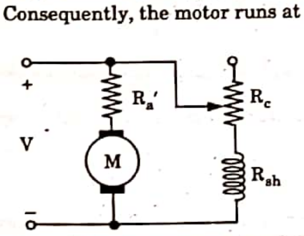


Fig. 3.7.1. Speed-control of a DC shunt motor by variation of field flux.

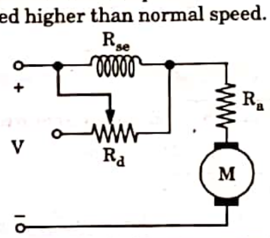


Fig. 3.7.2. Diverter in parallel with the series of DC motor.

7. For this reason, this method of speed-control is used to give motor speeds above normal or to correct for a fall in speed due to load.
8. The variation of field current in a series motor is done by any one of the following methods :
   a. A variable resistance R_d is connected in parallel with the series field windings as shown in Fig. 3.7.2. The parallel resistor is called the diverter. A portion of the main current is diverted through R_d.
      Thus, the diverter reduces the current flowing through the field winding. This reduces the flux and increases the speed.
   b. The second method uses a tapped field control as shown in Fig. 3.7.3. Here the ampere-turns are varied by varying the number of field turns. This arrangement is used in electric traction.

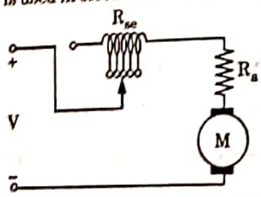


Fig. 3.7.3. Tapped series field on DC motor.

9. Fig. 3.7.4(a) and 3.7.4(b) shows the typical speed/torque curves for shunt and series motors respectively, whose speed are controlled by the variation of the field flux.

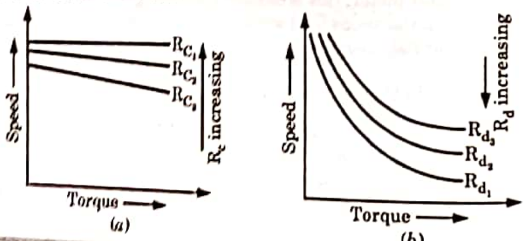


Fig. 3.7.4. Typical speed-torque curves (a) shunt motor (b) series motor.

Que 3.8. **Explain armature resistance control method in speed control of DC motor.**

Answer

1. In this method a variable series resistor R_e is put in the armature circuit.
2. In this case, the field is directly connected across the supply and therefore the flux ϕ is not affected by variation of R_e.

3. Fig. 3.8.1 shows the method of connection of external resistance R_e in the armature circuit of a DC series motor.
4. In this case the current and hence the flux are affected by the variation of the armature circuit resistance.
5. The voltage drop in R_e reduces the voltage applied to the armature and therefore the speed is reduced.
6. Fig. 3.8.3(a) and 3.8.3(b) shows typical speed-current characteristics for shunt and series motors respectively.

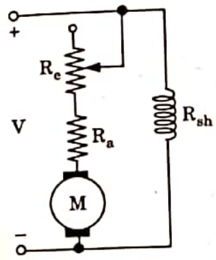


Fig. 3.8.1. Speed-control of a DC shunt motor by armature resistance control.

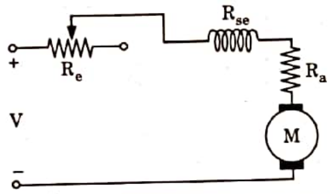


Fig. 3.8.2. Speed-control of a DC series motor by armature resistance control.

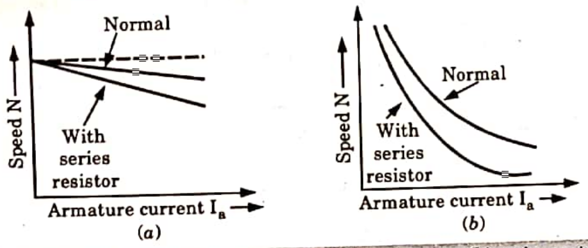


Fig. 3.8.3. Speed-current characteristics (a) shunt motor (b) series motor.

7. In both the cases the motor runs at a lower speed as the value of R_e is increased.
8. Since R_e carries full armature current, it must be designed to carry continuously the full armature current.

Que 3.9. **Write short note on Ward-Leonard method.**

Answer

1. In this method, speed control of DC motors can be obtained by varying the applied voltage to the armature.

2. In this system M is the main DC motor whose speed is to be controlled, and G is a separately excited DC generator.

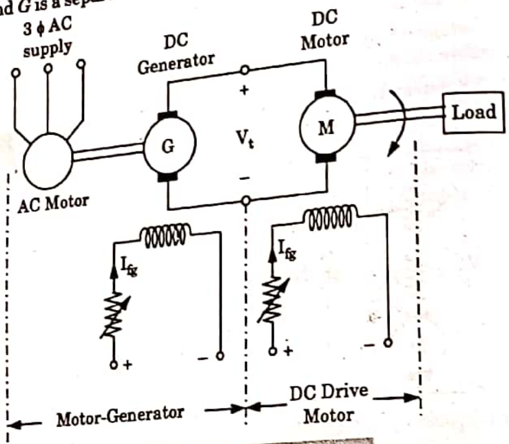


Fig. 3.9.1. Ward-Leonard drive.

3. The generator G is driven by 3ϕ driving motor which may be an induction motor or a synchronous motor.
4. The combination of AC driving motor and the DC generator is called the motor-generator set.
5. By changing the generator field current, the generator voltage is changed. This voltage when applied directly to the armature of the main DC motor M changes its speed.
6. The motor field current I_{fm} is kept constant so that the motor field flux ϕ_m also remains constant.
7. The motor armature current I_a is kept equal to its rated value during the speed control.
8. The generator field current I_{fg} is varied such that the armature voltage V_t changes from zero to its rated value.
9. The speed will change from zero to the base speed.
10. Since the speed control is carried out with rated current I_a and with constant motor field flux ϕ_m, a constant torque ($\propto \phi_m I_a$) upto base (rated) speed is obtained.
11. Since the power P (= torque × speed) is proportional to speed, it increases with speed.
12. Hence with armature voltage control method constant torque and variable power drive is obtained from speed below the base speed. This is shown in Fig. 3.9.2.

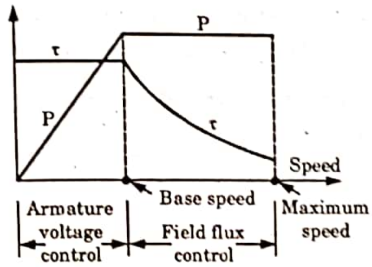


Fig. 3.9.2. Torque and power characteristics is combined armature voltage and field control.

Que 3.10. **Give the advantages and disadvantages of Ward-Leonard drives.**

Answer

A. Advantages :

1. Smooth speed control of DC motors over a wide range in both directions is possible.
2. It has inherent regenerative braking capacity.
3. By using an overexcited synchronous motor as the drive for DC generator, the lagging reactive volt-amperes of the plant are compensated. Therefore the overall power factor of the plant improves.
4. When the load is intermittent as in rolling mills, the drive motor used is an induction motor with a flywheel mounted on its shaft to smooth out the intermittent loading to a low value.

B. Disadvantages :

1. Larger size and weight.
2. Requires more floor area and costly foundation.
3. Frequent maintenance is needed.

Que 3.11. **What are the advantages of the field flux control over armature circuit resistance control method employed for the speed control of DC motors ?** **AKTU 2015-16, Marks 05**

Answer

1. This method is easy and convenient.
2. Since shunt field current is very small, the power loss in the shunt field is small.
3. As the field current is small, the size of rheostat required is small.

4. Speed control above rated speed is possible.
5. Efficiency is high as compared to armature resistance control method.

Que 3.12. **A 4-pole series wound fan motor draws an armature current of 50 amps, when running at 2000 rpm on a 230 V DC supply with four field coils connected in series. The four field coils are then reconnected in two parallel groups of two coils in series. Assuming flux/pole to be proportional to the exciting current and load torque proportional to the square of the speed, find the new speed and armature current.**

AKTU 2016-17, Marks 15

Answer

Given : $P = 4$, $I_1 = 50$ A, $N_1 = 2000$ rpm, $V_t = 230$ V
To Find : New speed, N_2 and new armature current, I_{a2}

1. Let r_s be the resistance of each coil.
$$r_a = \text{Resistance of armature}$$
$$N = \text{Speed in rpm}$$
2. When coils are connected in series
$$E_{b1} = V_t - I_{a1}(r_a + 4r_s) \propto N_1\phi_1 \quad ...(3.12.1)$$
3. When coils are connected in two parallel groups of two coils
$$E_{b2} = V_t - I_{a2}(r_a + r_s) \propto N_2\phi_2 \quad ...(3.12.2)$$
From eq. (3.12.1) and eq. (3.12.2), we get
$$\frac{E_{b1}}{E_{b2}} = \frac{\phi_1 N_1}{\phi_2 N_2} \quad ...(3.12.3)$$
4. $\because$ Flux is proportional to field current
$$\frac{E_{b1}}{E_{b2}} = \frac{I_{a1}N_1}{\frac{I_{a2}}{2}N_2} = \frac{V_t}{V_t}$$
$$\frac{230}{230} = \frac{I_{a1}N_1}{I_{a2}N_2} \times 2$$
$$N_2 = \frac{2I_{a1}N_1}{I_{a2}} \quad ...(3.12.4)$$
5. Load torque, $T_L \propto N^2$
Electromagnetic torque, $T_e \propto \phi I$
Under steady state,
$$T_L = T_e$$
$$N^2 \propto \phi I$$
$$\left(\frac{N_1}{N_2}\right)^2 = \frac{\phi_1 I_{a1}}{\phi_2 I_{a2}} = \frac{I_{a1}I_{a1}}{\frac{I_{a2}}{2}I_{a2}} = 2\left(\frac{I_{a1}}{I_{a2}}\right)^2$$

$$\frac{N_1}{N_2} = \sqrt{2}\frac{I_{a1}}{I_{a2}}$$

6. Putting value of $\dfrac{I_{a1}}{I_{a2}}$ from eq. (3.12.4), we get
$$N_2^2 = \sqrt{2}N_1^2$$
Putting, $N_1 = 2000$ rpm
$$N_2 = \text{New speed} = 2^{1/4} \times 2000 = 2378 \text{ rpm}$$
7. Putting value of N_2 in eq. (3.12.4), new armature current
$$I_{a2} = \frac{2I_{a1}N_1}{N_2} = \frac{2 \times 50 \times 2000}{2378} = 84.10 \text{ A}$$

Que 3.13. **A 400 V series motor has total armature resistance of 0.25 Ω. When running at 1200 rpm it draws a current of 25 A. When a regulating resistance of 2.75 Ω is included in the armature circuit, it draws a current of 15 A. Find the speed and ratio of the two mechanical outputs. Assume that the flux with 15 A is 70 % of that with 25 A.**

AKTU 2017-18, Marks 07

Answer

Given : $V_t = 400$ V, $R_a = 0.25\ \Omega$, $I_a = 25$ A, $N = 1200$ rpm
$$\phi_2 = \frac{70}{100} \times \phi_1 \quad \therefore \quad \frac{\phi_1}{\phi_2} = \frac{10}{7}$$
To Find : N_2 and ratio of two mechanical output.

1. $$E_{b1} = V_t - I_a R_a$$
$$E_{b1} = 400 - 25 \times 0.25 = 393.75 \text{ V}$$
2. $$E_{b2} = V_t - I_a(R_a + R_{se})$$
$$E_{b2} = 400 - 15\,(0.25 + 2.75) = 355 \text{ V}$$
4. We know that
$$\frac{N_2}{N_1} = \frac{E_2}{E_1} \times \frac{\phi_1}{\phi_2}$$
$$\frac{N_2}{1200} = \frac{355}{393.75} \times \frac{10}{7}$$
$$N_2 = 757.33 \text{ rpm}$$
4. So,
$$\frac{P_{m1}}{P_{m2}} = \frac{E_{b1}\,I_{a1}}{E_{b2}\,I_{a2}}$$
$$\frac{P_{m1}}{P_{m2}} = \frac{393.75 \times 25}{355 \times 15} = 1.84$$

PART-3

Efficiency and Testing of DC Machines (Hopkinson's and Swinburne's test), Applications.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 3.14. What are various losses that occur in DC machines ? Also, derive the condition for maximum efficiency of a DC generator.

AKTU 2016-17, Marks 10

Answer

A. **Losses in DC machines :**

1. **Copper losses or winding losses :** The copper losses are present because of the resistance of the windings. Currents flowing through these windings produce ohmic losses.
2. **Core losses or iron losses :** The core losses are the hysteresis losses and eddy-current losses. Since machines are usually operated at constant flux density and constant speed, these losses are almost constant.
3. **Brush losses :** There is a power loss at the brush contacts between the copper commutator and the carbon brushes.
4. **Mechanical losses :** The losses associated with mechanical effects are called mechanical losses. They consist of bearing friction loss and windage loss. Windage losses are associated with friction between the moving parts of the machine and the air inside the machine.
5. **Stray-load losses :** Stray-load loss consists of all losses, not covered above. These are the miscellaneous losses that result from such factors as
   i. The distortion of flux because of armature reaction.
   ii. Short circuit currents in the coil, undergoing commutation, etc.

B. **Efficiency of DC generator :**

1. Let
   R_{at} = Total resistance of the armature circuit
   I = Output current
   I_{sh} = Current through the shunt field
   I_a = Armature current = $I + I_{sh}$
   V = Terminal voltage
2. Total copper loss in the armature circuit = $I_a^2 R_{at}$

3. Power loss in the shunt circuit = VI_{sh}
4. Mechanical losses = Friction loss at bearings + Friction loss at commutator + Windage loss

   Core losses = Hysteresis loss + Eddy-current loss

   Stray loss = Mechanical loss + Core loss
5. The sum of the shunt field copper loss and stray losses may be considered as a combined fixed (constant) loss that does not vary with the load current I.

   ∴ Constant losses (in shunt and compound generators)
   = Stray loss + Shunt field copper losses

   $$\text{Total losses} = I_a^2 R_{at} + p_k + V_{BD} I_a$$
6. Generator efficiency,

   $$\eta_G = \frac{\text{Generator output}}{\text{Generator output + Losses}}$$

   $$= \frac{VI}{VI + I_a^2 R_{at} + V_{BD} I_a + p_k}$$

   $$I_a = I + I_{sh}$$
7. If I_{sh} is small compared with I, then $I_a = I$

   $$\eta_G = \frac{VI}{VI + I^2 R_{at} + V_{BD} I + p_k}$$

   $$= \frac{1}{1 + \frac{IR_{at}}{V} + \frac{V_{BD}}{V} + \frac{p_k}{VI}}$$
8. The efficiency η_G will be maximum when the denominator D_r is minimum, where $D_r = 1 + \frac{IR_{at}}{V} + \frac{V_{BD}}{V} + \frac{p_k}{VI}$
9. D_r is minimum when

   $$\frac{dD_r}{dI} = 0$$

   $$\frac{dD_r}{dI} = \frac{d}{dI}\left(1 + \frac{IR_{at}}{V} + \frac{V_{BD}}{V} + \frac{p_k}{VI}\right)$$

   $$0 = 0 + \frac{R_{at}}{V} + \frac{p_k}{V}\left(-\frac{1}{I^2}\right)$$

   $$I^2 R_{at} = p_k \quad ...(3.14.1)$$
10. Eq. (3.14.1) shows that the efficiency of a DC generator is maximum when those losses proportional to the square of the load current are equal to the constant losses of the DC generator.

Que 3.15. Discuss Hopkinson's test on DC machines.

AKTU 2016-17, Marks 7.5

OR

Explain the efficiency testing of DC machines in detail.

AKTU 2017-18, Marks 07

OR

Describe Swinburne's test in detail with its advantages and disadvantages.

AKTU 2018-19, Marks 07

Answer

A. Brake test :

1. For a DC motor, a brake test is carried out as illustrated in Fig. 3.15.1.
2. A belt around the air or water-cooled pulley has its ends attached to spring balances S_1 and S_2.

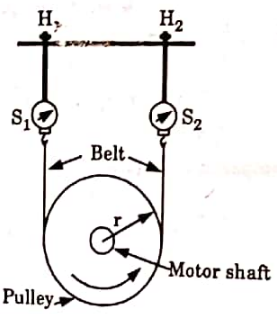


Fig. 3.15.1. Brake test on a DC motor.

3. The belt tightening hand wheels H_1 and H_2, help in adjusting the load on the pulley and, therefore, on the motor.
4. If spring balances are calibrated in kilograms, the motor output is given by,

$$\text{Motor output} = \omega\,(S_1 - S_2)\, r \times 9.81 \text{ watts}$$

where S_1 and S_2 are the tensions on the tight and slack sides of the belt, r is the effective radius of the brake-pulley in meters and ω is the motor speed in rad/sec.

5. If V_t is the motor terminal voltage and I_L is the line current, then power input to motor = $V_t I_L$ watts, and percentage motor efficiency,

$$\eta_m = \frac{\omega(S_1 - S_2) r \times 9.81}{V_t I_L} \times 100$$

6. **Advantages :**

i. This test is suitable for small DC motor.

ii. It can be performed under working condition of motor.

7. **Disadvantages :**

i. The spring balance readings are not steady.

ii. The friction torque, at a particular setting of the hand wheels H_1 and H_2, does not remain constant.

B. Swinburne's test :

1. This is no-load test, it cannot be performed on a DC series motor.
2. In this method, the machine, whether it is a motor or a generator is run at no-load as shunt motor at rated speed and rated terminal voltage V_t.

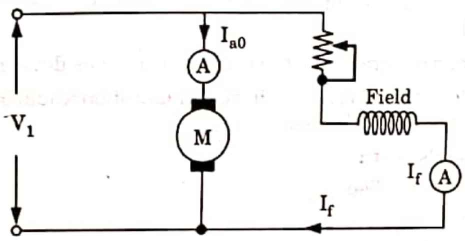


Fig. 3.15.2. Swinburne's test.

3. Let
$$I_f = \text{Field current}$$
$$I_{a0} = \text{No-load armature current}$$
$$I_L = \text{Load current}$$

4. The power absorbed by the armature

$$V_t I_{a0} = \text{No-load rotational losses } (W_0) + \text{Armature loss } (I_{a0}^2 r_a)$$

$$W_0 = V_t I_{a0} - I_{a0}^2 r_a$$

$$\text{Shunt field loss} = V_t I_f$$

5. **Generator efficiency :**

$$\text{Generator output} = V_t I_L$$
$$\text{Armature current, } I_a = I_L + I_f$$
$$\text{Armature circuit loss} = I_a^2 r_a$$
$$\text{Shunt field loss} = V_t I_f$$
$$\text{Total loss} = W_0 + I_a^2 r_a + I_f V_t$$

$$\therefore \quad \text{Efficiency, } \eta_g = 1 - \frac{\text{Losses}}{\text{Input power}}$$

$$\eta_g = 1 - \frac{W_0 + I_a^2 r_a + I_f V_t}{V_t I_L + W_0 + I_a^2 r_a + I_f V_t}$$

6. **Motor efficiency :** When machine is working as a motor, then $I_a = I_L - I_f$

$$\text{Motor input} = V_t I_L$$

$$\eta_m = 1 - \frac{W_0 + I_a^2 r_a + I_f V_t}{V_t I_L}$$

7. **Advantages :**
i. Low power is required for testing even large machines, since only no-load losses are to be supplied from the mains.
ii. The efficiency of the machine can be calculated at any desired load.
8. **Disadvantages :**
i. The stray-load loss cannot be determined and hence efficiency is over-estimated.
ii. Steady temperature rise of the machine cannot be determined.
iii. The test does not indicate whether communication would be satisfactory when the machine is loaded.

C. **Hopkinson's test :**
1. This test is also called
a. Regenerative test
b. Heat run test
c. Back to back test
2. In this method, two identical DC machines are coupled, both mechanically and electrically and are tested simultaneously.
3. Machine (I) running as a motor, drives machine (II) as a generator.
4. Since both the machines are coupled electrically, the power of generator (II) is fed to the motor (I). It is for this reason that Hopkinson's method is called "Regenerative method".
5. The speed of the set should be equal to the rated speed.

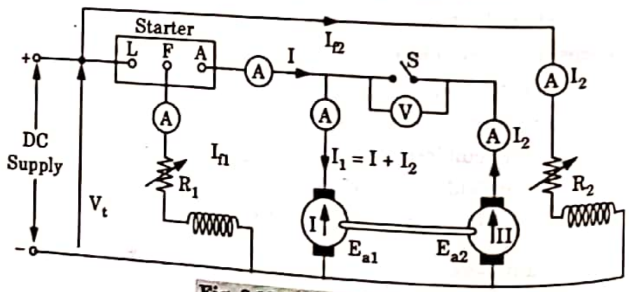


Fig. 3.15.3. Hopkinson's test.

6. I_1 and I_2 are armature currents of motor and generator respectively and V_t is the terminal voltage of both machines.

$\therefore$ Input to motor armature $= V_t I_1$

7. If η_m is the motor efficiency, then the output power $= \eta_m V_t I_1$

And if η_g is the generator efficiency, then input of generator

$$= \frac{V_t I_2}{\eta_g}$$

$$V_t I_2 = \text{Generator output}$$

8. Since the generator is driven by motor,

$$\text{Motor output} = \text{Generator input}$$

$$V_t I_1 \eta_m = \frac{V_t I_2}{\eta_g}$$

$$\eta_g \eta_m = \frac{I_2}{I_1}$$

9. Let $\eta_g = \eta_m = \eta$

then
$$\eta^2 = \frac{I_2}{I_1}$$

$$\eta = \sqrt{\frac{I_2}{I_1}} = \sqrt{\frac{\text{Generator armature current}}{\text{Motor armature current}}}$$

10. Actually $\eta_g \neq \eta_m$

Generator efficiency, $\eta_g = \left(1 - \dfrac{W_g}{V_t I_2 + W_g}\right)$

$\because$ Motor input $= V_t (I_1 + I_{f1})$

Total motor losses, $W_m = \dfrac{W_0}{2} + V_t I_{f1} + I_1^2 r_a$

Motor efficiency, $\eta_m = \left[1 - \dfrac{W_m}{V_t (I_1 + I_{f1})}\right]$

11. **Advantages :**
i. The total power taken from the supply is very low. Therefore this method is very economical.
ii. Temperature rise and the commutation condition can be checked under rated condition.
iii. Stray losses are considered in both machines.
iv. Efficiency at different loads can be determined.
12. **Disadvantages :** Two identical DC machines are required. Consequently this test is suitable for manufacturers of large DC machines.

Que 3.16. **A 240 V, 25 kW shunt motor has a maximum efficiency of 90 % and a speed of 800 rpm, when delivering 80 % of its rated output. The resistance of its shunt field is 200 Ω. Determine the efficiency and speed when the motor draws a current of 68 A from mains.**

AKTU 2018-19, Marks 07

Answer

Given : V = 240 volt, Rated output = 25 kW, N_1 = 800 rpm, $\eta_{max} = 90\%$, $\eta_d = 80\%$, $R_{sh} = 200\ \Omega$, $I_{L2} = 68$ Amp
To Find : η, N_2

1. Rated output = 25 kW = 25000 W
2. Efficiency of machine, $\eta = \dfrac{\text{Output}}{\text{Output + Losses}}$

   or total losses $= \dfrac{(1-\eta)}{\eta} \times \text{Output}$

   $= \left(\dfrac{1}{\eta} - 1\right) \times \text{Output} = \left(\dfrac{1}{0.90} - 1\right) \times 25000$

   = 2777.77 W
3. At maximum efficiency, constant losses

   $= \dfrac{\text{Total losses}}{2} = \dfrac{2777.77}{2} = 1388.88$ W
4. Motor input power,

   $P_{in} = P_{out}$ + Total losses

   = 25000 × 0.80 + 2777.77 = 22777.77 W
5. Input line current, $I_{L1} = \dfrac{P_{in}}{V} = \dfrac{22777.77}{240} = 94.90$ Amp
6. Shunt field current, $I_{Sh} = \dfrac{V}{R_{Sh}} = \dfrac{240}{200} = 1.2$ Amp
7. Armature current, $I_{a1} = I_{L1} - I_{Sh}$

   = 94.90 – 1.2 = 93.7 Amp
8. Armature copper loss,

   $I_{a1}^2 R_a = 1388.88$ W

   $R_a = \dfrac{1388.88}{I_{a1}^2} = \dfrac{1388.88}{93.7^2}$

   $= \dfrac{1388.88}{8779.69} = 0.158$ ohm
9. Armature current, $I_{a2} = I_{L2} - I_{Sh}$

   = 68 – 1.2 = 66.8 Amp
10. Armature copper loss

    $= I_{a2}^2 R_a = (66.8)^2 \times 0.158 = 705.03$ W
11. Motor input power = VI

    = 240 × 68 = 16320 W
12. Motor output = Motor input – Constant losses

– Armature copper loss

= 16320 – 1388.88 – 705.03 = 14226.09 W

13. Motor efficiency, $\eta = \dfrac{\text{Output}}{\text{Input}} \times 100 = \dfrac{14226.09}{16320} \times 100 = 87.16\%$
14. Assume flux remaining the same, the speed of the motor

    $N_2 = N_1 \times \dfrac{E_{b_2}}{E_{b_1}} = N_1 \times \dfrac{V - I_{a_2} R_a}{V - I_{a_1} R_a}$

    $= 800 \times \dfrac{240 - 66.8 \times 0.158}{240 - 93.7 \times 0.158}$

    $N_2 = 800 \times \dfrac{229.45}{225.2} = 815$ rpm

Que 3.17. **The Hopkinson's test on two identical shunt machines gave the following results :**
Input voltage = 250 V
Input current = 10 A
Output current of generator = 60 A
Field current of generator = 4 A
Field current of motor = 3 A
Armature resistance of each machine is 0.1 Ω. Determine efficiency of motor and generator.

Answer

Given : I_L = 10 A, R_a = 0.1 Ω, I_{fg} = 4 A, I_{fm} = 3 A, I_g = 60 A, V = 250 V
To Find : Efficiency of motor, η_m and efficiency of generator, η_g.

1. Generator armature current,

   $I_{ga} = I_g + I_{fg} = 60 + 4 = 64$ A
2. Input motor current,

   $I_m = I_L + I_g = 10 + 60 = 70$ A
3. Motor armature current,

   $I_{ma} = 70 - 3 = 67$ A
4. Copper loss in motor armature,

   $I_{ma}^2 R_a = (67)^2 \times 0.1 = 448.9$ W
5. Copper loss in generator armature,

   $I_{ga}^2 \times R_a = (64)^2 \times 0.1 = 409.6$ W
6. Total armature copper loss of set = 448.9 + 409.6 = 858.5 W
7. ∴ Total stray loss of set = Input – Total losses in armature

   = 2500 – 858.5 = 1641.5 W
8. Stray loss per machine $= \dfrac{1641.5}{2} = 820.75$ W

Motor efficiency :

1. Input power = $VI_m = 250 \times 70 = 17500$ W
2. Armature copper loss = 448.9 W
3. Field copper loss = $250 \times 3 = 750$ W
4. Stray loss = 820.75 W
5. Total loss = $448.9 + 750 + 820.75 = 2019.65$ W
6. $$\eta_m = \frac{\text{Input} - \text{Losses}}{\text{Input}} \times 100$$
$$= \frac{17500 - 2019.65}{17500} \times 100 = 88.45\ \%$$

Generator efficiency :

1. Output power = $250 \times 64 = 16000$ W
2. Armature copper loss = 409.6 W
3. Field copper loss = $250 \times 4 = 1000$ W
4. Stray loss = 820.75 W
5. Total loss = $409.6 + 1000 + 820.75 = 2230.35$ W
6. Generator efficiency, $$\eta_g = \frac{\text{Output}}{\text{Output} + \text{Losses}} \times 100$$
$$= \frac{16000}{16000 + 2230.35} \times 100 = 87.76\ \%$$

Que 3.18. **The following test results were obtained while Hopkinson's test was performed on two similar DC shunt machines :**
Supply voltage = 250 V,
Field current of motor = 2 A,
Field current of generator = 2.5 A,
Armature current of generator = 60 A,
Current taken by the two armatures from supply = 15 A,
Resistance of each armature circuit = 0.2 Ω.
Calculate the efficiency of the motor and generator under these conditions of load.

AKTU 2017-18, Marks 07

Answer

The procedure is same as Q. 3.17, Page 3–24B, Unit-3.
(**Ans.** $\eta_m = 86.66\ \%$ and $\eta_g = 86.7\ \%$)

Que 3.19. **Draw the speed-torque characteristics of DC shunt, series and compound motors. A 200 V shunt motor has $R_a = 0.1\ \Omega$, $R_f = 240\ \Omega$ and rotational loss 236 W. On full-load the line current is 9.8 A with the motor running at 1450 rpm. Determine**

a. The mechanical power developed.
b. The power output.
c. The load torque.

d. The full-load efficiency.

AKTU 2016-17, Marks 10

Answer

A. Speed-torque characteristics : Refer Q. 3.3, Page 3–4B, Unit-3.
B. Numerical :

Given : $V = 200$ V, $R_a = 0.1\ \Omega$, $R_{sh} = R_f = 240\ \Omega$; Line current, $I_L = 9.8$ A
To Find :
a. The mechanical power developed.
b. The output power, P_o.
c. The load torque.
d. The full-load efficiency, η.

1. $$I_{sh} = \frac{200}{240} = 0.83 \text{ A}$$
2. Armature current,
$$I_a = I_L - I_{sh} = 9.8 - 0.83 = 8.97 \text{ A}$$
$$E_b = V - I_a R_a = 200 - 8.97 \times 0.1 = 199.103 \text{ V}$$

a. ∴ Mechanical power developed
$$= E_b I_a$$
$$= 199.103 \times 8.97 = 1785.95 \text{ W}$$

b. Output power, P_o = Power developed – Rotational losses
$$= 1785.95 - 236 = 1549.95 \text{ W}$$

c. $$\text{Load torque} = \frac{60 \times P_o}{2\pi N} = \frac{60 \times 1549.95}{2\pi \times 1450} = 10.21 \text{ N-m}$$

d. Motor input = $VI_L = 200 \times 9.8 = 1960$ W
Full-load efficiency,
$$\eta = \frac{\text{Motor output}}{\text{Motor input}} \times 100 = \frac{1549.95}{1960} \times 100 = 79.08\ \%$$

Que 3.20. **A 15 kW, 250 V, 1200 rpm, shunt motor has 4 poles, 4 parallel armature paths and 900 armature conductors. Assume $R_a = 0.2\ \Omega$. At rated speed and rated output the armature current is 75 A and $I_f = 1.5$ A.**
Calculate :
i. The flux/pole
ii. The torque developed
iii. Rotational losses
iv. Efficiency
v. The shaft load.

AKTU 2014-15, Marks 10

Answer

Given : $V = 250$ V, $N = 1200$ rpm, $P = 4$, $A = 4$, $Z = 900$, $R_a = 0.2\ \Omega$, $I_a = 75$ A, $I_f = 1.5$ A

To Find :
i. Flux/pole, ϕ.
ii. Torque developed, τ.
iii. Rotational losses.
iv. Efficiency.
v. Shaft load, τ_{useful}.

i.
$$E = V - I_a R_a$$
$$= 250 - 75 \times 0.2 = 235 \text{ V}$$

$$\therefore \quad E = \frac{NP\phi Z}{60\text{ A}}$$

$$235 = \frac{1200 \times 4 \times \phi \times 900}{60 \times 4}$$

$$\phi = 0.013 \text{ Wb per pole}$$

ii.
$$\tau = \frac{60EI_a}{2\pi N} = \frac{60 \times 235 \times 75}{2\pi \times 1200} = 140.25 \text{ Nm}$$

iii. Armature input $= VI_a = 250 \times 75 = 18750$ W

Armature copper loss $= I_a^2 R_a = (75)^2 \times 0.2 = 1125$ W

Power developed $= VI_a - I_a^2 R_a = 18750 - 1125 = 17625$ W

$\therefore$ Rotational losses = Power developed – Total power output
$= 17625 - 15000 = 2625$ W

iv. Total input to motor $= VI = V(I_a + I_f)$
$= 250 \times (75 + 1.5) = 19125$ W

$$\text{Motor efficiency} = \frac{\text{Motor output}}{\text{Motor input}} = \frac{15 \times 10^3}{19125} \times 100 = 78.43\ \%$$

v.
$$\tau_{useful} = \tau_{shaft}$$
$$\tau_{useful} \times \frac{2\pi N}{60} = P_{out}$$
$$\therefore \quad \tau_{useful} = \frac{60 \times 15 \times 10^3}{2\pi \times 1200} = 119.366 \text{ N-m}$$

Que 3.21.

i. Explain the Hopkinson's test for determining the efficiency of the DC shunt machine.

ii. A 50 kW, 250 V compound motor takes a current of 9 A running at no-load at rated voltage and rated speed. The shunt field current is 5 A. The resistance of the windings is as armature winding 0.1 Ω, series field 0.07 Ω, interpolar windings 0.03 Ω. The brush drop is 2 V. Determine the motor output and the efficiency of the motor when the intake is 155 A.

AKTU 2015-16, Marks 15

Answer

i. **Hopkinson's test :** Refer Q. 3.15, Page 3–18B, Unit-3.

ii. **Numerical :**

Given : $V = 250$ V, $I_{L0} = 9$ A, $I_{sh} = 5$ A, $R_a = 0.1\ \Omega$, $R_{se} = 0.07\ \Omega$, $R_{ip} = 0.03\ \Omega$, $V_{brush} = 2$ V

To Find : Motor output, P_o and efficiency of motor, η.

1. Assume long shunt compound motor.
On no-load, P_{in} = No-load losses $= V \times I_L = 250 \times 9 = 2250$ W

2.
$$\text{Field copper loss} = I_{sh}^2 R_{sh} = 5^2 \times \left(\frac{250}{5}\right) = 1250 \text{ W}$$
$$I_{a0} = I_{L0} - I_{sh} = 9 - 5 = 4 \text{ A}$$

3. Armature copper loss $= I_{a0}^2 (R_a + R_{ip} + R_{se}) = 4^2 \times (0.07 + 0.03 + 0.1)$
$= 3.2$ W

Brush loss $= V_{brush} \times I_{a0} = 2 \times 4 = 8$ W

$$R_{sh} = \frac{V}{I_{sh}} = \frac{250}{5} = 50\ \Omega$$

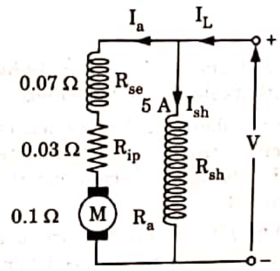


Fig. 3.21.1.

4. $\therefore$ Iron and friction losses
= No-load losses – Field copper loss – Armature copper loss – Brush loss
$= 2250 - 1250 - 3.2 - 8 = 988.8$ W

5. These losses are assumed constant at all loads.
On load, $I_L = 155$ A
$I_a = I_L - I_{sh} = 155 - 5 = 150$ A

6. Field copper loss $= I_{sh}^2 R_{sh} = 5^2 \times \left(\frac{250}{5}\right) = 1250$ W

Brush loss $= V_{brush} \times I_a = 2 \times 150 = 300$ W

Armature copper loss $= I_a^2 (R_a + R_{ip} + R_{se})$

$= 150^2 \times (0.07 + 0.03 + 0.1) = 4500$ W

7. Output power, $P_o = P_{in} -$ Total losses

$= (250 \times 155) - 988.8 - 1250 - 4500 - 300$

$= 31711$ W

Efficiency, $\eta = \frac{31711}{38750} \times 100 = 81.8\ \%$

PART-4

Introduction to Brushless DC Motor, Stepper Motor and DC Servomotor and their Applications.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 3.22. **Explain construction and working principle of brushless DC motors with applications.**

Answer

A. Construction :

1. Fig. 3.22.1 shows an elementary form of 3-phase, 3-pulse brushless DC motor along with its electronic controller.
2. The stator has three-phase winding which is star-connected. The neutral, or star, point of the winding is connected to positive terminal of the DC supply. Full bridge diode converts AC to DC and capacitor C serves as a filter circuit.
3. The three transistors TR_1, TR_2 and TR_3 are turned ON in appropriate sequence so that unidirectional torque is developed.
4. When TR_1 is turned ON, phase A is energized; when TR_2 is ON, phase B is energized and so on.
5. When phase windings are energized in sequence ABC, the rotor rotation is clockwise. With sequence ACB, the rotor revolves anticlockwise.
6. The rotor-position sensor mounted on the motor shaft provides a position feedback. It monitors the shaft position and sends signals to the drive circuitry of the inverter circuit.

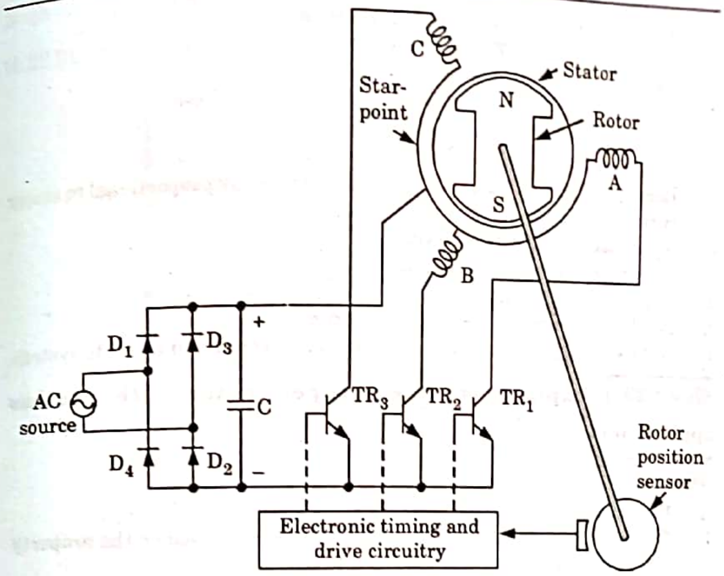


Fig. 3.22.1. Three-phase three-pulse brushless DC motor.

7. In response to these signals, the inverter allows the flow of current to stator phase windings in a controlled sequence so that motor produces the desired torque and speed.

B. Operating principle :

1. Fig. 3.22.2 shows an elementary form of three-phase stator winding and the permanent-magnet rotor with two poles.
2. When phase A is energized, stator S and N poles are created as shown in Fig. 3.22.2. Stator S pole repels rotor S pole and attracts rotor N pole, thus producing clockwise torque.

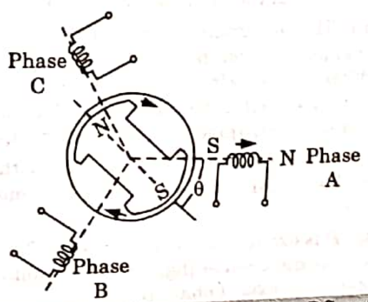


Fig. 3.22.2. An elementary form of brushless DC motor.

3. The magnitudes of this torque is given by

$$T_e = K_1 \phi_s \phi_r \sin \theta \quad ...(3.22.1)$$

where ϕ_s = Stator field flux
ϕ_r = Rotor field flux
θ = Torque angle
K_1 = Torque constant.

Here, ϕ_r is constant and stator field flux is directly proportional to stator current.

C. Applications of BLDC motor :

1. Hard disk drives for computer.
2. Low cost instruments.
3. Small fans for cooling electronic instruments.
4. Higher rating brushless DC motor used in aircraft and satellite system.

Que 3.23. **Explain variable stepper motor with various applications.**

Answer

A. Principle :

1. The principle of operation of a stepper motor is based on the property of flux lines to occupy low reluctance path.
2. The stator and rotor therefore get aligned such that the magnetic reluctance is minimum.
3. A stepper motor can be single-stack type or multi-stack type.

B. Construction :

1. It has salient pole stator with concentrated windings placed over it.
2. The number of phases of stator depends upon the connection of stator coils.
3. The rotor is a slotted structure made from ferromagnetic material and carries no winding.
4. Both stator and rotor made up of high quality materials having high permeability so that the exciting current required is small.

C. Operation : The elementary operation of a variable reluctance motor can be explained through the Fig. 3.23.1.

1. It is a 4ϕ, 4/2 pole (4 poles in stator and 2 in rotor), single-stack, variable reluctance stepper motor. Four phases A, B, C, and D are connected to DC source and are energized in the sequence A, B, C, D, A.
2. When winding A is excited, the rotor aligns with axis of phase A. The rotor is stable in this position and cannot move until phase A is de-energized.
3. Next phase B is excited, A is disconnected. The rotor moves through 90° in clockwise direction to align with the resultant air-gap field which now lies along the axis of phase B.

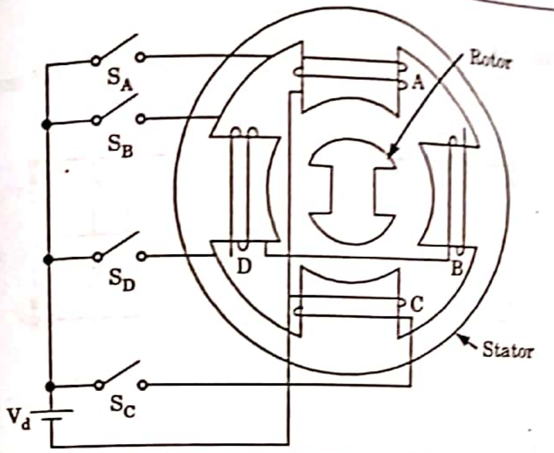


Fig. 3.23.1. 4ϕ, 4/2 pole variable reluctance stepper motor.

4. Further, phase C is excited and B is disconnected, the rotor moves further a step of 90° in the clockwise direction. Thus, as the phases are excited in the sequence A, B, C, D, A the rotor moves through a step of 90° at each transition in clockwise direction.
5. The rotor completes one revolution in four steps. The direction of rotation can be reversed by reversing the sequence of switching the windings, *i.e.*, A, D, C, B and A.
6. The magnitude of step angle for any VR stepper motor is given by,

$$\beta = \frac{360°}{MN_r}$$

where, β = Step angle
M = Number of stator phases or stacks
N_r = Number of rotor teeth or (rotor poles)

The step angle is also expressed as,

$$\beta = \frac{N_s - N_r}{N_s N_r} \times 360°$$

where, N_s = Number of stator teeth or (stator poles)

By choosing different combinations of number of rotor teeth or stator exciting coils, any desired step angle can be obtained.

D. Applications :

1. In computer peripherals such as serial printers, tape drives, floppy disc drives, memory access mechanisms etc.
2. In serial printers, in typewriters or word processor systems, numerical control of machine tools, robotic control systems, number of process control systems, actuators, spacecrafts and watches etc.

Que 3.24. **Explain the mathematical modelling of a DC servomotor.**

Answer

1. A schematic diagram of a field controlled DC motor (DC servomotor) shown in Fig. 3.24.1.

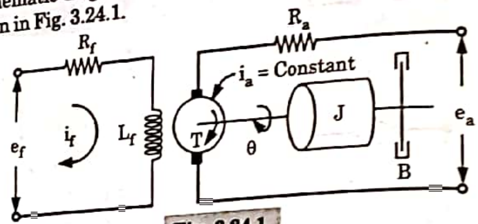


Fig. 3.24.1.

2. Here, R_f = Field winding resistance
   L_f = Field winding inductance
   I_f = Field winding current
   R_a = Armature resistance
   i_a = Armature current
   θ = Angular displacement.
3. The torque T developed by the motor is proportional to product of the air-gap flux ϕ and armature current i_a so we get
$$T = K_1 \phi i_a \quad ...(3.24.1)$$
where K_1 is constant.
4. But the air gap flux ϕ and the field current i_f are proportional for the usual operating range of the motor and i_a is assumed to be constant, we can rewrite the above equation as $T = K_2 i_f$ ...(3.24.2)
where K_2 is a constant.
5. The equations for this system are
$$L_f \frac{di_f}{dt} + R_f i_f = e_f \quad ...(3.24.3)$$
and
$$\frac{Jd^2\theta}{dt^2} + \frac{Bd\theta}{dt} = T = K_2 i_f \quad ...(3.24.4)$$
6. By taking the Laplace transform on both sides of eq. (3.24.3) and (3.24.4) where all initial conditions are zero, we get
$$(L_f s + R_f)\, i_f(s) = E_f(s) \quad ...(3.24.5)$$
$$(Js^2 + Bs)\, \theta(s) = K_2 i_f(s) \quad ...(3.24.6)$$
7. From the eq. (3.24.5) and (3.24.6), the transfer function of this system is obtained as
$$\frac{\theta(s)}{E_f(s)} = \frac{K_2}{s(L_f s + R_f)(Js + B)} \quad ...(3.24.7)$$
8. Block diagram is shown in Fig. 3.24.2.

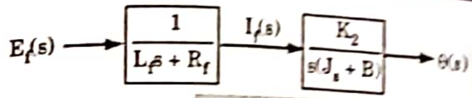


Fig. 3.24.2.

VERY IMPORTANT QUESTIONS

Following questions are very important. These questions may be asked in your SESSIONALS as well as UNIVERSITY EXAMINATION.

Q. 1. Describe performance characteristic of shunt motor (DC). Also describe torque versus current plot.

Ans. Refer Q. 3.1

Q. 2. Compare the speed-torque characteristics of DC shunt, series and compound motor. Which machine is most suitable for traction purpose ?

Ans. Refer Q. 3.3.

Q. 3. Describe a 3-point starter using a neat diagram. Compare and distinguish it with a four point starter.

Ans. Refer Q. 3.5.

Q. 4. Write short note on field flux control in speed control of DC motor.

Ans. Refer Q. 3.7.

Q. 5. Explain armature resistance control method in speed control of DC motor.

Ans. Refer Q. 3.8.

Q. 6. What are the advantages of the field flux control over armature circuit resistance control method employed for the speed control of DC motors ?

Ans. Refer Q. 3.11.

Q. 7. Discuss Hopkinson's test on DC machines.

Ans. Refer Q. 3.15.

Q. 8. Explain construction and working principle of brushless DC motors with applications.

Ans. Refer Q. 3.22.

☺☺☺

4 UNIT

Single Phase Transformers

CONTENTS

PART-1

Pre-Requisites : Construction and Principle, Ideal and Practical Transformer, Equivalent Circuit and Phasor Diagram, Losses in Transformers.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 4.1. **What is transformer ? Explain the constructional features of different types of transformer.**

Answer

A. **Transformer :** A transformer is a static electrical device transfer electrical energy between two or more circuits through electromagnetic induction.

B. **Types :**

a. **Core-type transformer :**

1. In the core-type transformer, the magnetic circuit consists of two vertical legs or limbs with two horizontal sections, called yokes.
2. To keep the leakage flux to a minimum, half of each winding is placed on each leg of the core as shown in Fig. 4.1.1.
3. The low-voltage winding is placed next to the core and the high-voltage winding is placed around the low-voltage winding to reduce the insulating material required.
4. Thus, the two windings are arranged as concentric coils. Such a winding is, therefore, called concentric winding or cylindrical winding.

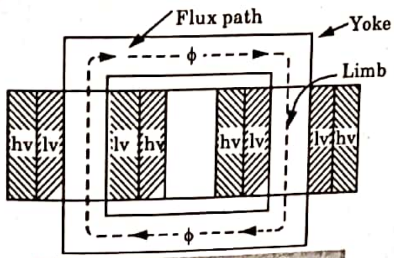


Fig. 4.1.1. Core-type transformer.

b. Shell-type transformer :

1. In the shell-type transformer (Fig. 4.1.2), both primary and secondary windings are wound on the central limb, and the two outer limbs complete the low-reluctance flux paths.

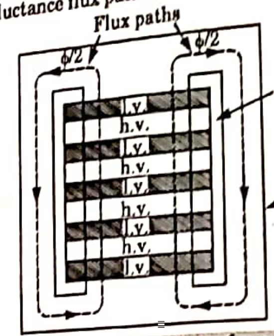


Fig. 4.1.2. Shell-type transformer.

2. Each winding is subdivided into sections. Low-voltage (*lv*) and high-voltage (*hv*) subsections are alternately put in the form of a sandwich. Such a winding is, therefore, called sandwich or disc winding.

Que 4.2. **Explain working of single phase transformer.**

Answer

1. Consider two coils 1 and 2 wound on a simple magnetic circuit as shown in Fig. 4.2.1. These two coils are insulated from each other and there is no electrical connection between them.

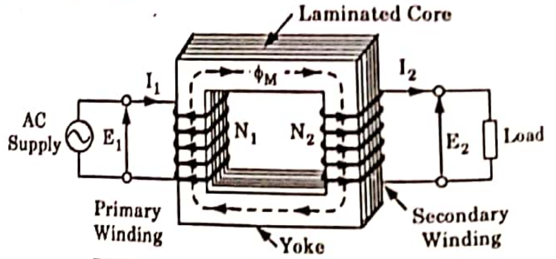


Fig. 4.2.1. Arrangements of a transformer.

2. Let N_1 and N_2 be the number of turns in coils 1 and 2 respectively.
3. When a source of alternating voltage V_1 is applied to coil 1, an alternating current I_0 flows in it. This alternating current produces an alternating flux ϕ_M in the magnetic circuit.
4. The mean path of this flux is shown in Fig. 4.2.1 by the dotted line.
5. This alternating flux links the turns N_1 of coil 1 and induces in them an alternating voltage E_1 by self-induction.

6. Thus, all the flux produced by coil 1 also links N_2 turns of coil 2 and induces in them a voltage E_2 by mutual induction.
7. If coil 2 is connected to a load then an alternating current will flow through it and energy will be delivered to the load.
8. Thus, electrical energy is transferred from coil 1 to coil 2 by a common magnetic circuit.
9. Coil 1, which receives energy from the source of AC supply, is called the primary coil or primary winding or simply the primary.
10. Coil 2, which is connected to load and delivers energy to the load, is called the secondary coil or secondary winding or simply the secondary.

Que 4.3. **Give the difference between ideal transformer and practical transformer.**

Answer

Difference :

S. No.	Ideal transformer	Practical transformer
1.	It has 100 % efficiency.	It has below 100 % efficiency.
2.	It has no losses.	It has losses.
3.	There is no ohmic resistance drop.	There is ohmic resistance drop.
4.	It has no leakage drop.	It has leakage drop.

Que 4.4. **Derive emf-equation for a single phase transformer.**

Answer

1. Let the flux at any instant be given by

$$\phi = \phi_m \sin \omega t \qquad ...(4.4.1)$$

2. The instantaneous emf induced in a coil of N turns linked by this flux is given by Faraday's law as

$$e = -\frac{d}{dt}(\phi N) = -N\frac{d\phi}{dt} = -N\frac{d}{dt}(\phi_m \sin \omega t)$$
$$= -N\omega\phi_m \cos \omega t$$
$$= N\omega\phi_m \sin(\omega t - \pi/2)$$
$$e = E_m \sin(\omega t - \pi/2) \qquad ...(4.4.2)$$

where $E_m = N\omega\phi_m$ = Maximum value of e.

3. For a sine wave, the rms value of emf is given by

$$E_{rms} = E = E_m / \sqrt{2}$$

$$E = \frac{N\omega\phi_m}{\sqrt{2}} = \frac{N(2\pi f)\phi_m}{\sqrt{2}}$$

$$\therefore \quad E = 4.44\,\phi_m f N \qquad \ldots(4.4.3)$$

eq. (4.4.3) is called the emf equation of a transformer.

4. The emf induced in each winding of the transformer can be calculated from its emf equation. Let subscripts 1 and 2 be used for primary and secondary quantities. The primary rms voltage is

$$E_1 = 4.44\,\phi_m f N_1 \qquad \ldots(4.4.4)$$

5. The secondary rms voltage is

$$E_2 = 4.44\,\phi_m f N_2 \qquad \ldots(4.4.5)$$

where ϕ_m is the maximum of flux in webers (Wb), f is the frequency in hertz (Hz) and E_1 and E_2 are in volts.

Que 4.5. **Derive and explain the equivalent circuit of a transformer.**

Answer

1. Transformer has 3 main parts :
i. Primary winding
ii. Core
iii. Secondary winding.
2. Primary winding is shown by series combination of resistance R_1 and reactance X_{L1}, whereas secondary winding is shown by series combination of resistance R_2 and reactance X_{L2}.
3. The core of transformer is assumed to be parallel combination of resistance R_0 and reactance X_0. R_0 represents the core loss and hence known as core loss resistance, whereas X_0 represents magnetising reactance of the core.

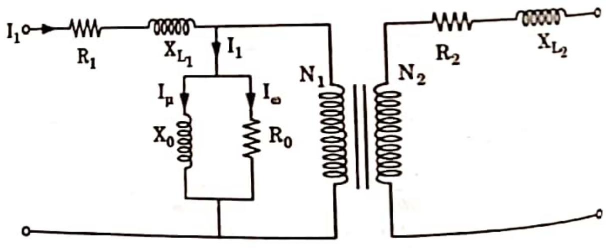


Fig. 4.5.1.

4. N_1 and N_2 show number of turns. The voltage levels of primary and secondary are different.

5. To bring all the components of equivalent circuit to one voltage level, either primary side components are to be shifted on secondary or secondary side components to be shifted on primary.

i. **Equivalent circuit as referred to primary or secondary components shifted to primary :**

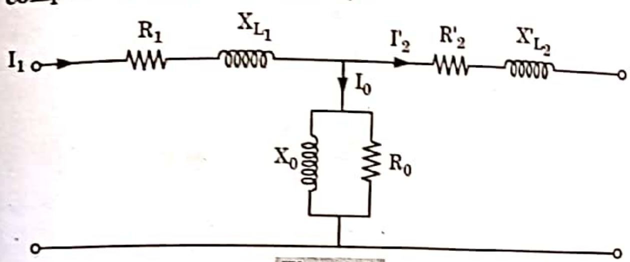


Fig. 4.5.2.

ii. **Equivalent circuit as referred to secondary :**

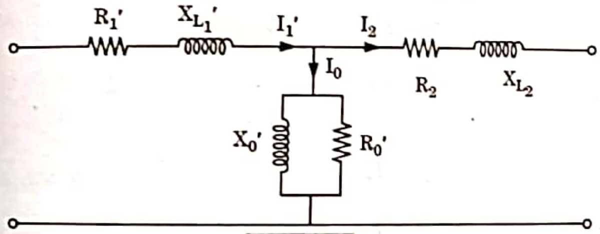


Fig. 4.5.3.

Que 4.6. **Explain the phasor diagram of 1ϕ transformer at the following loads :**
i. Unity pf load
ii. Lagging pf load
iii. Leading pf load

Answer

Phasor diagram of 1ϕ transformer :

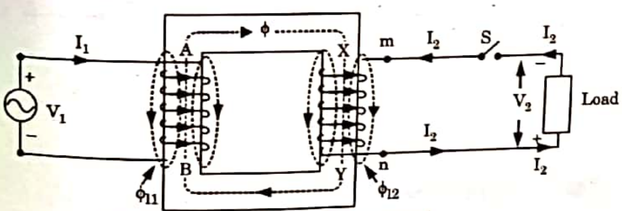


Fig. 4.6.1. Transformer under load.

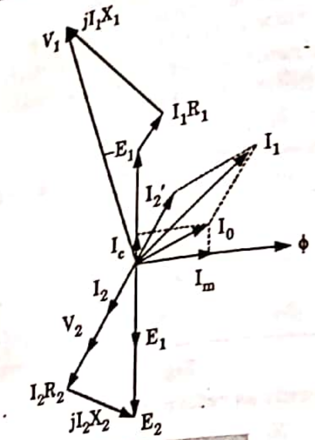


Fig. 4.6.2. Unity pf load.

$$V_1 = -E_1 + I_1R_1 + jI_1X_1$$
$$E_2 = V_2 + I_2R_2 + jI_2X_2$$
$$\vec{I}_0 = \vec{I}_m + \vec{I}_c$$
$$\vec{I}_1 = \vec{I}_0 - \vec{I}_2'$$

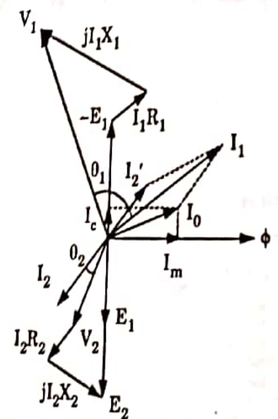


Fig. 4.6.3. Lagging pf.

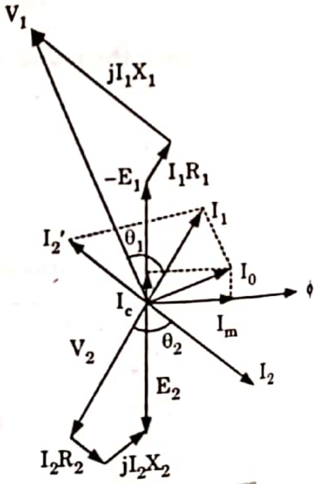


Fig. 4.6.4. Leading pf.

Que 4.7. **Describe the various losses in a transformer.**

Answer

Losses in transformer :

A. **Iron loss or core loss P_i :**

1. Iron loss occurs in the magnetic core of the transformer. This loss is the sum of hysteresis loss (P_h) and eddy current loss (P_e),
$$P_i = P_h + P_e$$
2. The hysteresis and eddy current losses are given by
$$P_h = K_h f B^x_m$$
$$P_e = K_e f^2 B^2_m$$
where, K_h, K_e = Proportionality constant.
B_m = Maximum flux density in the core.
f = Frequency of the alternating flux.
3. The exponent x is called Steinmetz constant. Its value varies from 1.5 to 2.5, depending upon the magnetic properties of the core material.
4. The total core loss can be written as
$$P_i = P_h + P_e$$
$$P_i = K_h f B^x_m + K_e f^2 B^2_m \quad ...(4.7.1)$$

B. **Copper loss or I^2R loss (P_c) :**

1. Copper loss is the I^2R loss which takes place in the primary and secondary windings because of the winding resistances.
2. Total copper loss in a transformer = Primary winding copper loss + Secondary winding copper loss
$$P_c = I_1^2R_1 + I_2^2R_2$$

C. **Stray load loss :** Leakage fields present in a transformer induce eddy current in conductors, tanks, channels, bolts etc., and these eddy current give rise to stray load loss.

D. **Dielectric loss :** This loss occurs in the insulating materials, *i.e.*, in the transformer oil and the solid insulation of h.v. transformers.

PART-2

Efficiency and Voltage Regulation, All Day Efficiency, Excitation Phenomenon and Harmonics in Transformers.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 4.8. **Define transformer efficiency and derive the condition for maximum efficiency.**

Answer

Transformer efficiency :

1. The ratio of the output power to input power in a transformer is known as transformer efficiency (η).

$$\eta = \frac{\text{Output power}}{\text{Input power}}$$

$$= \frac{\text{Output power}}{\text{Output power + Copper loss + Iron loss}} \text{ pu}$$

2. Thus, the per unit efficiency at load current I_2 and power factor $\cos\phi_2$ is

$$\eta = \frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + I_2^2 R_{e_2} + P_i} \text{ pu}$$

where
η = Efficiency
V_2 = Load voltage
I_2 = Load current
$\cos\phi_2$ = Power factor
P_i = Iron loss

$$\therefore \quad \eta = \frac{V_2 \cos\phi_2}{V_2 \cos\phi_2 + I_2 R_{e_2} + (P_i / I_2)}$$

3. At maximum efficiency

$$d\eta / dI_2 = 0$$

4. Since V_2 and $\cos\phi_2$ are constants for a given load, the efficiency will be a maximum when the denominator $D_r\left(= V_2 \cos\phi_2 + I_2 R_{e_2} + \frac{P_i}{I_2}\right)$ is a minimum.

5. For a minimum value of the denominator D_r

$$\frac{dD_r}{dI_2} = 0 \text{ and } \frac{d^2 D_r}{dI_2^2} > 0$$

$$\frac{dD_r}{dI_2} = \frac{d}{dI_2}\left(V_2 \cos\phi_2 + I_2 R_{e_2} + \frac{P_i}{I_2}\right) = 0 + R_{e_2} - \frac{P_i}{I_2^2}$$

6. For a minimum D_r,

$$R_{e_2} - \frac{P_i}{I_2^2} = 0$$

$$I_2^2 R_{e_2} = P_i \quad \text{...(4.8.1)}$$

7. The efficiency of a transformer for a given power factor is a maximum when the variable copper loss is equal to the constant iron (core) loss.

Que 4.9. **Explain voltage regulation of a transformer.**

Answer

1. The voltage regulation of a transformer is defined as the arithmetical difference in the secondary terminal voltage between no-load ($I_2 = 0$) and full-rated load ($I_2 = I_{2fl}$) at a given power factor with the same value of primary voltage for both rated load and no-load.
2. It is expressed as either a per unit or a percentage of the rated load voltage.
3. Per-unit voltage regulation at full load

$$= \left.\frac{|\,|V_{2nl}| - |V_{2fl}|\,|}{|V_{2fl}|}\right|_{|V_1| = \text{constant}}$$

Percent voltage regulation at full-load,

$$= \frac{|\,|V_{2nl}| - |V_{2fl}|\,|}{|V_{2fl}|} \times 100$$

where V_{2fl} = Rated secondary terminal voltage at rated load
V_{2nl} = No-load secondary terminal with the same value of primary voltage for both rated load and no-load.

Que 4.10. **Write short note on all-day efficiency.**

Answer

1. All-day efficiency is defined as the ratio of the energy output to the energy input taken over a 24 hour period.
2.
$$\eta_{AD} = \frac{\text{Energy output over 24 hours}}{\text{Energy input over 24 hours}}$$

$$= \frac{\text{Energy output over 24 hours}}{\text{Energy output over 24 hours + Energy losses over 24 hours}}$$

$$= 1 - \frac{\text{Daily losses in kWh}}{\text{Daily input in kWh}}$$

3. If load cycle is known, the all-day efficiency can be determined.

Que 4.11. **Write short note on excitation phenomena in transformers.**

Answer

1. The no-load current in a transformer is non-sinusoidal. The basic cause for this phenomenon lies in hysteresis and saturation non-linearity of the core material.

2. Assume that the voltage V_1 applied to the transformer is sinusoidal. Since the ohmic drop $(R_1 i_0)$ is assumed negligible compared to the magnitude of the applied voltage, the induced emf which balances the applied voltage must also be sinusoidal and so must be the flux established in the core.
3. Further the flux must lag the induced emf by 90° as shown in the emf and flux waveform drawn in Fig. 4.11.1.
4. The current necessary to set up sinusoidal flux can be obtained graphically by looking up the hysteresis curve ($\phi - i_0$ curve).
5. After the steady-state obtained, the hysteresis loop of Fig. 4.11.1 is being repeated in successive cycles of v_1.

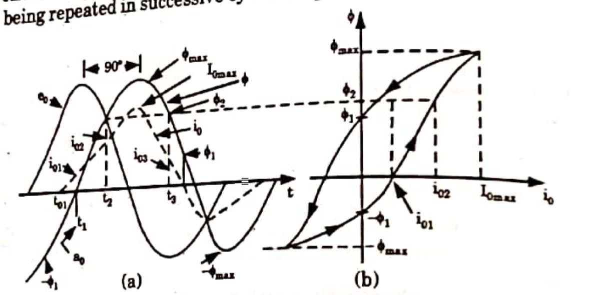


Fig. 4.11.1. Effect of hysteresis and saturation on waveform of exciting current (flux sinusoidal).

6. Consider the instant
   At flux = ϕ_1, the exciting current being zero.
   At flux = 0, the current is a small positive value i_{01}.
   At flux = ϕ_2, there are two possible value of current, i_{02} when the flux is on the increasing part of hysteresis loop and i_{03}, when the flux is on decreasing part, $i_{02} > i_{03}$.
7. The ϕ_{max} coincides with the current maximum $+i_{max}$, and current becomes zero once again.
8. So for the positive half of exciting current has been traced out; the negative half will be odd symmetrical, this is the excitation phenomenon in transformers.
9. From current wave shape of Fig. 4.11.1, it is observed that it is nonsinusoidal.

Que 4.12. **Explain how harmonics are produced in transformers even when the supply voltage is purely sinusoidal ?**

Answer

A. Harmonics :

1. Harmonics are the distortion in the waveform of the voltage and current. It is the integral multiple of some reference waves.

2. The harmonic wave increases the core and copper loss of the transformer and hence reduces their efficiency, it also increases the dielectric stress on the insulation of the transformer.
3. In a transformer, the non-sinusoidal nature of magnetising current produces sinusoidal flux which gives rise to the undesirable phenomenon.
4. The phase magnetising currents in transformer should contain third harmonics and higher harmonics necessary to produce a sinusoidal flux.
5. If the phase voltage across each phase is to remain sinusoidal then the phase magnetizing currents must be of the following form :

$$I_{AO} = I_m \sin \omega t + I_{3m} \sin (3\omega t + \phi_3) + I_{5m} \sin (5\,\omega t + \phi_5) + ... \quad ...(4.12.1)$$

$$I_{BO} = I_{1m} \sin (\omega t - 120°) + I_{3m} \sin [3\,(\omega t - 120°) + \phi_3] + I_{5m} \sin [5\,(\omega t - 120°) + \phi_5] + ...$$

$$I_{BO} = I_{1m} \sin (\omega t - 120°) + I_{3m} \sin [3\,(\omega t + \phi_3) + I_{5m} \sin (5\,\omega t + 120° + \phi_5) + ... \quad ...(4.12.2)$$

$$I_{CO} = I_{1m} \sin (\omega t - 240°) + I_{3m} \sin [3\,(\omega t - 240°) + \phi_3] + I_{5m} \sin [5\,(\omega t - 240°) + \phi_5] + ...$$

$$I_{CO} = I_{1m} \sin (\omega t - 240°) + I_{3m} \sin (3\omega t + \phi_3) + I_{5m} \sin (5\omega t + 240° + \phi_5) + ... \quad ...(4.12.3)$$

6. It is seen from eq. (4.12.1), (4.12.2) and (4.12.3) that the third harmonics in the three currents are cophasal, that is they have the same phase and the fifth harmonics have different phases.

B. Neutralization of harmonics in transformers :

1. The effect of third harmonic voltages in high voltage star-star connected transformers can be neutralized with isolated neutrals. With isolated neutral, the triple frequency current cannot flow in the circuit.
2. The alternative way of overcoming third harmonics is to use a tertiary winding which provides a circuit in which the third harmonics can flow. Thus the effect of third harmonics is neutralized.

Que 4.13. **What is meant by transformer inrush current ? Explain the effect of hysteresis and saturation during excitation phenomenon in transformers.** AKTU 2014-15, Marks 10

OR

Write short notes on inrush current in transformers.

AKTU 2015-16, Marks 05

Answer

A. **Inrush current :**

1. Inrush current is the maximum, instantaneous input current drawn by the transformer during switching on.
2. Let a sinusoidal voltage
$$v_1 = V_{1m} \sin(\omega t + \alpha) \quad ...(4.13.1)$$
be applied to the primary of a transformer, the secondary of which is an open-circuit. Here, α is the angle of voltage sinusoid at $t = 0$.
3. Suppose for the moment we neglect core losses and primary resistance, then
$$v_1 = T_1 \frac{d\phi}{dt} \quad ...(4.13.2)$$
where T_1 is the number of primary turns and ϕ is the flux in core.
In steady state, $V_{1m} = \omega \phi_m T_1$
4. From eq. (4.13.1) and (4.13.2),
$$T_1 \frac{d\phi}{dt} = V_{1m} \sin(\omega t + \alpha)$$
$$\frac{d\phi}{dt} = \frac{V_{1m}}{T_1} \sin(\omega t + \alpha) \quad ...(4.13.3)$$
5. From eq. (4.13.2) and (4.13.3)
$$\frac{d\phi}{dt} = \omega \phi_m \sin(\omega t + \alpha) \quad ...(4.13.4)$$
6. Integrating eq. (4.13.4) gives
$$\phi = -\phi_m \cos(\omega t + \alpha) + \phi_c$$
7. At $t = 0$,
$$\phi = \phi_r$$
$$\therefore \quad \phi_r = -\phi_m \cos\alpha + \phi_c$$
$$\phi_c = \phi_r + \phi_m \cos\alpha \quad ...(4.13.5)$$
8. Eq. (4.13.5) becomes
$$\phi = \underbrace{-\phi_m \cos(\omega t + \alpha)}_{\text{Steady - state component}} + \underbrace{\phi_r + \phi_m \cos\alpha}_{\text{Transient component}} \quad ...(4.13.6)$$
9. Eq. (4.13.6) shows that the flux consists of two components, the steady-state component and the transient component. The magnitude of transient component,
$$\phi_c = \phi_r + \phi_m \cos\alpha,$$
is a function of α.

3. **Drawback :** It may cause improper operation of protective devices like unwanted tripping of relays, momentary large voltage drops and large humming due to magnetostriction of the core.

Excitation phenomenon : Refer Q. 4.11, Page 4–10B, Unit-4.

ue 4.14. **A 500 kVA transformer has an efficiency of 95 % at full-d and also at 60 % of full-load; both at unity power factor.**

i. Separate out the losses of the transformer.
ii. Determine the efficiency of the transformer at 3/4th full-load.

AKTU 2014-15, Marks 10

AKTU 2017-18, Marks 07

Answer

Given : $\eta_1 = 0.95, x_1 = 1, \eta_2 = 0.60, x_2 = 0.6$
$\cos\phi = 1$, kVA = 500 kVA

To Find :
i. Losses, P_i and P_c, ii. Efficiency, η at $x = 3/4$.

i. 1. At full-load, $x_1 = 1, \eta_1 = 0.95, \cos\phi = 1$
$$\eta = \frac{xVA\cos\phi}{xVA\cos\phi + P_i + x^2 P_c}$$
$$0.95 = \frac{500 \times 10^3}{500 \times 10^3 + P_i + P_c}$$
$$\therefore \quad P_i + P_c = 26315.78 \quad ...(4.14.1)$$
2. At 60 % of full-load *i.e.*, $x_2 = 0.6$,
$$0.95 = \frac{500 \times 10^3 \times 0.6}{0.6 \times 500 \times 10^3 + 0.36 P_c + P_i}$$
$$P_i + 0.36\, P_c = 1578.47 \quad ...(4.14.2)$$
3. Solving eq. (4.14.1) and eq. (4.14.2), we get
$$P_i = 9868.4 \text{ W}$$
$$P_c = 16447.37 \text{ W}$$

ii. At $x = \dfrac{3}{4}$,
$$\eta = \frac{0.75 \times 500 \times 10^3 \times 1}{0.75 \times 500 \times 10^3 \times 1 + 9868.42 + (0.75)^2 \times 16.44}$$
$$= 0.95148 = 95.148\ \%$$

Que 4.15. **A 2300/220 V 500 kVA, 50 Hz distribution transformer has the core losses of 1600 W at rated voltage and copper loss 7.5 kW at full load. During the day, it is loaded as follows :**

Load	0 %	20 %	50 %	80 %	100 %	125 %
Power Factor		0.7 lag	0.8 lag	0.9 lag	1	0.85 lag
Hours	2	4	4	5	7	2

AKTU 2015-16, Marks 10

Answer

1. Assuming we have to determine all day efficiency of transformer.
   Energy output = kVA × cos ϕ × hours kWh. Total energy output over the 24 hour period is given in the Table 4.15.1 :

Table 4.15.1

% Rated load	p.f.	kVA cos ϕ	kW	Hours	Output energy (kWh)
20	0.7	$0.2 \times 500 \times 0.7$	70	4	280
50	0.8	$0.5 \times 500 \times 0.8$	200	4	800
80	0.9	$0.8 \times 500 \times 0.9$	360	5	1800
100	1.0	$1.0 \times 500 \times 1.0$	500	7	3500
125	0.85	$1.25 \times 500 \times 0.85$	531.25	2	1062.5
					7442.5

2. Total energy output over 24 hour period,
   $$W_{out} = 7442.5 \text{ kWh}$$
3. Total energy loss in the core for 24 hours load,
   $$W_i = P_i \times t = \frac{1600}{1000} \times 24 = 38.4 \text{ kWh}$$
   Copper loss at rated load = 7.5 kW
4. Copper loss at any other load = m^2 × copper loss at rated load
   where $m = \dfrac{\text{Given load}}{\text{Full load}}$
   The various energy losses in the winding of the transformer can be calculated as given in the following table.

Table 4.15.2.

% Rated load	m	Copper loss $= m^2 P_{cfl}$	Hours (h)	Energy loss in the winding ($m^2 P_{cfl}$ h) kWh
20	0.2	$(0.2)^2 \times 7.5$	4	1.2
50	0.5	$(0.5)^2 \times 7.5$	4	7.5
80	0.8	$(0.8)^2 \times 7.5$	5	24.0
100	1.0	$(1.0)^2 \times 7.5$	7	52.5
125	1.25	$(1.25)^2 \times 7.5$	2	23.44
				108.64 kWh

5. Total energy loss in the transformer winding for 24 hours,
   $$W_c = 108.64 \text{ kWh}$$
6. Total energy loss in 24 hours
   $$= W_i + W_c = 38.4 + 108.64 = 147.04 \text{ kWh}$$
7. Total energy output in 24 hours,
   $$W_{out} = 7442.5 \text{ kWh}$$
8. All-day efficiency,
   $$\eta_{AD} = \frac{W_{out}}{W_{out} + W_i + W_c} = \frac{7442.5}{7442.5 + 147.04} = 0.9808$$
   $$= 98.06\ \%$$

PART-3

Testing of Transformers : O.C. and S.C. Tests, Polarity Test, Sumpner's Test.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 4.16. **Explain the procedure of O.C. and S.C. tests for a transformer. How different parameters of the transformer can be determined from these tests ?**

AKTU 2016-17, Marks 10

AKTU 2018-19, Marks 07

Answer

A. **Open-circuit test :**
1. The open-circuit (O.C.) or no-load test gives the following information :
   a. Core-loss at rated voltage and frequency.
   b. The shunt branch parameters of the equivalent circuit, *i.e.*, R_c and X_m.
   c. Turns ratio of the transformer.
2. The circuit diagram for performing open-circuit test on single-phase transformer is given in Fig. 4.16.1.
3. A voltmeter, wattmeter and an ammeter are connected on the low voltage side of the transformer.
4. The rated frequency voltage applied to the low voltage side, is varied with the help of a variable ratio auto- transformer and high voltage side is kept open circuited.

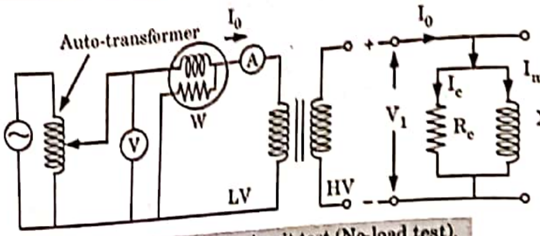


Fig. 4.16.1. Open-circuit test (No-load test).

5. The ammeter records the no-load current or exciting current I_0. I_0 is quite small (2 to 6 %) of rated current so primary leakage impedance drop is negligible.
6. The wattmeter recorded input power consists of core loss and ohmic loss.
7. The readings of the instruments in an open-circuit test are as follows :

Ammeter reading = No-load current, I_0

Voltmeter reading = Primary rated voltage, V_1

Wattmeter reading = Iron or core loss, P_i

From these measured values the components of the no-load equivalent circuit can be determined.

$$P_i = V_1 I_0 \cos \phi_0$$

The no-load power factor, $\cos \phi_0 = \dfrac{P_i}{V_1 I_0}$

$$I_c = I_0 \cos \phi_0, I_m = I_0 \sin \phi_0$$

$$R_c = \frac{V_1}{I_c}, \quad X_m = \frac{V_1}{I_m}$$

B. Short-circuit test :

1. The purpose of this test is to determine full-load copper loss and equivalent impedance to metering side.
2. In this test, the terminals of secondary winding are short circuited by a thick wire or strip through an ammeter and variable low voltage is applied to primary through an auto-transformer.
3. The transformer now becomes equivalent to a coil having an impedance equal to impedance of both winding.
4. The applied voltage V_s to primary is gradually increased till the ammeter indicates full-load rated current of metering side.
5. Since applied voltage is very low (5-8 % of rated voltage) so flux linking with core is very small and therefore iron losses are so small that these can be neglected.

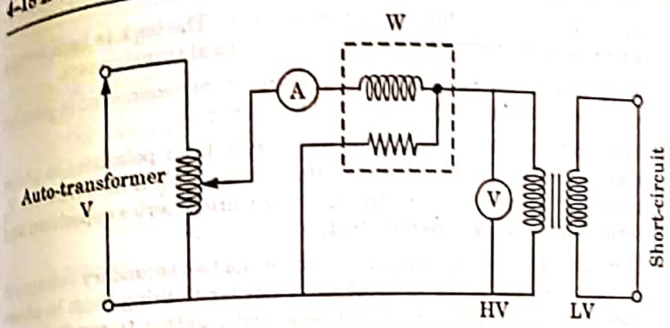


Fig. 4.16.2. Short-circuit test.

6. Thus the power input gives the total copper loss at rated load, output being nil.
7. Full-load copper loss,

$$P_c = I_s^2 R_{eq}$$

8. Equivalent resistance,

$$R_{eq} = \frac{P_c}{I_s^2}$$

9. Equivalent impedance,

$$Z_{eq} = \frac{V_s}{I_s}$$

10. Equivalent reactance,

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

Que 4.17. **Explain the back to back test for testing of the single-phase transformers. Also explain how the reading of the wattmeter recording the core losses remain unaffected when the low voltage is injected in the secondary series circuit ?**

AKTU 2015-16, Marks 10

OR

Discuss the following test on 1ϕ transformers :

i. Sumpner's back to back test

ii. Polarity test

AKTU 2016-17, Marks 7.5

Answer

i. Sumpner's back to back test :

1. In order to determine the maximum temperature rise, it is necessary to conduct a full-load test on a transformer or "back to back" test, it is also

called "Regenerative test or Sumpner's test". The back to back test on single-phase transformer requires two identical transformers.

2. The primary winding of the two transformers are connected in parallel and rated voltage is applied at rated frequency.
3. The secondary are connected in series with their polarities in phase opposition which can be checked by the voltmeter V_2. If the voltmeter V_2 across a, b, point reads zero, the secondary are in series opposition and terminals a and b are used for test.
4. If voltmeter V_2 voltage is equal to sum of the two secondary voltages it means these are in the same phase. In order to bring them in phase opposition, terminal a, d, should be joined together to result in zero voltage across terminal b, c.
5. If the primary circuit is closed, the total voltage across the two secondary in series will be zero. There will be no current in the secondary windings.
6. If their secondary windings are open circuited, the reading of wattmeter W_1 gives the iron losses of both the transformer.
7. A small voltage is injected in secondary circuit by voltage regulator. The magnitude of the injected voltage is adjusted till the ammeter A_2 reads full-load secondary current.
8. The secondary current produces full-load current to flow through the primary windings.
9. This current will follow a circulatory path through the main busbars. The reading of wattmeter W_1 will not be affected by this current.
10. Thus, wattmeter W_2 gives the full-load copper losses of the two transformers.

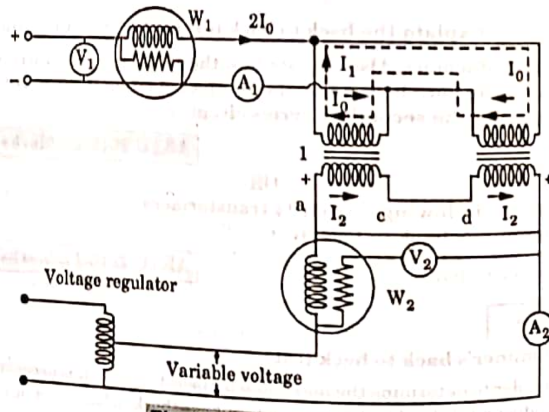
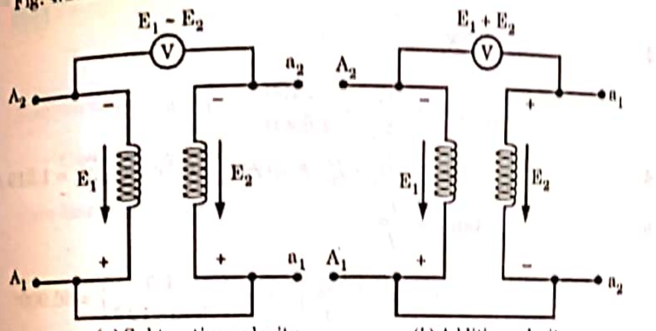


Fig. 4.17.1. Sumpner's test.

ii. **Polarity test :**

1. In determining the relative polarity of the two-windings of a transformer, the two-windings are connected in series across a voltmeter while one of the winding is excited from a suitable voltage source as shown in Fig. 4.17.2.



(a) Subtractive polarity (b) Additive polarity

Fig. 4.17.2. Polarity test.

2. If the polarities of the windings are similar as shown in Fig. 4.17.2(b) then the voltmeter should read $(E_1 + E_2)$, which is called additive polarity.
3. On account of these reasons, the polarity marking of one of the windings must be interchanged, then after interchanging polarity voltmeter reads $E_1 - E_2$ is called subtractive polarity. Subtractive polarity is preferable to additive polarity.

Que 4.18. **The parameters of the equivalent circuit of a 150 kVA, 2400/240 V transformer are :**
R_1 = 0.2 Ω, R_2 = 2 × 10^{-3} Ω, X_1 = 0.45 Ω, X_2 = 4.5 × 10^{-3} Ω, R_i = 10 kΩ, X_m = 1.6 kΩ (as seen from 2400 V side).
Calculate :
i. Open-circuit current, power and power factor when LV is excited at rated voltage.
ii. The voltage at which the HV should be excited to conduct a short circuit test (LV shorted) with full-load current flowing. What is the input power and power factor ?

AKTU 2014-15, Marks 10

Answer

Given : $R_i = R_c = 10$ kΩ, $R_1 = 0.2$ Ω, $X_m = 1.6$ kΩ, $R_2 = 2 \times 10^{-3}$ Ω
$K = V_2/V_1 = 0.1$, $X_1 = 0.45$ Ω, $X_2 = 4.5 \times 10^{-3}$ Ω
To Find : i. I_0, W_0 and $\cos \phi_0$, ii. V_s, W_s and $\cos \phi_s$.

i.

1. All given values are referred to HV side,

$$R_c = V_0 / I_c$$

2. ∴ $$I_c = \frac{V_0}{R_c} = \frac{2400}{10 \times 10^3} = 240 \times 10^3 \text{ A}$$

3. $$X_m = \frac{V_0}{I_m}$$

∴ $$I_m = \frac{V_0}{X_m} = \frac{2400}{1.6 \times 10^3} = 1.5 \text{ A}$$

4. ∴ $$|I_0| = \sqrt{I_c^2 + I_m^2} = \sqrt{(240 \times 10^{-3})^2 + (1.5)^2} = 1.519 \text{ A}$$

5. $$\tan \phi_0 = \frac{I_m}{I_c}$$

$$\phi_0 = \tan^{-1}\left(\frac{I_m}{I_c}\right) = \tan^{-1}\left(\frac{1.5}{240 \times 10^{-3}}\right) = 80.909°$$

6. ∴ $$\cos \phi_0 = \cos 0.909° = 0.158$$

7. If LV is excited, $V_0 = 240$ V, hence current becomes I_0 / K *i.e.*,

$$I_0 = 15.19 \text{ A}$$

8. ∴ $$W_0 = V_0 I_0 \cos \phi_0 = 240 \times 15.19 \times 0.158 = 576 \text{ W}$$

ii.

1. $$I_{fl1} = \frac{VA}{V_1} = \frac{150 \times 10^3}{2400} = 62.5 \text{ A} = I_s$$

2. $$R_{1e} = R_1 + \frac{R_2}{K^2} = 0.2 + \frac{2 \times 10^{-3}}{(0.1)^2} = 0.4\ \Omega$$

3. $$X_{1e} = X_1 + \frac{X_2}{K^2} = 0.45 + \frac{4.5 \times 10^{-3}}{(0.1)^2} = 0.9\ \Omega$$

4. ∴ $$Z_{1e} = \sqrt{R_{1e}^2 + X_{1e}^2} = \sqrt{(0.4)^2 + (0.9)^2} = 0.9848\ \Omega$$

5. $$V_s = Z_{1e} I_s = 0.9848 \times 62.5 = 61.555 \text{ V}$$

6. $$W_s = I_s^2 R_{1e} = (62.5)^2 \times 0.4 = 1562.5 \text{ W}$$

7. ∴ $$\cos \phi_s = \frac{W_s}{V_s I_s} = \frac{1562.5}{61.555 \times 62.5} = 0.4061 \text{ (lagging)}$$

Que 4.19. **A transformer on no-load has a core loss of 50 W, draws a current of 2 A (rms) and has an induced emf of 230 V (rms). Determine the no-load power factor, core-loss current and magnetizing current. Also calculate the no-load circuit parameters of the transformer. Neglect winding resistance and leakage flux.**

AKTU 2017-18, Marks 07

Answer

Given : $P_i = 50$ W, $I_o = 2$ A, $V_1 = 230$ V

To Find : No load circuit parameters.

1. Power factor,

$$\cos \theta_0 = \frac{50}{2 \times 230} = 0.108 \text{ lagging;}$$

$$\theta_0 = 83.76°$$

2. Magnetizing current,

$$I_m = I_0 \sin \theta_0 = 2 \sin (\cos^{-1} 0.108) = 1.988 \text{ A}$$

3. Core-loss current,

$$I_i = I_0 \cos \theta_0 = 2 \times 0.108 = 0.216 \text{ A}$$

4. Core loss is given by

$$G_i V_1^2 = P_i$$

$$G_i = \frac{P_i}{V_1^2} = \frac{50}{(230)^2} = 0.945 \times 10^{-3}\ \mho$$

5. Also $$I_m = B_m V_1$$

$$B_m = \frac{I_m}{V_1} = \frac{1.988}{230} = 8.64 \times 10^{-3}\ \mho$$

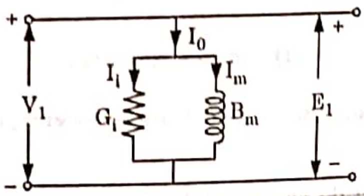


Fig. 4.19.1. Circuit model of transformer on no-load (exciting current).

Que 4.20. **Define voltage regulation in transformer. A 20 kVA, 2500/500 V, single phase transformer has the following parameters :**

HV side : $r_1 = 8\ \Omega$, $x_1 = 17\ \Omega$

LV side : $r_1 = 0.3\ \Omega$, $x_1 = 0.7\ \Omega$

Find the voltage regulation at full load for a power factor of 0.8 lagging.

AKTU 2018-19, Marks 07

Answer

i. **Voltage regulation :** Refer Q. 4.9, Page 4–10B, Unit-4.

ii. **Numerical :**

1. Equivalent resistance referred to *lv* or secondary winding.

$$r_{e2} = 0.3 + 8\left(\frac{500}{2500}\right)^2 = 0.62\ \Omega$$

2. Equivalent reactance referred to secondary winding,

$$x_{e2} = 0.7 + 17\left(\frac{1}{25}\right)^2 = 1.38\ \Omega$$

3. Full load secondary current $= \dfrac{20,000}{500} = 40$ A

4. The full-load voltage drop in the secondary terminal voltage, for a lagging pf is,

$$E_2 - V_2 = I_2 r_{e2} \cos\theta_2 + I_2 x_{e2} \sin\theta_2$$
$$= 40(0.62)\,(0.8) + 40(1.38)\,(0.6) = 52.96 \text{ V}$$

5. Secondary terminal voltage, $V_2 = 500 - 52.96 = 447.04$ V

6. Voltage regulation $= \dfrac{E_2 - V_2}{E_2} = \dfrac{52.96}{500} = 0.1059$ or $10.59\ \%$

PART-4

Auto-transformer : Single-Phase and Three-Phase Auto-transformers, Volt-ampere Relation, Copper Saving in Auto-transformer, Efficiency, Merits and Demerits and Applications.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 4.21. **What do you mean by "1ϕ auto-transformer" and "3ϕ auto-transformer" ? Also mention its advantages and limitations over 1ϕ, two-winding transformers.**

Answer

A. 1ϕ auto-transformer :

1. A 1ϕ auto-transformer is a one winding transformer in which a part of the winding is common to both high-voltage and low-voltage sides.
2. Consider a single winding *abc* of Fig. 4.21.1. The terminals *a* and *c* are the high-voltage terminals. The low-voltage terminals are *b* and *c* where *b* is a suitable tapping point.
3. The portion *bc* of the full winding *abc* is common to both high-voltage and low-voltage sides. The winding *bc* is called the common winding and the smaller winding *ab* is called the series winding because it is connected in series with the common winding.

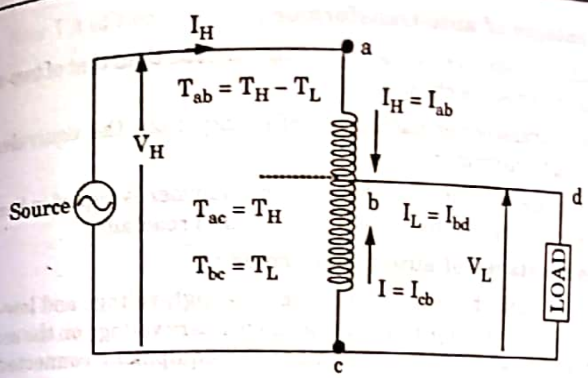


Fig. 4.21.1. Step-down auto-transformer.

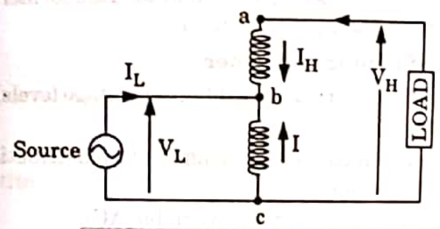


Fig. 4.21.2. Step-up auto-transformer.

B. 3ϕ auto-transformer :

1. 3ϕ auto-transformers are used for small ratios of transformations.
2. Delta connections are avoided and star connections are normally used for three-phase auto-transformers.
3. The main application of such transformers is for interconnecting two power systems of different voltages, for example, 66 kV to 132 kV systems, 110 to 220 kV systems, 132 to 220 kV systems, 220 to 400 kV systems etc.
4. A three-phase star-connected auto-transformer is shown in Fig. 4.21.3.

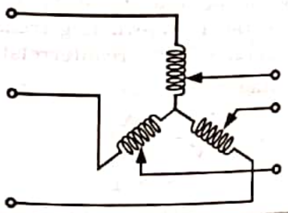


Fig. 4.21.3. A 3ϕ star-connected auto-transformer.

C. Advantages of auto-transformer :

1. An auto-transformer uses less winding material than that of two-winding transformer so it's cheaper.
2. An auto-transformer has higher efficiency than the equivalent two-winding transformer.
3. The voltage regulation of the auto-transformer is superior because of reduced voltage drops in the resistance and reactance.

D. Disadvantages of auto-transformer :

1. There is a direct connection between the high-voltage and low-voltage sides. In case of an open-circuit the full primary voltage on the secondary may burn out or seriously damage the equipment connected to the secondary side.
2. The effective per-unit impedance of an auto-transformer is smaller as compared to a two-winding transformer.

E. Applications of auto-transformer :

1. Interconnection of power systems of different voltage levels. For example, 132 kV and 230 kV.
2. Boosting of supply voltage by a small amount in distribution systems to compensate voltage drop.
3. Auto-transformer is used as variac (variable AC).

Que 4.22. Show that the VA rating of the auto-transformer is more than the corresponding two-winding transformer.
Show that in case of an auto-transformer

$$\frac{\text{Inductively transferred power}}{\text{Total power}} = \frac{\text{High voltage} - \text{Low voltage}}{\text{High voltage}}$$

AKTU 2015-16, Marks 10

Answer

A. **Proof : VA rating of the auto-transformer is more than the corresponding two winding transformer :**

1. Fig. 4.22.1 is known as an auto-transformer. The auto-transformer differs from a conventional two-winding transformer in the way in which the primary and secondary are interrelated.
2. The two-winding voltage ratio is

$$K = \frac{V_1 - V_2}{V_2} = \frac{N_1}{N_2}$$

3. The auto-transformer voltage ratio is

$$K' = \frac{V_1}{V_2} = \frac{(V_1 - V_2) + V_2}{V_2}$$

$$K' = 1 + K$$

4. Now VA of two-winding transformer $(VA)_{TW} = (V_1 - V_2) I_1 = (I_2 - I_1) V_2$ ...(4.22.1)

$$(VA)_{Auto} = V_1 I_1 = V_2 I_2$$

$$= \frac{I_2 - I_1}{I_1} = \frac{N_1}{N_2} = K$$

$$I_1 = \left(\frac{1}{1+K}\right) I_2 \quad \text{...(4.22.2)}$$

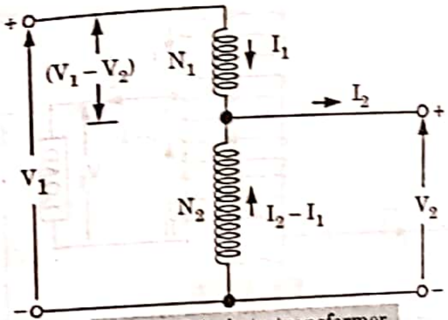


Fig. 4.22.1. Auto-transformer.

5. Substituting eq. (4.22.2) in (4.22.1),

$$(VA)_{TW} = \left(1 - \frac{1}{1+K}\right) V_2 I_2 = \left(1 - \frac{1}{K'}\right) (VA)_{Auto}$$

$$(VA)_{Auto} = \left(\frac{1}{1 - \frac{1}{K'}}\right) (VA)_{TW}$$

$$\therefore \quad (VA)_{Auto} > (VA)_{TW}$$

B. **Proof :**

$$\frac{\text{Inductively transferred power}}{\text{Total power}} = \frac{\text{High voltage} - \text{Low voltage}}{\text{High voltage}}$$

1. The voltage rating of two-winding transformer

$$= (V_1 - V_2) I_1 = (I_2 - I_1) V_2$$

when used as an auto-transformer.

2. Voltage rating as an auto-transformer $= V_1 I_1 = V_2 I_2$
3. $$\frac{\text{Voltampere rating as an auto-transformer}}{\text{Voltampere rating as two-winding transformer}} = \frac{V_1 I_1}{(V_1 - V_2) I_1}$$

$$= \frac{V_2 I_2}{V_2 (I_2 - I_1)} = \frac{1}{1 - K}$$

4. The power delivered to load $= V_2 I_2$
Power in winding $AC = E_{AC} I_1 = (V_1 - V_2) I_1$

Power transformed = Power in winding BC

$$= V_2(I_2 - I_1) = V_2 I_2\left(1 - \frac{I_1}{I_2}\right) = V_2 I_2 (1-K)$$

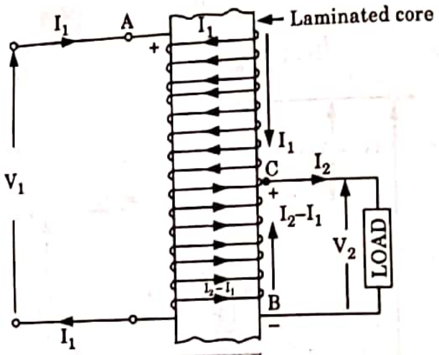


Fig. 4.22.2.

6. Ratio of power transformed to total power delivered

$$= \frac{V_2 I_2 (1-K)}{V_2 I_2} = (1-K)$$

7. Power conducted directly = Power delivered to load – Power transferred by transformation action

$$= V_2 I_2 - V_2 I_2 (1-K) = KV_2 I_2 = K \times \text{Output power}$$

8. $$\frac{\text{Inductively transferred power}}{\text{Total power}} = 1 - K = 1 - \frac{V_2}{V_1} = \frac{V_1 - V_2}{V_1}$$

$$= \frac{\text{High voltage} - \text{Low voltage}}{\text{High voltage}}$$

Que 4.23. **Show that the VA rating of the auto-transformer is more than the corresponding two winding transformer. Derive an expression for copper saving in case of auto-transformer.**

AKTU 2018-19, Marks 07

Answer

A. **VA rating :** Refer Q. 4.22, Page 4–25B, Unit-4.

B. **Copper saving :**

1. Current in a conductor is proportional to cross-section of conductor. Length is proportional to number of turns. So, weight of conductor is proportional to product of current and number of turns.
2. Weight of conductor material for two-winding transformer,

In primary $\propto I_H T_H$

In secondary $\propto I_L T_L$

Total weight $\propto (I_H T_H + I_L T_L)$

3. In Fig. 4.23.1 portion ab has $(T_H - T_L)$ turns and current through it is I_H. Weight of conductor material in section ab

$$\propto I_H(T_H - T_L)$$

4. Portion bc has T_L turns and the current through it is

$$I = I_L - I_H$$

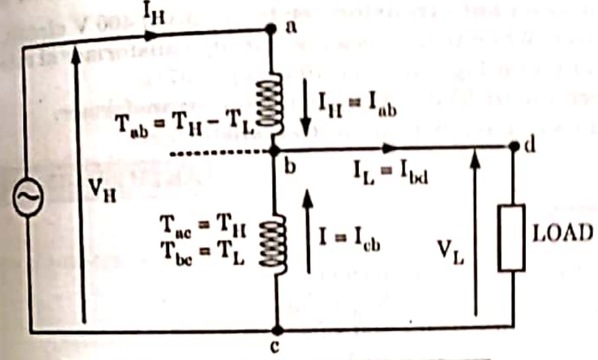


Fig. 4.23.1. Step-down auto-transformer.

5. Weight of conductor material in section $bc \propto (I_L - I_H)\, T_L$
6. Total weight of conductor material

$$\propto [I_H (T_H - T_L) + (I_L - I_H)\, T_L]$$

7. $$\frac{\text{Weight of auto-transformer conductor material}}{\text{Weight of two-winding conductor material}}$$

$$= \frac{W_{auto}}{W_{two\text{-}winding}} = \frac{I_H(T_H - T_L) + (I_L - I_H)T_L}{I_H T_H + I_L T_L}$$

$$= \frac{2I_H T_H - 2I_H T_L}{2I_H T_H} \qquad [\because\ I_L T_L = I_H T_H]$$

$$= 1 - \frac{T_L}{T_H} = 1 - \frac{1}{a_A}$$

8. $$\frac{W_{auto}}{W_{two\text{-}winding}} = 1 - \frac{1}{a_A}$$

$$\therefore \quad 1 - \frac{W_{auto}}{W_{two\text{-}winding}} = \frac{1}{a_A}\ \text{pu}$$

9. Saving in conductor material in using auto-transformer

$$= W_{\text{two-winding}} - W_{\text{auto}} = \frac{1}{a_A} W_{\text{two-winding}}$$

10. Efficiency,
$$\eta = \frac{\text{Output}}{\text{Input}}$$
$$= 1 - \frac{\text{Losses}}{\text{Input}}$$

Que 4.24. **A 400/100 V, 10 kVA, 2-winding transformer is to be employed as an auto-transformer to supply a 400 V circuit from a 500 V source. When tested as a 2-winding transformer at rated load, 0.85 power factor lagging, its efficiency is 97 %.**
i. Determine its kVA rating as an auto-transformer.
ii. Find its efficiency as an auto-transformer.

AKTU 2014-15, Marks 10

Answer

1. For a two-winding transformer
$$S_{in} = S_{out} = V_H I_H = V_L I_L$$
$$10 \times 1000 = 400 \times I_H$$
$$I_H = 25 \text{ A}$$
and
$$10 \times 1000 = 100 \times I_L$$
$$I_L = 100 \text{ A}$$
Fig. 4.24.1 shows the use of two-winding transformer as an auto-transformer to supply power at 400 V from 500 V source.

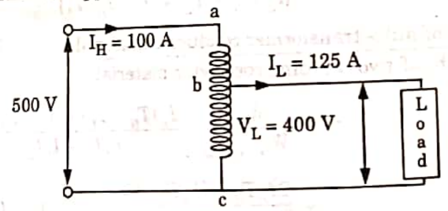


Fig. 4.24.1.

2. For auto-transformer,
$$V_H = 500 \text{ V}, V_L = 400 \text{ V}$$
3. Transformation ratio,
$$a_A = \frac{V_H}{V_L} = \frac{500}{400} = 1.25$$
$$I_H = \frac{I_L}{a_A} = \frac{I_L}{1.25}$$
4. Current through 400 V winding,

$$I_{cb} = I_L - I_H = I_L - \frac{I_L}{1.25} = 0.2 I_L$$

5. Since current rating of 400 V is 25 A,
$$0.2 I_L = 25$$
$$I_L = 125 \text{ A}$$
6. The kVA output (rating)
$$= \frac{V_L I_L}{1000} = \frac{400 \times 125}{1000} = 50 \text{ kVA}$$
7. Efficiency,
$$\eta = \frac{\text{Output}}{\text{Output} + \text{Losses}}$$
$$\text{Losses} = \left(\frac{1}{\eta} - 1\right) \times \text{Output}$$
For 2-winding transformer losses
$$= \left(\frac{1}{0.97} - 1\right) \times 10000 \times 0.85 = 262.88 \text{ W}$$
8. Loss of auto-transformer = Loss of two-winding transformer
$$= 262.88 \text{ W}$$
9.
$$\text{Efficiency, } \eta = \frac{\text{Output}}{\text{Output} + \text{Losses}} = \frac{50 \times 1000 \times 0.85}{50 \times 1000 \times 0.85 + 262.88}$$
$$= \frac{42500}{42500 + 262.88} = 99.34 \%$$

VERY IMPORTANT QUESTIONS

Following questions are very important. These questions may be asked in your SESSIONALS as well as UNIVERSITY EXAMINATION.

Q. 1. What is transformer ? Explain the constructional features of different types of transformer.
Ans. Refer Q. 4.1.

Q. 2. Derive and explain the equivalent circuit of a transformer.
Ans. Refer Q. 4.5.

Q. 3. Explain the phasor diagram of 1ϕ transformer at the following loads :
i. Unity pf load
ii. Lagging pf load
iii. Leading pf load

Ans. Refer Q. 4.6.

Q. 4. Define transformer efficiency and derive the condition for maximum efficiency.

Ans. Refer Q. 4.8.

Q. 5. Write short note on all-day efficiency.

Ans. Refer Q. 4.10.

Q. 6. Write short note on excitation phenomena in transformers.

Ans. Refer Q. 4.11.

Q. 7. Explain the procedure of O.C. and S.C. tests for a transformer. How different parameters of the transformer can be determined from these tests ?

Ans. Refer Q. 4.16.

Q. 8. Explain the back to back test for testing of the single-phase transformers. Also explain how the reading of the wattmeter recording the core losses remain unaffected when the low voltage is injected in the secondary series circuit ?

Ans. Refer Q. 4.17.

Q. 9. What do you mean by "1ϕ auto-transformer" and "3ϕ auto-transformer" ? Also mention its advantages and limitations over 1ϕ, two-winding transformers.

Ans. Refer Q. 4.21.

Q. 10. Show that the VA rating of the auto-transformer is more than the corresponding two winding transformer. Derive an expression for copper saving in case of auto-transformer.

Ans. Refer Q. 4.23.

☺☺☺

5 UNIT

Three Phase Transformers

CONTENTS

PART-1

Pre-Requisites : Three Phase Connections – Star/Delta, Phasor Groups and Their Connections.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 5.1. **Write short notes on phasor groups in 3ϕ transformers.**

Answer

A. Phasor groups :

1. Phasor groups are used to denote different connection methods for 3ϕ transformers. This knowledge is required for connecting the 3ϕ transformers in parallel.
2. 3ϕ transformers are divided into four main groups according to the phase difference between the corresponding line voltages on the *HV* and *LV* sides.
3. The phase difference is the angle by which the *LV* line voltage lags the *HV* line voltage, and is measured in units of 30° in clockwise direction.
4. These groups are :

   Group-1 : no phase displacement

   Group-2 : 180° phase displacement

   Group-3 : (– 30°) phase displacement

   Group-4 : (+ 30°) phase displacement

B. 3ϕ transformer connections :

1. A 3ϕ transformer consists of three transformers, either separate or combined on one core.
2. The primaries and secondaries of any 3ϕ transformer can be independently connected in either a star (Y) or delta (Δ).
3. Thus, there are four possible connections for a 3ϕ transformer bank :
   i. Δ – Δ (Delta primary – Delta secondary)
   ii. Y – Y (Star primary – Star secondary)
   iii. Δ – Y (Delta primary – Star secondary)
   iv. Y – Δ (Star primary – Delta secondary)
4. Here it is assumed that all transformers in the bank have same kVA rating.

Que 5.2. **Explain delta-delta connection for 0° and 180° phase shift.**

Answer

A. Delta-Delta (Δ-Δ) connection for 0° phase shift :

1. Fig. 5.2.1(*a*) shows the Δ – Δ connection of three identical single-phase transformers or three identical windings on each of the primary and secondary sides of the 3ϕ transformer.
2. Fig. 5.2.1(*b*) shows the phasor diagrams for lagging power factor cos ϕ.
3. The secondary line-to-line voltage V_{ab}, V_{bc} and V_{ca} are in phase with primary line-to-line voltage V_{AB}, V_{BC} and V_{CA} with voltage ratios equal to the turns ratio :

$$\frac{V_{AB}}{V_{ab}} = \frac{V_{BC}}{V_{bc}} = \frac{V_{CA}}{V_{ca}} = a$$

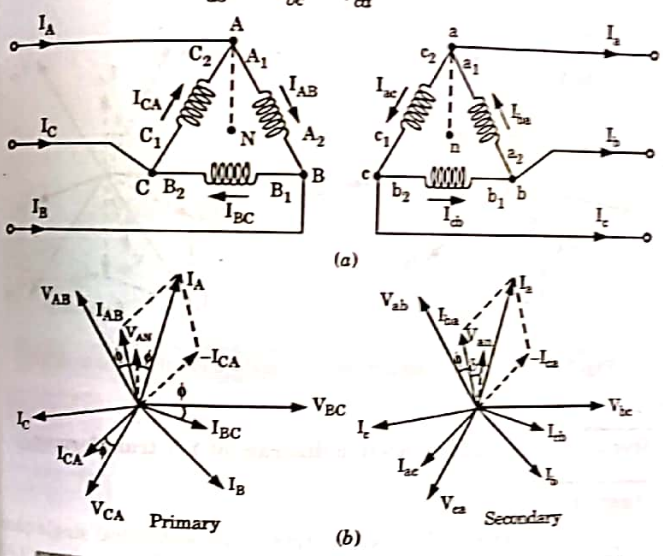


Fig. 5.2.1. Delta-Delta connection of transformer (0° phase shift).

4. The current ratios when the magnetizing current is neglected are

$$\frac{I_{AB}}{I_{ab}} = \frac{I_{BC}}{I_{bc}} = \frac{I_{CA}}{I_{ca}} = \frac{I_A}{I_a} = \frac{I_B}{I_b} = \frac{I_C}{I_c} = \frac{1}{a}$$

5. It is to be noted that in Fig. 5.5.1 each winding is drawn along the line of the phasor of its induced voltage.
6. The primary and secondary line voltages are in phase. This connection is called 0° – connection.

B. Delta-Delta connection (Δ – Δ) for 180° phase shift :

1. The connections of the phase windings are reversed on either side to obtain the phase difference of 180° between the primary and secondary systems. Such a connection is known as 180° – connection.

2. In Fig. 5.2.2 delta-delta connection with 180° phase shift is shown.

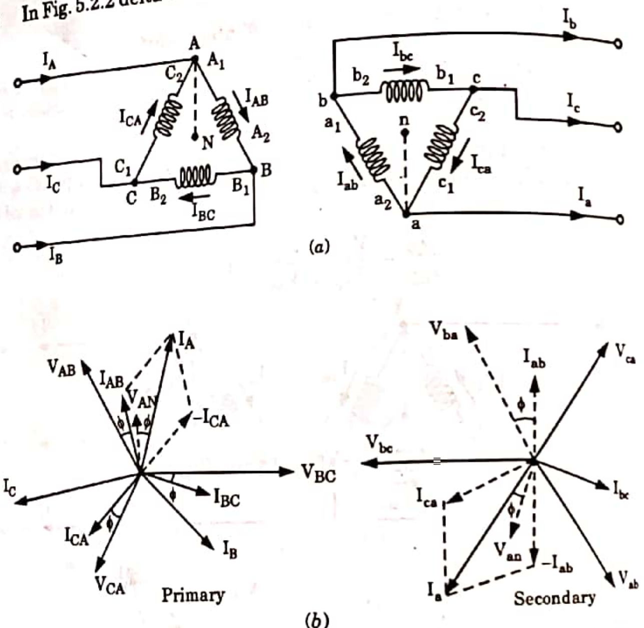


Fig. 5.2.2. Delta-Delta connection of transformer (180° phase shift).

Que 5.3. **Draw the connection diagram of Y-Y transformer.**

Answer

1. Fig. 5.3.1 shows the $Y-Y$ connection of three identical single-phase transformers or the three identical windings on each of the primary and secondary sides of the 3ϕ transformer.
2. The phase current is equal to the line current and they are in phase.
3. The line voltage is $\sqrt{3}$ times the phase voltage. There is a phase separation of 30° between line and phase voltages.
4. For ideal transformer the voltage ratios are

$$\frac{V_{AN}}{V_{an}} = \frac{V_{BN}}{V_{bn}} = \frac{V_{CN}}{V_{cn}} = a$$

and current ratios are

$$\frac{I_A}{I_a} = \frac{I_B}{I_b} = \frac{I_C}{I_c} = \frac{1}{a}$$

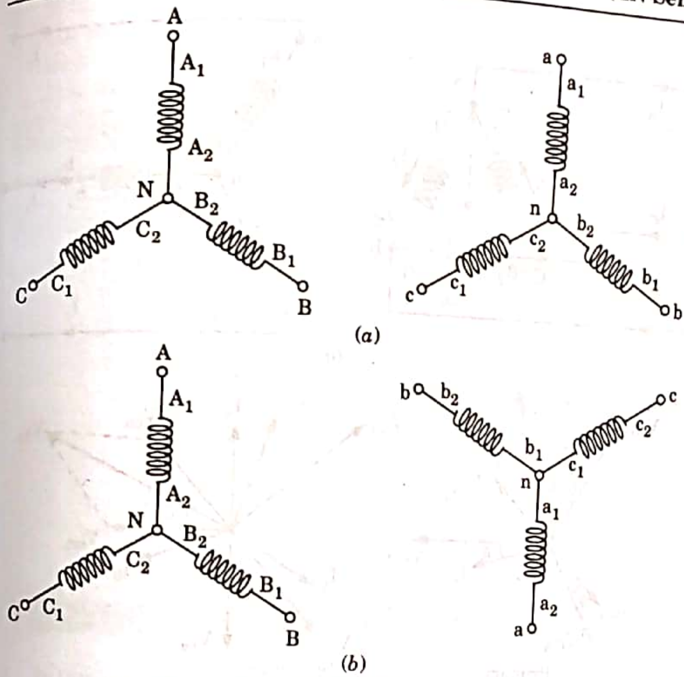


Fig. 5.3.1. Star-star connection of transformer (*a*) 0° phase shift (*b*) 180° phase shift.

Que 5.4. **Draw + 30° and – 30° delta-star connection of 3ϕ transformer.**

Answer

1. A $\Delta - Y$ connection of 3ϕ transformers is shown in Fig. 5.7.1(*a*). In $\Delta - Y$ connection, the primary line voltage is equal to the primary phase voltage ($V_{LP} = V_{pP}$). The relationship between secondary voltage is $V_{LS} = \sqrt{3}\, V_{pS}$.
2. The line-to-line voltage ratio of this connection is

$$\frac{V_{LP}}{V_{LS}} = \frac{V_{pP}}{\sqrt{3} V_{pS}}$$

3. But

$$\frac{V_{pP}}{V_{pS}} = a$$

$\therefore$

$$\frac{V_{LP}}{V_{LS}} = \frac{a}{\sqrt{3}}$$

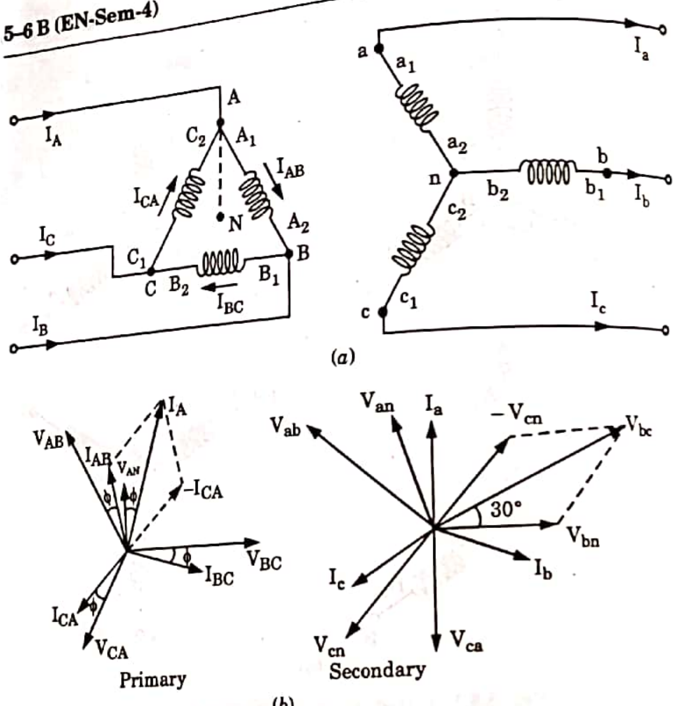


Fig. 5.4.1. (a) Delta-star connection of transformer (phase shift 30° lead), (b) Phasor diagrams.

4. Fig. 5.4.1(b) shows the phasor diagrams for the $\Delta - Y$ connection supplying a balanced load at power factor cos ϕ lagging.

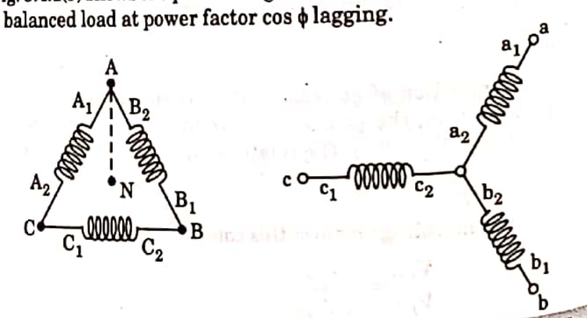


Fig. 5.4.2. Delta-star connection of transformer (phase shift 30° lag).

5. It is seen from the phasor diagram that the secondary phase voltage V_{an} leads the primary phase voltage V_{AN} by 30°. Similarly, V_{bn} leads V_{BN} by 30° and V_{cn} leads V_{CN} by 30°.

6. This connection is called + 30° connection.
7. The connections made by reversing the connections on either side, the secondary system voltage can be made to lag the primary system by 30°. This connection is called – 30° connection.

Que 5.5. **Draw +30° and – 30° star-delta connection of 3ϕ transformer.**

Answer

1. The $Y - \Delta$ connection of three-phase transformers is shown in Fig. 5.5.1.

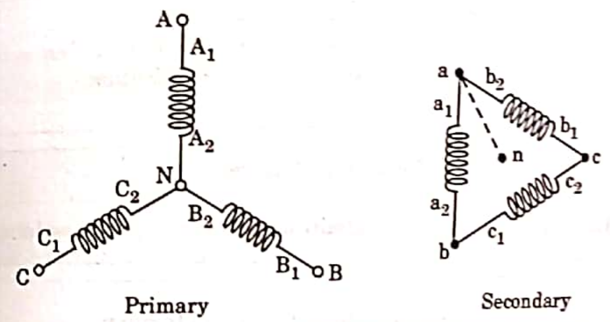


Fig. 5.5.1. Y-Δ connections of transformer (Phase shift of 30° lead).

2. In this connection, the primary line voltage is equal to $\sqrt{3}$ times the primary phase voltage ($V_{LP} = \sqrt{3}\, V_{pP}$).
3. The secondary line voltage is equal to the secondary phase voltage ($V_{LS} = V_{pS}$).
4. The voltage ratio of each phase is $\dfrac{V_{pP}}{V_{pS}} = a$.

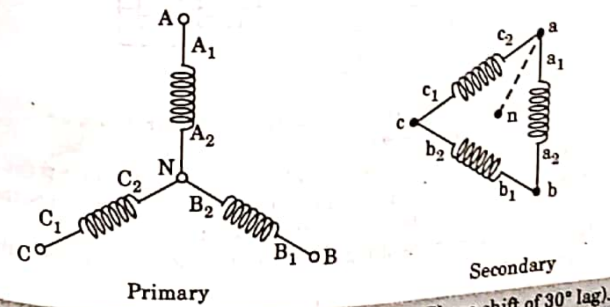


Fig. 5.5.2. Star-delta connection of a transformer (Phase shift of 30° lag).

5. Therefore line-to-line voltage ratio of a Y-Δ connection is

$$\frac{V_{LP}}{V_{LS}} = \frac{\sqrt{3}\, V_{pP}}{V_{pS}} = \sqrt{3}\, a$$

6. The Δ-Y connection or Y-Δ connection has no problem with unbalanced loads and third harmonics.
7. The delta connection assures balanced phase voltages on the Y side and provides a path for the circulation of the third harmonics and their multiples without the use of a neutral wire.

PART-2

Construction of Three Phase Transformer, Open Delta Connection, Three to Two Phase and Their Application.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 5.6. **Discuss construction of 3φ transformer.**

Answer

A. 3φ core-type transformer :

1. A 3φ core-type transformer is constructed by combining three single-phase core-type transformers positioned at 120° to each other as shown in Fig. 5.6.1(*a*).

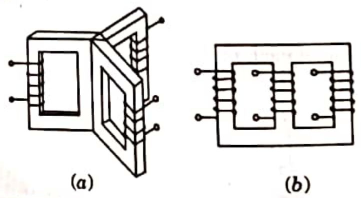


Fig. 5.6.1. Development of a 3φ core-type transformer :
(*a*) Three single-phase cores in contact with another.
(*b*) Usual construction, with the three limbs in the same plane.

2. If balanced 3φ sinusoidal voltages are applied to the windings, the fluxes ϕ_a, ϕ_b and ϕ_c will also be sinusoidal and balanced.
3. Usually the structure of Fig. 5.6.1(*b*) with the three limbs in the same plane is used.
4. It can be built using stacked laminations. Each leg carries both low voltage and high voltage windings.

5. Since it is easier to insulate the *LV* windings from the core than the *HV* windings, the *LV* windings are placed next to the core with suitable insulation between the core and the *LV* windings.

B. 3φ shell-type transformer :

1. The shell-type 3φ transformer can be constructed by stacking three single-phase shell transformers as shown in Fig. 5.6.2.

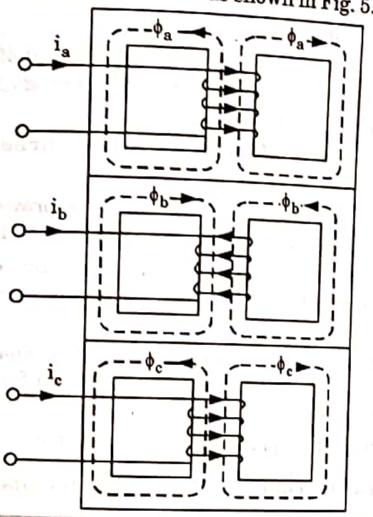


Fig. 5.6.2. Development of a 3φ shell-type transformer.

2. The winding direction of the central unit *b* is made opposite to that of units *a* and *c*. If the system is balanced with phase sequence *a* – *b* – *c*, the fluxes will also be balanced. That is,

$$\phi_a = \alpha\phi_b = \alpha^2\phi_c$$

where $\alpha = 1\angle 120°,\ \alpha^2 = 1\angle 240°$

3. The adjacent yoke sections of units *a* and *b* carry a combined flux of

$$\frac{1}{2}\phi_a + \frac{1}{2}\phi_b = \frac{1}{2}\phi_a(1\angle 0° + 1\angle 240°) = \frac{1}{2}\phi_a \angle -60°$$

4. Thus, the magnitude of this combined flux is equal to the magnitude of each its components.
5. In this way the cross-sectional area of the combined yoke sections may be reduced to the same value as that used in the outer legs and in the top and bottom yokes.

Que 5.7. **Describe the advantages of 3φ unit transformer and three single-phase transformer bank over one-another.**

Answer

A. Advantages of a 3ϕ unit transformer :

1. It takes less space.
2. It is lighter, smaller and cheaper.
3. It is slightly more efficient.
4. The costly high voltage terminals to be brought out of the transformer housing are reduced to three rather than six necessary for three separate single-phase transformers.

B. Advantages of transformer bank of three single-phase transformer :

1. One single-phase transformer in a bank may be provided with a higher kVA rating than the others to supply an imbalanced load.
2. When one single-phase transformer of a bank is damaged and removed from the service, the remaining two units may be used in open-delta or V-V at reduced capacity.
3. Where single units are concerned only one spare single-phase transformer is needed as a standby instead of a complete spare 3-phase transformer.
4. The transport of single-phase transformers is more convenient.

Que 5.8. **Draw the connection diagram for open delta system and show that** $\dfrac{S_{\text{open }\Delta}}{S_{\text{closed }\Delta}} = \dfrac{1}{\sqrt{3}}$.

Answer

1. If one transformer of a $\Delta-\Delta$ system is damaged or accidently opened, the system will continue to supply 3ϕ power. If this defective transformer is disconnected and removed, the remaining two transformers continue to function as a 3ϕ bank with rating reduced to about 58 per cent of that of the original $\Delta-\Delta$ bank. This is known as open-delta or $V-V$ system.
2. The open-delta connection is given in Fig. 5.8.1.
3. Let V_{AB}, V_{BC} and V_{CA} be the applied voltages of the primary. The voltage induced in transformer secondary or LV winding I is V_{ab}. The voltage induced in LV winding II is V_{bc}.
4. There is no winding between points a and c, but there is a potential difference between a and c.
5. This voltage may be found by applying KVL around closed path made up on points a, b and c.

$$V_{ab} + V_{bc} + V_{ca} = 0 \quad \text{...(5.8.1)}$$
$$V_{ca} = -V_{ab} - V_{bc} \quad \text{...(5.8.2)}$$

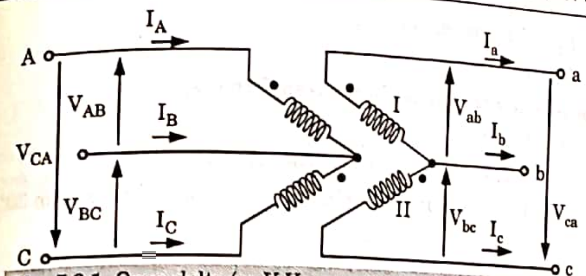


Fig. 5.8.1. Open-delta (or V-V connection) Schematic diagram.

6. Let $V_{AB} = V_p \angle 0°$, $V_{BC} = V_p \angle -120°$ and $V_{CA} = V_p \angle +120°$ where V_p is the magnitude of the line voltage on the primary side.
7. If the leakage impedances of the transformers are negligible, then $$V_{ab} = V_s \angle 0° \text{ and } V_{bc} = V_s \angle -120°$$ where V_s is the magnitude of the secondary voltage.
8. Substituting the values of V_{ab} and V_{bc} in eq. (5.10.2), $$V_{ca} = -V_s \angle 0° - V_s \angle -120° = -V_s - (-0.5\, V_s - j0.866\, V_s)$$ $$= -0.5V_s + j0.866\, V_s = V_s \angle +120°$$
9. If V_{2B} and I_{2B} are the rated secondary voltage and rated secondary current of transformer, the line current to load of a closed delta system is $\sqrt{3}\, I_{2B}$.

   $\therefore$ Closed delta load VA,
   $$S_{\Delta-\Delta} = \sqrt{3} \times \text{line voltage} \times \text{line current} = \sqrt{3}\, V_{2B}(\sqrt{3}\, I_{2B}) = 3V_{2B}I_{2B}$$
10. When one transformer is removed the $\Delta-\Delta$ transformer becomes open delta connected transformer.
11. The VA load that can be carried by the open-delta bank without exceeding the ratings of the transformers is $$S_{V-V} = \sqrt{3}\, V_{2B}I_{2B}$$
12. $$\frac{S_{V-V}}{S_{\Delta-\Delta}} = \frac{\sqrt{3}\, V_{2B}I_{2B}}{3V_{2B}I_{2B}} = \frac{1}{\sqrt{3}} = 0.577$$
13. Hence $$\frac{S_{\text{open }\Delta}}{S_{\text{closed }\Delta}} = \frac{1}{\sqrt{3}}$$

Que 5.9. **How much power is supplied by open-delta system ?**

Answer

1. When a $V-V$ bank of two transformers supplies a balanced 3ϕ load operating at a power factor cos ϕ, the angle between the line voltage and line current in one transformer is $(30° + \phi)$ while the angle between the line voltage and line current in the other transformer is $(30° - \phi)$.
2. Therefore one transformer operates at a power factor of cos $(30° + \phi)$ and the other at cos $(30° - \phi)$ and the powers supplied by the two transformers are

$P_1 = V_L I_L \cos(30° + \phi)$

$P_2 = V_L I_L \cos(30° - \phi)$.

3. The total power supplied by the transformers,

$$P = P_1 + P_2$$
$$= V_L I_L \cos(30° + \phi) + V_L I_L \cos(30° - \phi)$$
$$= V_L I_L [\cos 30° \cos \phi - \sin 30° \sin \phi + \cos 30° \cos \phi + \sin 30° \sin \phi]$$
$$= 2 V_L I_L \cos 30° \cos \phi$$
$$P = \sqrt{3}\, V_L I_L \cos \phi$$

4. At unity power factor of the load, $\cos \phi = 1, \phi = 0°$.
5. Therefore the power supplied by each transformer is

$$P_1 = P_2 = V_L I_L \cos 30° = \frac{\sqrt{3}}{2} V_L I_L$$

Que 5.10. **Write short note on three-phase to two-phase connection.**

AKTU 2015-16, Marks 05 **AKTU 2016-17, Marks 7.5**

OR

Explain Scott connection.

OR

With a neat diagram, explain how a balanced three-phase supply can be converted to balance two-phase supply using transformer.

AKTU 2018-19, Marks 07

Answer

Scott three-phase to two-phase connection :

1. Scott connection is the most common method of connecting two single-phase transformers to perform 3ϕ to 2ϕ conversion and vice-versa.
2. The two transformers are connected electrically but not magnetically. One transformer is called main transformer and the other is known as auxiliary or teaser transformer.
3. Fig. 5.10.1 shows the Scott transformer connection. The main transformer is centre-tapped at D and is connected across the lines B and C of the 3ϕ side.
4. It has primary BC and secondary a_1a_2.
5. The teaser transformer is connected between the line terminal A and the centre tapping D. It has primary AD and secondary $b_1\, b_2$.
6. Each transformer has primary winding of T_p turns and is provided with tappings at 0.289 T_p, 0.5 T_p and 0.866 T_p.

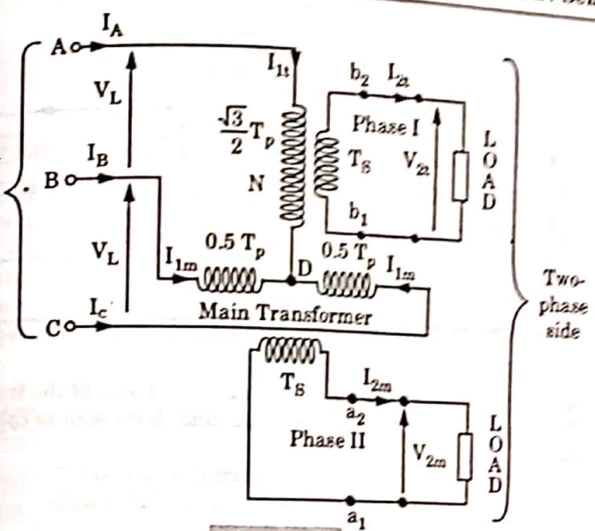


Fig. 5.10.1.

Que 5.11. **What are the applications of Scott-connection ?**

Answer

Applications of Scott connection :

1. Electric furnace installations where it is desired to operate two single-phase furnaces together and draw a balanced load from the 3-phase supply.
2. To supply single-phase loads such as electric trains which are so scheduled as to keep the load on the 3-phase system as nearly balanced as possible.
3. To link a 3-phase system with a 2-phase system with flow of power in either direction.

Que 5.12. **A 500 kVA, 11/0.43 kV, 3φ delta/star connected transformer has on rated load. The *HV* copper loss of 2.5 kW and the *LV* loss of 2 kW and the total leakage reactance of 0.06 per unit. Find the ohmic values of the equivalent resistance and leakage reactance on the delta side.**

AKTU 2016-17, Marks 10

Answer

1. On star side, $I_{L2} = I_{ph2}$; $V_{L2} = 0.430 \text{ kV} = 430 \text{ V}$

$$I_{ph2} = \frac{VA}{\sqrt{3}V_{L2}} = \frac{500 \times 10^3}{\sqrt{3} \times 430} = 671.33 \text{ A}$$

2. On delta side, $V_{L1} = V_{ph1} = 11 \text{ kV} = 11000 \text{ volts}$

$$I_{ph1} = \frac{VA}{\sqrt{3}V_{L1}} = \frac{500 \times 10^3}{\sqrt{3} \times 11000} = 15.15 \text{ A}$$

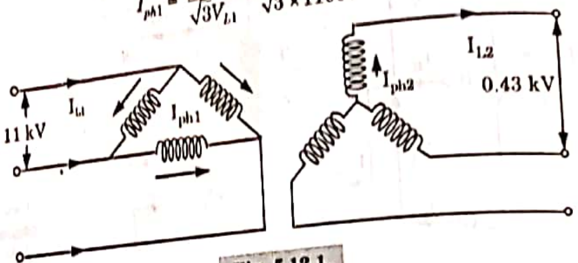


Fig. 5.12.1.

At rated load, rated current is flowing on star side of the transformer. The resistance of each phase on star and delta side is calculated as below :

R_{ph} = Phase resistance on star side
$R_{ph\Delta}$ = Phase resistance on delta side

On star side, $P_{cu} = 3I_{ph}^2 R_{ph}$

$$\therefore \quad R_{ph} = \frac{P_{cu}}{3\,I_{ph}^2} = \frac{2 \times 10^3}{3 \times (671.33)^2} = 0.00147\ \Omega$$

4. On delta side, $P_{cu} = 3I_{ph}^2 R_{ph\Delta}$

$$\therefore \quad R_{ph\Delta} = \frac{P_{cu}}{3\,I_{ph}^2} = \frac{2.5 \times 10^3}{3 \times (15.15)^2} = 3.63\ \Omega$$

Total equivalent resistance on delta side $= R_{ph\Delta} + \dfrac{R_{ph}}{K^2}$

$$K = \text{Transformation ratio} = \frac{V_{2ph}}{V_{1ph}} = \frac{(430/\sqrt{3})}{(11 \times 10^3)} = 0.02525$$

$$\therefore \quad R_{eq\Delta} = 3.63 + \frac{0.00147}{(0.02525)^2} = 3.63 + 2.30 = 6.93\ \Omega$$

$$\therefore \quad R_{eq\Delta} = 6.93\ \Omega$$

5. Now total leakage reactance is given as 0.06 pu

$$\therefore \quad X_{eq} = 0.06$$

This value is given in per unit.

Let $V_{ph\Delta}$ be base voltage on *HV* 11 kV side,
$I_{ph\Delta}$ be base current on *HV* 11 kV side.

Base impedance, $Z_b = \dfrac{V_{ph\Delta}}{I_{ph\Delta}} = \dfrac{11 \times 10^3}{15.15} = 726\ \Omega$

6. $$X_{eq} = \frac{\text{Actual ohmic value of } X_{eq} \text{ on delta side}}{\text{Base impedance}}$$

$$\therefore \quad 0.06 = \frac{X_{eq\Delta\,side}}{726}$$

$$\therefore \quad X_{eq\Delta\,side} = (0.06)\,(726) = 43.56\ \Omega$$

Que 5.13. **Two single-phase furnaces 1 and 2 are supplied at 80 V by means of a Scott connected transformer combination fed by a 3ϕ 6600 V system. The voltage of furnace 1 is leading. Calculate the line currents on the 3ϕ side when the furnaces take 500 kW and 800 kW respectively**

a. At unity pf

b. Furnace 1 at unity pf and furnace 2 at 0.7 pf (lagging).

AKTU 2016-17, Marks 10

Answer

Given : Supply voltage = 80 V
Voltage of Scott connected transformer = 6600 V
Power of main transformer, P_{2m} = 880 kW
Power of teaser transformer, P_{2t} = 500 kW
To Find : Line currents on 3ϕ side, I_A, I_B and I_C.

a. At unity pf :

1. $$a = \frac{6600}{80}$$

2. $$I_{2t} = \frac{500 \times 10^3}{80 \times 1} = 6250 \text{ A}$$

3. $$I_{1t} = I_A = \frac{2}{\sqrt{3}}\frac{I_{2t}}{a} = \frac{2}{\sqrt{3}} \times \frac{6250 \times 80}{6600} = 87.47 \text{ A}$$

4. $$I_{2m} = \frac{800 \times 10^3}{80 \times 1} = 10{,}000 \text{ A}$$

5. $$\frac{I_{2m}}{a} = \frac{80}{6600} \times 10{,}000 = 121.212 \text{ A}$$

6. $$|I_B| = |I_C| = \sqrt{\left(\frac{I_{2m}}{a}\right)^2 + \left(\frac{I_{1t}}{2}\right)^2} = \sqrt{(121.212)^2 + \left(\frac{87.47}{2}\right)^2}$$
$$= 128.86 \text{ A}$$

b. Furnace 1 at unity pf and furnace 2 at 0.7 pf :

1. $$I_{2t} = \frac{500 \times 10^3}{80 \times 1} = 6250 \text{ A}$$

2. $$I_{2m} = \frac{800 \times 10^3}{80 \times 0.7} = 14285.7 \text{ A}$$

3. Let V_{2m} be taken as reference.

4. $I_{2t} = 6250 \angle 90° = j\,6250$ A

5. $I_{2m} = 14285.7 \angle -\cos^{-1} 0.7 = 14285.7 \angle -45.57$

$$= (10000 - j10201.51) \text{ A}$$

6. $$I_A = \frac{2}{\sqrt{3}}\frac{I_{2t}}{a} = \frac{2}{\sqrt{3}} \times \frac{j6250 \times 80}{6600} = j\,87.47 \text{ A}$$

$$|I_A| = 87.47 \text{ A}$$

7. Again
$$I_B = \frac{-1}{2} I_A + \frac{I_{2m}}{a}$$
$$= \frac{-1}{2} j\,87.47 + \frac{(10000.0 \times j\,10201.51) \times 80}{6600}$$
$$= (121.21 - j\,167.39) \text{ A}$$

$\therefore$
$$|I_B| = \sqrt{(121.21)^2 + (167.39)^2} = 206.66 \text{ A}$$

8. $\therefore$
$$I_C = \frac{-1}{2} I_A - \frac{I_{2m}}{a}$$
$$= -j\frac{87.47}{2} - \frac{(10000 - j10201.51) \times 80}{6600}$$
$$= (-212.21 + j\,79.92) \text{ A}$$

$\therefore$
$$|I_C| = \sqrt{(121.2)^2 + (79.92)^2} = 145.18 \text{ A}$$

Que 5.14. **Two 1-phase furnaces A and B are supplied at 100 V by means of a Scott-connected transformer combination from a 3-phase 6600 V system. The voltage of furnace A is leading. Calculate the line currents on the 3-phase side, when the furnace A takes 400 kW at 0.707 pf lagging and B takes 800 kW at unity pf.**

AKTU 2017-18, Marks 07

Answer

The procedure is same as Q. 5.13, Page 5–15B, Unit-5.

(Ans. I_A = 99 A, I_B = 93 A, I_C = 160 A and I_{BC} = 121.2 A)

PART-3

Three Winding Transformers, Parallel Operation of Single Phase and Three Phase Transformers and Load Sharing.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 5.15. **Write a short note on three-winding transformers.**

Answer

A. Three winding transformers :

1. Transformers may be constructed with a third winding in addition to the primary and secondary. The third winding is called tertiary.
2. The primary has the highest voltage rating, the tertiary has the lowest voltage rating, and the secondary has the intermediate voltage rating.
3. The tertiary winding is connected in delta. The main advantage of using tertiary windings is that the delta connection suppresses any harmonic voltages that may be generated in star-connected primaries and secondaries of transformers.
4. In case of unbalanced secondary load currents, which are reflected as unbalanced primary currents, an increased circulating current is reduced in the tertiary windings.
5. This tends to restore both primary and secondary phase voltages to their normal phase magnitudes and angles.
6. Thus, the secondary and primary imbalance is reduced and the secondary load imbalance is more evenly distributed among primary phases.

B. Tertiary windings are also used for the following purposes :

1. Tertiary windings are used to supply substation auxiliaries (for example, lights, fans and pumps) at a voltage different from those of primary and secondary windings.
2. Synchronous capacitors or static high-voltage capacitors are connected across the delta-connected output of the tertiary windings for reactive power injection into the system for either power factor correction or voltage regulation or both.
3. Tertiary windings are used to interconnect three supply systems operating at different voltages.
4. A delta-connected tertiary reduces the impedance offered to the zero-sequence currents to allow sufficient earth fault current for proper operation of protective devices.
5. Tertiary can be used for measuring voltage of high voltage testing transformers.

Que 5.16. **What do you mean by parallel operation of 3ϕ transformers ? Discuss the advantages and disadvantages of parallel operation of 3ϕ transformers.**

AKTU 2016-17, Marks 10

Answer

A. Parallel operation of 3ϕ transformers :

1. This is an arrangement in which the primaries of two or more transformers are energized from the same source (*i.e.*, the same generator or the same output winding of a bigger transformer or voltage regulator), and the secondaries are connected to supply the same load.

2. In other words the transformers are said to be connected in parallel when their windings are connected to HV and LV busbars common to both.

B. Conditions for proper parallel operation of 3ϕ transformers :

1. The polarities of the transformers must be same.
2. Identical primary and secondary voltage ratings.
3. Impedances inversely proportional to the kVA ratings.
4. Identical X/R ratios in the transformer impedances.
5. The phase sequence must be same.
6. The phase shift between primary and secondary voltages must be same for all transformers which are to be connected in parallel.

C. Advantages of parallel operation :

1. If the amount of power to be transformed is greater than which can be handled by one transformer, it becomes necessary to employ 2 or more units in parallel.
2. New installation is easy.
3. Replacement of units becomes easy.
4. Overload cost of system decreases.

D. Disadvantages of parallel operation : In parallel connection of 2 or more transformers, the short-circuit current is increased, sometimes to a level beyond the interrupting capacity of the existing over-current devices.

Que 5.17. What are the necessary and desirable conditions for parallel operation of 1ϕ transformers ?

Answer

A. Necessary conditions :

1. The polarities of the transformers must be the same.
2. The turn ratios of the transformers should be equal.

B. Desirable conditions :

1. The voltages at full load across transformers internal impedances should be equal.
2. The ratios of their winding resistances to reactance should be equal for both transformers. This condition ensures that both transformers operate the same power factor, thus sharing active power and reactive voltamperes according to their ratings.

Que 5.18. Explain the operation of parallel transformer on no-load and also derive the expression for equal voltage ratios in division of load between transformers in parallel.

AKTU 2014-15, Marks 10

OR

Explain the parallel operation of transformers in detail.

AKTU 2017-18, Marks 07

OR

Two transformers having equal voltage ratio are operated in parallel. Obtain expressions for the maximum possible kVA loading of the two transformers in parallel. State assumptions made if any. Also write the condition required for parallel operation of two transformer.

AKTU 2018-19, Marks 07

Answer

A. Condition required for parallel operation : Refer Q. 5.16, Page 5–17B, Unit-5.

B. Operation of parallel transformers on no-load :

1. Fig. 5.18.1 shows two transformers paralleled on both side with proper polarities but on no-load.

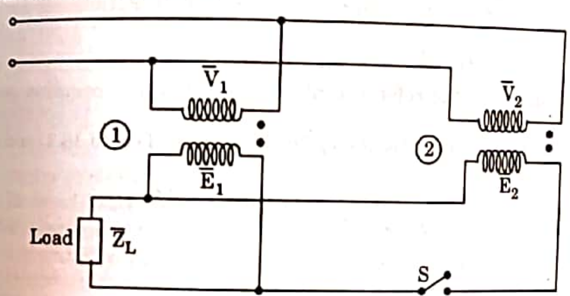


Fig. 5.18.1. Transformer in parallel.

2. It is seen that primary voltage V_1 and V_2 are equal. If the voltage ratio of the two transformers is not identical, the secondary induced emf's E_1 and E_2 though in phase will not be equal in magnitude and the difference $(E_1 - E_2)$ will appear across switch S.
3. When secondaries are paralleled by closing the switch, a circulating current appears even though the secondaries are not supplying load.
4. The circulating current will depend upon the total leakage impedance of the two transformers and the difference in their voltage ratios.

C. Division of load between transformers at equal voltage ratios :

1. When the transformers have equal voltage ratio, $E_1 = E_2$, the equivalent circuit of the two transformers would then be as shown in Fig. 5.18.2.
2.

$$\bar{I}_1 = \frac{\bar{Z}_2}{\bar{Z}_1 + \bar{Z}_2} \bar{I}_L \quad ...(5.18.1)$$

and

$$\bar{I}_2 = \frac{\bar{Z}_1}{\bar{Z}_1 + \bar{Z}_2} \bar{I}_L \quad ...(5.18.2)$$

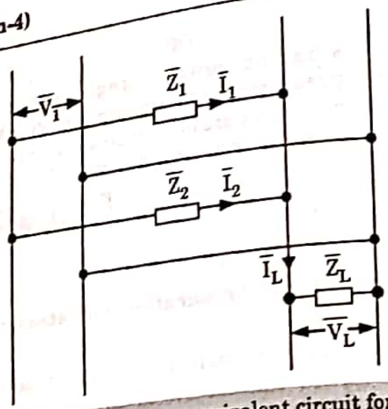


Fig. 5.18.2. Approximate equivalent circuit for two transformers in parallel (equal turn-ratio).

$$\bar{I}_1 + \bar{I}_2 = \bar{I}_L$$

3. Taking $\bar{V}_L$ as the reference phasor and defining complex power as $\bar{V}_L^* \bar{I}$, the multiplication of $\bar{V}_L^*$ on both sides of eq. (5.18.1) and (5.18.2) gives

$$\bar{S}_1 = \frac{\bar{Z}_2}{\bar{Z}_1 + \bar{Z}_2}\bar{S}_L \qquad ...(5.18.3)$$

$$\bar{S}_2 = \frac{\bar{Z}_1}{\bar{Z}_1 + \bar{Z}_2}\bar{S}_L \qquad ...(5.18.4)$$

where
$$\bar{S}_1 = \bar{V}_L^* \bar{I}_1$$
$$\bar{S}_2 = \bar{V}_L^* \bar{I}_2$$
$$\bar{S}_L = \bar{V}_L^* \bar{I}_L$$

$$\frac{Z_1}{Z_2} = \frac{S_2\text{ (rated)}}{S_1\text{ (rated)}} \qquad ...(5.18.5)$$

4. This condition is independent of the power factor of the total load. The condition of eq. (5.18.5) can be written as

$$\frac{Z_1}{Z_2} = \frac{V_L I_2\text{ (rated)}}{V_L I_1\text{ (rated)}}$$

$$\frac{Z_1 I_1\text{ (rated)}}{V_L} = \frac{Z_2 I_2\text{ (rated)}}{V_L} \qquad ...(5.18.6)$$

$$Z_1\text{(pu)} = Z_2\text{(pu)}$$

5. It means that if individual transformer loadings are to be in the ratio of their respective kVA ratings, their per unit impedances should be equal.

6. If $$Z_1 < Z_2 \frac{S_2\text{ (rated)}}{S_1\text{ (rated)}}$$

the transformer 1 will be the first to reach its rated loading as the total kVA load is raised. The maximum permissible kVA loading of the two in parallel without overloading anyone is then given by

$$S_1\text{(rated)} = \frac{Z_2}{|\bar{Z}_1 + \bar{Z}_2|} S_L\text{(max)}$$

$$S_L\text{(max)} = S_1\text{(rated)} \frac{|\bar{Z}_1 + \bar{Z}_2|}{Z_2}$$

7. Similarly if $$Z_2 < Z_1 \frac{S_1\text{(rated)}}{S_2\text{(rated)}}$$

then $$S_L\text{(max)} = S_1\text{(rated)} \frac{|\bar{Z}_1 + \bar{Z}_2|}{Z_1}$$

In either case $S_L\text{(max)} < S_1\text{(rated)} + S_2\text{(rated)}$

Que 5.19. **What do you mean by "load sharing" in 3ϕ transformers ? Also mention its basic role and limitations in 3ϕ transformers.**

Answer

A. **Load sharing :** Load sharing means generally equally share the load in power system.

B. **Role of load sharing in three-phase transformer :**

1. If a large size means large rating of transformer is not available which can actually fulfill the total requirement of load, two or more small size transformers can be connected in parallel to increase the capacity.
2. If installation place like substation is located far away, then transportation of smaller size of transformer is easier and may be economical. It will directly affect the cost.
3. If more than one the transformers running in parallel is out due to fault, other parallel transformers in the system will share the load, hence power supply may not be interrupted.
4. If numbers of transformers run in parallel, we can shut down any one of them for maintenance purpose. Other parallel transformers in system will fulfill the load without total interruption of power.

C. **Limitations :**

1. Increasing short-circuit currents that increase necessary breaker capacity.
2. The risk of circulating currents running from one transformer to another transformer. Circulating currents that diminish load capability and increased losses.
3. The bus ratings could be too high.
4. Paralleling transformers reduces the transformer impedance significantly, *i.e.*, the parallel transformers may have very low impedance, which creates the high short circuit currents. Therefore, some current limiters are needed, *e.g.*, reactors, fuses, high impedance buses, etc.

Que 5.20.

i. Explain the conditions to be satisfied for the successful parallel operation of the single-phase transformers.

ii. Two single-phase transformers rated 1000 kVA and 500 kVA respectively are connected in parallel on both *HV* and *LV* sides. They have equal voltage rating of 11 kV/400 V and their per unit impedances are (0.02 + *j*0.07) Ω and (0.025 + *j*0.0875) Ω respectively. What is the largest value of the unity power factor load that can be delivered by the parallel combination at the rated voltage ?

AKTU 2015-16, Marks 15

Answer

i. **Conditions for parallel operation of single-phase transformers :**
Refer Q. 5.16, Page 5–17B, Unit-5.

ii. **Numerical :**

Given : S_1 (rated) = 1000 kVA; S_2 (rated) = 500 kVA
Per unit impedances, $\bar{Z}_1 = (0.02 + j0.07)\ \Omega$, $\bar{Z}_2 = (0.025 + j0.0875)\ \Omega$
To Find : Largest value of the unity power factor load, S_L.
Assumption : Choose a kVA base of 1000 kVA.

1. $$\bar{Z}_1 = \frac{1000}{1000}(0.02 + j0.07) = 0.0728 \angle 74°\ \Omega$$
$$\bar{Z}_2 = \frac{1000}{500}(0.025 + j0.0875)$$
$$= 0.05 + j0.175 = 0.182 \angle 74°\ \Omega$$

2. $$\bar{Z}_1 + \bar{Z}_2 = 0.07 + j0.245 = 0.255 \angle 74°\ \Omega$$

3. $$S_1 = \frac{\bar{Z}_2}{|\bar{Z}_1 + \bar{Z}_2|} S_L \quad ...(5.20.1)$$

4. $$S_2 = \frac{\bar{Z}_1}{|\bar{Z}_1 + \bar{Z}_2|} S_L \quad ...(5.20.2)$$

5. From eq. (5.20.1),
$$S_L = 1000 \times \frac{0.255}{0.182} = 1400 \text{ kVA}$$

6. From eq. (5.20.2),
$$S_L = 500 \times \frac{0.255}{0.0728} = 1751 \text{ kVA}$$

7. As total load is increased 1000 kVA, transformer 1 will be the first to reach its full load.

8. ∴ S_L (max) = 1400 kVA

Que 5.21. **A 20 kVA, 50 Hz, 2000/200 V distribution transformer has a leakage impedance of 0.42 + *j*0.52 Ω in the HV winding and 0.004 + *j*0.05 Ω in the LV winding. When seen from the LV side, the shunt branch admittance Y_0 is (0.002 – *j*0.015) ℧ (at rated voltage and frequency). Draw the equivalent circuit referred to**

i. HV side

ii. LV side

Indicating all impedances on the circuit.

AKTU 2017-18, Marks 07

Answer

Given : Rating of transformer = 20 kVA, f = 50 Hz, N = 2000/200
$X_{LHV} = 0.42 + j0.52\ \Omega$, $X_{LLV} = 0.004 + j0.05\ \Omega$
$Y_{OLV} = 0.002 - j0.015$ ℧
To Draw : Equivalent circuit referred to HV and LV side.

The HV side will be referred as 1 and LV side as 2.
Transformation ratio,
$$a = \frac{N_1}{N_2} = \frac{2000}{200} = 10 \text{ (ratio of rated voltages)}$$

a. **Equivalent circuit referred to HV side (side 1) :**
$$\bar{Z}_2' = (10)^2 (0.004 + j\,0.005) = 0.4 + j\,0.5\ \Omega$$
$$\bar{Y}_0' = \frac{1}{(10)^2}(0.002 - j\,0.015)$$

The equivalent circuit is drawn in Fig. 5.21.1.

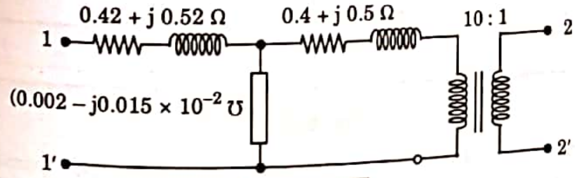


Fig. 5.21.1.

b. **Equivalent circuit referred to LV side (side 2) :**
$$\bar{Z}_1' = \frac{1}{(10)^2}(0.42 + j\,0.52) = 0.0042 + j\,0.0052$$

The equivalent circuit is drawn in Fig. 5.21.2.

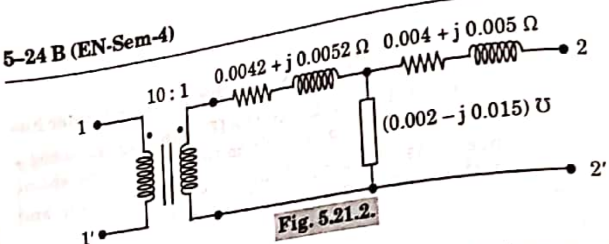


Fig. 5.21.2.

Que 5.22. **A 500 kVA, 11/0.43 kV, 3 phase delta/star connected transformer has on rated load. The HV copper loss of 2.5 kW and the LV loss of 2 kW and the total leakage reactance of 0.08 per unit. Find the ohmic values of the equivalent resistance and leakage reactance on the delta side.**

AKTU 2018-19, Marks 07

Answer

1. On star side, $I_{L2} = I_{ph2}$; $V_{L2} = 0.430 \text{ kV} = 430 \text{ V}$

$$I_{ph2} = \frac{VA}{\sqrt{3}V_{L2}} = \frac{500 \times 10^3}{\sqrt{3} \times 430} = 671.33 \text{ A}$$

2. On delta side, $V_{L1} = V_{ph1} = 11 \text{ kV} = 11000$ volts

$$I_{ph1} = \frac{VA}{\sqrt{3}V_{L1}} = \frac{500 \times 10^3}{\sqrt{3} \times 11000} = 26.24 \text{ A}$$

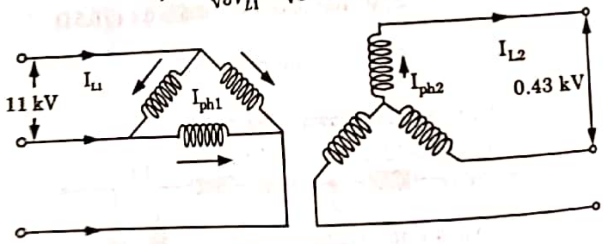


Fig. 5.22.1.

3. At rated load, rated current is flowing on star side of the transformer. The resistance of each phase on star and delta side is calculated as below :

R_{ph} = Phase resistance on star side

$R_{ph\Delta}$ = Phase resistance on delta side

On star side, $P_{cu} = 3I_{ph2}^2 R_{ph}$

$$\therefore \quad R_{ph} = \frac{P_{cu}}{3\, I_{ph2}^2} = \frac{2 \times 10^3}{3 \times (671.33)^2} = 0.00147 \,\Omega$$

4. On delta side, $P_{cu} = 3I_{ph1}^2 R_{ph\Delta}$

$$\therefore \quad R_{ph\Delta} = \frac{P_{cu}}{3\, I_{ph1}^2} = \frac{2.5 \times 10^3}{3 \times (26.24)^2} = 1.21 \,\Omega$$

5. K = Transformation ratio $= \dfrac{V_{2ph}}{V_{1ph}} = \dfrac{(430/\sqrt{3})}{(11 \times 10^3)} = 0.02257$

6. Total equivalent resistance on delta side $= R_{ph\Delta} + \dfrac{R_{ph}}{K^2}$

$$\therefore \quad R_{eq\Delta} = 3.63 + \frac{0.00147}{(0.02257)^2} = 3.63 + 2.88 = 6.51 \,\Omega$$

7. Now total leakage reactance is given as 0.08 pu

$$\therefore \quad X_{eq} = 0.08$$

This value is given in per unit.

Let $V_{ph\Delta}$ be base voltage on hv 11 kV side,

$I_{ph\Delta}$ be base current on hv 11 kV side.

Base impedance, $Z_b = \dfrac{V_{ph\Delta}}{I_{ph\Delta}} = \dfrac{11 \times 10^3}{26.24} = 419.20 \,\Omega$

8. $$X_{eq} = \frac{\text{Actual ohmic value of } X_{eq} \text{ on delta side}}{\text{Base impedance}}$$

$$\therefore \quad 0.08 = \frac{X_{eq\Delta\,\text{side}}}{419.20}$$

$$\therefore \quad X_{eq\Delta\,\text{side}} = (0.08)(419.20) = 33.53 \,\Omega$$

VERY IMPORTANT QUESTIONS

Following questions are very important. These questions may be asked in your SESSIONALS as well as UNIVERSITY EXAMINATION.

Q. 1. Write short notes on phasor groups in 3ϕ transformers.

Ans. Refer Q. 5.1.

Q. 2. Explain delta-delta connection for 0° and 180° phase shift.

Ans. Refer Q. 5.2.

Q. 3. Draw the connection diagram of Y-Y transformer.

Ans. Refer Q. 5.3.

Q. 4. Write short note on three-phase to two-phase connection.

Ans. Refer Q. 5.10.

Q. 5. A 500 kVA, 11/0.43 kV, 3ϕ delta/star connected transformer has on rated load. The *HV* copper loss of 2.5 kW and the *LV* loss of 2 kW and the total leakage reactance of 0.06 per unit. Find the ohmic values of the equivalent resistance and leakage reactance on the delta side.

Ans. Refer Q. 5.12.

Q. 6. Write a short note on three-winding transformers.

Ans. Refer Q. 5.15.

Q. 7. Explain the operation of parallel transformer on no- load and also derive the expression for equal voltage ratios in division of load between transformers in parallel.

Ans. Refer Q. 5.18.

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1 UNIT

Principles of Electromechanical Energy Conservation (2 Marks Questions)

1.1. Write the energy balance equation for the generator.

Ans. Energy balance equation for generator can be written as :
(Mechanical energy input) = (Energy to electrical losses) + (Energy to mechanical losses) + (Energy to field storage in the electrical system) + (Electrical energy output)

1.2. Based on the principle of conservation of energy, write an energy balance equation of the motor.

AKTU 2015-16, Marks 02

OR

Write the energy balance equation for motor action and draw power flow diagram. **AKTU 2016-17, Marks 02**

OR

Write the energy balance equation for the generator and motor. **AKTU 2018-19, Marks 02**

Ans.

A. Energy balance equation for generator : Refer Q. 1.1, Page SQ–1B, Unit-1, Two Marks Questions.

B. Energy balance equation for motor can be written as :
(Electrical energy input) = (Energy to electrical losses) + (Energy to field storage in the electrical system) + (Mechanical energy output)

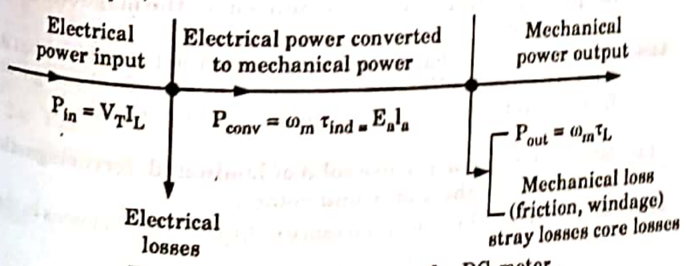

Fig. 1. Power-flow diagram of a DC motor.

1.3. Define energy and co-energy. AKTU 2016-17, Marks 02

Ans. **Energy :** The area between the magnetization curve and the flux is called energy. It is denoted by W_f.

Co-energy : The area between the magnetization curve and the current or mmf axis called the co-energy. It is denoted by the W_f'.

Co-energy has no physical significance.

1.4. State the phenomenon useful for the electromechanical energy conversion in rotating machines. AKTU 2015-16, Marks 02

Ans. **The two electromagnetic phenomena are :**

1. When a conductor moves in a magnetic field, voltage is induced in the conductor.
2. When a current-carrying conductor is placed in a magnetic field, the conductor experiences a mechanical force.

1.5. What is electromechanical conversion device ?

Ans. It converts electrical energy into mechanical energy. It takes place via the medium of magnetic field or electric field.

1.6. Write the applications of singly-excited system.

Ans.

1. Used in electromagnets.
2. As reluctance motors.
3. Moving iron instruments in measurement of AC and DC.

1.7. Write the two basic magnetic field effects resulting in the production of mechanical forces.

Ans. **The two basic effects are :**

1. Alignment of flux lines.
2. Interaction between magnetic fields and current-carrying conductors.

1.8. Give the reason why ferromagnetic rotor experiences a torque urging it towards a region where the magnetic field is stronger ?

Ans. This is due to fact that the torque is exerted on the rotor so that it tries to position itself to given minimum reluctance for the magnetic flux. The reluctance is dependent upon the rotor angle.

1.9. Why is it necessary to use solid or laminated ferromagnetic materials for the stator and rotor ?

Ans. It is used to reduce the reluctance of flux paths and losses in the machines.

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2 UNIT

DC Machines-I (2 Marks Questions)

2.1. Why is the wave winding useful for high voltage low current DC machines ? AKTU 2018-19, Marks 02 AKTU 2015-16, Marks 02

Ans. In wave winding, the total number of conductors gets divided into two parallel paths always, irrespective of number of poles of the machine. As the numbers of parallel paths are less, it is preferable for low current, high voltage DC machines.

2.2. Explain why equalizer connections are used in lap-winding and dummy coils are sometimes used in wave-windings. AKTU 2017-18, Marks 02

Ans.

1. **Equalizer connection :** It is used to reduce the magnetic flux unbalance that cause potential difference in various parallel paths in lap winding.
2. **Dummy coils :** It is used to provide mechanical balance in wave winding.

2.3. Describe how a DC machine is to be maintained for a long satisfactory performance. AKTU 2017-18, Marks 02

Ans. Satisfactory operation of DC machine can be achieved by :

1. Using compensating winding.
2. Using interpoles.
3. Using delayed commutation.
4. Shifting of brushes.

2.4. Explain the function of a commutator in a DC machine for motoring and generating action. AKTU 2017-18, Marks 02

Ans. **In motoring :** It converts DC to AC.
In generating : It converts AC to DC.

2.5. Define reactance voltage in commutation process.

AKTU 2016-17, Marks 02

Ans. If t_c is the time of short circuit and L is the inductance of the coil then the average value of the self induced voltage is

$$L\frac{di}{dt} = \frac{L \times 2I}{t_c} = \frac{2LI}{t_c}$$

This is called the reactance voltage.

2.6. What are the effects of armature reaction ?

AKTU 2016-17, Marks 02

Ans.

1. Distortion of the main field flux thereby causing non-uniform distribution of flux under the main poles.
2. Shifting of the MNA in the direction of rotation for a generator and against the direction of rotation for a motor.
3. Reduction of the main field flux from its no-load value due to magnetic saturation.

2.7. What is field winding ?

Ans. The winding through which a current is passed to produce the main flux is called the field winding.

2.8. Write the purpose of using yoke.

Ans. **The yoke serves the following two purposes :**

1. It supports the pole cores and acts as protecting cover to the machine.
2. It forms a part of the magnetic circuit. It provides a path of low reluctance for magnetic flux.

2.9. How interpoles provide more mmf than the armature mmf in the commutating zone ?

Ans.

1. It neutralises the armature cross flux in the commutating zone.
2. In addition, it provides extra interpolar flux in the commutating zone.

2.10. Differentiate between LAP winding and WAVE winding.

Ans.

S.No.	LAP winding	WAVE winding
1.	The ends of each armature coil are connected to adjacent segments on the commutator.	The ends of each armature coil are connected to commutator segment some distance apart.
2.	The total number of parallel paths is equal to the total number of poles, $A = P$.	Only two parallel paths are provided between the positive and negative brushes, $A = 2$.
3.	Equalizer ring is required.	Equalizer ring is not required.

2.11. On what factors does the flux distribution in the air gap of a DC generator depend ?

Ans. **The flux distribution in the air gap of a DC generator depends on :**

1. The main field flux distribution
2. The armature reaction flux waveform
3. The length of the air gap and
4. Whether the magnetic circuit is saturated or not.

2.12. What is armature reaction ?

Ans. It is the effect of magnetic flux set up by armature current upon the distribution of flux under the main poles.

2.13. Why we use pole shoe in the magnetic field system ?

Ans. We use pole shoe because it supports the field coils. It increases the cross-sectional area of the magnetic circuit and reduces its reluctance.

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3 UNIT

DC Machines-II (2 Marks Questions)

3.1. Write voltage equation of DC motor.

AKTU 2018-19, Marks 02

Ans. The direction of rotation of the DC shunt motor can be changed by reversing the connections of either the field winding or the armature but not both.

3.2. How the direction of rotation of the DC shunt motor can be changed ?

AKTU 2018-19, Marks 02

AKTU 2015-16, Marks 02

Ans. The direction of rotation of the DC shunt motor can be changed by reversing the connections of either the field winding or the armature but not both.

3.3. Explain why a DC motor should not be started direct-on-line.

AKTU 2017-18, Marks 02

Ans. Direct-on-line (DOL) starting are not used for DC motor because the starting current will be enormously high which will cause large voltage drop in the supply mains and armature may get damaged due to excessive heating.

3.4. What is back-emf in a DC motor ?

AKTU 2016-17, Marks 02

Ans. When the motor armature rotates, its conductor cuts the magnetic flux and emf of rotation is induced in them known as back emf or counter emf. The back emf opposes the applied voltage.

Back emf, $E_b = \dfrac{NP\phi Z}{60A}$

3.5. What is the effect of frequency and supply voltage on iron losses ?

AKTU 2016-17, Marks 02

Ans. Iron loss : $P_c = P_h + P_e$

$$= k_h V^x f^{1-x} + k_e V^2$$

where k_h and k_e proportionality constant.
Iron loss directly proportional to voltage and frequency.

3.6. Differentiate between armature voltage control and flux control of DC shunt motor.

AKTU 2016-17, Marks 02

Ans.

S. No.	Armature Voltage Control	Flux Control
1.	Applied voltage is varied.	Field flux is varied.
2.	Higher initial cost due to two additional machines.	Initial cost is comparatively low.

3.7. What is the need of starter while starting the DC motor ?

AKTU 2016-17, Marks 02

Ans. The motor draws large starting armature current from the supply mains. In order to limit starting current, starters are necessary for suitable operation of DC machines.

3.8. How the back EMF does make the DC machine self-regulatory ?

AKTU 2015-16, Marks 02

Ans.

1. When the load on the motor falls, the electromagnetic torque developed is momentarily in excess of the load requirement and therefore, the motor armature accelerates.
2. With the increase in armature speed, back emf increases causing armature current to decrease.
3. The decrease in armature current causes decrease in electromagnetic torque and the steady state conditions are attained when the electromagnetic torque developed matches the load torque.
4. Thus it is evident that back emf acts like a governor *i.e.*, it makes the motor self-regulating so that it draws as much current as just required.

3.9. Give two applications of the DC shunt motor and DC compound generator.

AKTU 2015-16, Marks 02

Ans. **Applications of the DC shunt motor are :**

1. It is used for lathes.
2. It is used in centrifugal pumps, reciprocating pumps.

Applications of the DC compound generator are :

1. It is useful in arc welding generator.
2. It is generally useful for lighting and power services.

3.10. What are the various drawbacks of armature resistance control ?

Ans.
1. A large amount of power is wasted in the external resistance R_e.
2. Control is limited to give speeds below normal and increase of speed cannot be obtained by this method.
3. For a given value of R_e the speed reduction is not constant but varies with the motor load.

3.11. What are the advantages of Ward Leonard drives ?

Ans.
1. It has inherent regenerative braking capacity.
2. Smooth speed control of DC motors over a wide range in both directions is possible.

3.12. Write the drawbacks of Ward Leonard system.

Ans.
1. Higher initial cost due to use of two additional machines ($M - G$) set of the same rating as the main DC motor.
2. Requires more floor area and costly foundation.
3. Frequent maintenance is needed.
4. Lower efficiency due to higher losses.

3.13. What is the function of no-volt release in a three-point starter ?

Ans. The function of no-volt release is to stop the DC motor. This is achieved by bringing the starter handle back to OFF position in case magnetic force of no-volt release, or hold-coil, becomes less than the spiral-spring force.

3.14. Write the limitations of Swinburne's test.

Ans.
1. Swinburne's test is applicable to those machines in which the flux is practically constant, that is shunt machines and level compound generators.
2. Series machines cannot be tested by this method as they cannot run on light loads and secondly flux and speed vary greatly.

3.15. What are the advantages of Hopkinson's test ?

Ans.
1. The total power taken from the supply is very low. Therefore this method is very economical.
2. The temperature rise and the commutation conditions can be checked under rated load condition.
3. Stray losses are considered, as both the machines are operated under rated load conditions.

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4 UNIT

Single Phase Transformers (2 Marks Questions)

4.1. Draw phasor diagram of transformer at no load condition.

AKTU 2018-19, Marks 02

Ans.

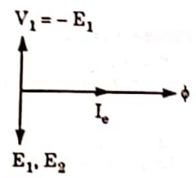

Fig. 1. Ideal transformer at no load.

4.2. How are the transformer losses affected by the power factor of the connected load ?

AKTU 2018-19, Marks 02

Ans. If the power factor is lower than unity then the connected load will take higher current and higher current gives rise to higher copper losses in transformers.

4.3. An auto transformer has primary voltage V_1 and secondary voltage V_2, where $V_1 > V_2$. Calculate the fraction of power transferred inductively.

AKTU 2018-19, Marks 02

AKTU 2015-16, Marks 02

Ans. Given : Primary voltage = V_1
Secondary voltage = V_2
Here $V_1 > V_2$
The power delivered to load = $V_2 I_2$
Power transformed = Power in winding BC

$$= V_2 (I_2 - I_1) = V_2 I_2 \left(1 - \frac{I_1}{I_2}\right)$$

$$= V_2 I_2 (1 - K) = V_1 I_1 (1 - K) = (1 - K) \times \text{Input power}$$

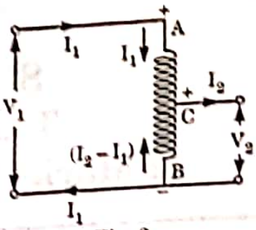

Fig. 2.

4.4. Explain Faraday's laws of electromagnetic induction and Lenz's law. **AKTU 2017-18, Marks 02**

Ans.

i. **Faraday's Law :** Faraday's law of electromagnetic induction states that an emf is induced in a coil when the magnetic flux linking this coil changes with time. It is expressed as

$$e = \frac{d\lambda}{dt} = N\frac{d\phi}{dt}$$

where,
e = Emf induced in volts
N = Number of turns in the coil
$\lambda = N\phi$ = Flux linkages with the coil in Wb-turns
t = Time in seconds

ii. **Lenz's law :** According to this law, the induced current develops a flux which always opposes the change responsible for inducing this current.

$$e = -\frac{d\lambda}{dt} = -N\frac{d\phi}{dt}$$

4.5. State why the core of a transformer should be made up of magnetic material. **AKTU 2017-18, Marks 02**

Ans. Because magnetic materials permits easy establishment of flux through core and hence through winding.

4.6. Why short circuit test is performed on HV side of transformer ? **AKTU 2016-17, Marks 02**

Ans. **Short-circuit test is performed on HV side because :**
1. The rated current on HV side is lower than the LV side. This current can be safely measured with the available laboratory ammeters.
2. 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 HV side is used as the primary.

4.7. How are the transformer losses affected by the power factor of the connected load ? **AKTU 2015-16, Marks 02**

Ans. If the power factor is lower than unity then the connected load will take higher current and higher current gives rise to higher copper losses in transformers.

4.8. If P_i and P_o represents iron loss and full-load ohmic loss, then find the fractional load at which the maximum power shall be transferred. **AKTU 2015-16, Marks 02**

Ans.
I_{2fl} = Full-load secondary current
I_{2M} = Secondary current at maximum efficiency

For maximum efficiency, variable copper loss = constant iron loss

$$I_{2M}^2 R_{e_2} = P_i$$

$$I_{2M}^2 = \frac{P_i}{R_{e_2}} = \frac{I_{2fl}^2 P_i}{I_{2fl}^2 R_{e_2}}$$

$$I_{2M} = I_{2fl}\sqrt{\frac{P_i}{I_{2fl}^2 R_{e_2}}} = I_{2fl}\sqrt{\frac{P_i}{P_o}}$$

4.9. A 1000 kVA, 50 kV/40 kV single-phase auto-transformer is fully loaded. Find the current in the common section of the winding. **AKTU 2015-16, Marks 02**

Ans.

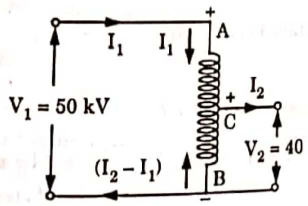

Fig. 3.

$$I_1 = \frac{\text{kVA}}{\text{kV}} = \frac{1000}{50} = 20$$

$$K = \frac{V_2}{V_1} = \frac{40}{50} = \frac{I_1}{I_2}$$

$$\frac{4}{5} = \frac{I_1}{I_2}$$

$\therefore$ $$I_2 = 20 \times \frac{5}{4} = 25\text{ A}$$

Current in common section of winding = $(I_2 - I_1) = 25 - 20 = 5$ A

4.10. Define transformer.

Ans. A transformer is a static device which consists of two or more stationary electric circuits interlinked by a common magnetic circuit for the purpose of transferring electrical energy between them. The transfer of energy from one circuit to another takes place without a change in frequency.

4.11. Differentiate between core-type and shell-type transformer.

Ans.

S. No.	Core-type	Shell-type
1.	The magnetic circuit consists of two vertical legs or limbs with two horizontal sections.	In this both primary and secondary windings are wound on the central limb and the two outer limbs complete the low reluctance flux paths.
2.	It provides longer magnetic path, and hence magnetizing current is higher.	It provides a shorter magnetic path and hence magnetizing current is lesser.

4.12. Define voltage regulation.

Ans. It is defined as the arithmetical difference in the secondary terminal voltage between no-load ($I_2 = 0$) and full-rated load ($I_2 = I_{2fl}$) at a given power factor with the same value of primary voltage for the rated load and no-load.

$$\text{Per unit voltage regulation} = \left.\frac{|V_{n1}| - |V_{2fl}|}{|V_{2fl}|}\right|_{|V_1| = \text{Constant}}$$

4.13. What is all day efficiency ?

Ans. It is defined as the ratio of the energy output to the energy input taken over a 24-hour period. It is denoted by η_{AD}.

$$\eta_{AD} = \frac{\text{Energy output over 24 hours}}{\text{Energy output over 24 hour + Energy losses over 24 hours}}$$

4.14. Write the applications of transformers.

Ans.

1. To change the level of voltage and current in electric power system.
2. As a coupling device.
3. To measure voltage and current, these are known as instrument transformers.

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5 UNIT Three Phase Transformers (2 Marks Questions)

5.1. What is the need of tertiary winding in a 3ϕ transformer ?

AKTU 2016-17, Marks 02

Ans.

1. Tertiary windings are used to supply substation auxiliaries (for example lights, fans and pumps) at a voltage different from those of primary and secondary windings.
2. Synchronous capacitors or static high-voltage capacitors are connected across the delta-connected output of the tertiary windings for reactive power injection into the system for either power factor correction or voltage regulation or both.
3. Tertiary can be used for measuring voltage of high voltage testing transformers.

5.2. State the advantages of three-phase unit transformer.

Ans.

1. It takes less space.
2. It is lighter, smaller and cheaper.
3. It is slightly more efficient.

5.3. What are the factors that affect the choice of connections ?

Ans.

1. Insulation to ground and voltage stress.
2. Parallel operation with other transformers.
3. Operation under fault conditions.
4. Economic consideration.

5.4. What are the advantages of Δ-Δ transformation ?

Ans.

1. The Δ-Δ connection is satisfactory for both balanced and unbalanced loading.
2. If a third harmonics is present, it circulates in the closed path and therefore does not appear in the output voltage wave.
3. If one transformer fails, the remaining two transformers will continue to supply three-phase power.

5.5. Write the applications of open-delta system.

Ans.
1. As a temporary measure when one transformer of Δ-Δ system is damaged and removed for repair and maintenance.
2. To supply a combination of large 1ϕ and smaller 3ϕ loads.

5.6. What are the applications of Scott connection ?

Ans.
1. Electric furnace installations where it is desired to operate two 1ϕ furnaces together and draw a balanced load from the 3ϕ supply.
2. Supply 1ϕ loads such as electric trains which are so scheduled as to keep the load on the 3ϕ system as nearly balanced as possible.
3. To link a 3ϕ system with a 2ϕ system with flow of power in either direction.

5.7. Define polarity of transformer.

Ans. Polarities of a transformer identify the relative directions of induced voltages in the two windings. The polarities result from the relative direction in which the two windings are wound on the core. It is necessary to know the relative polarities for operating transformers in parallel.

5.8. What are the reasons for parallel operation in transformers ?

Ans.
1. For large loads, it may be impracticable or uneconomical to have a single large transformer.
2. There is a scope of future expansion of a substation to supply a load beyond the capacity of the transformer already installed.
3. In substations, the total load required may be supplied by an appropriate number of transformers of stand and size. This reduces the spare capacity of the substation.

5.9. What are the undesirable effects of circulating current in single-phase transformer ?

Ans.
1. They increase the copper loss.
2. They overload one transformer and reduce the permissible load kVA.

5.10. What are the necessary conditions for parallel operation of 1ϕ transformers ?

Ans.
1. The polarities of the transformers must be the same.
2. The turn ratio of the transformers should be equal.

5.11. Write the desirable conditions for parallel operations of 1ϕ transformers.

Ans.
1. The voltages at full-load across transformers internal impedances should be equal.
2. The ratios of the winding resistance to reactance must be equal for both transformers. This condition ensures that both transformers operate the same power factor, thus sharing active power and reactive voltamperes according to their ratings.

5.12. What do you mean by inrush current ?

Ans. Due to the doubling effect, core flux achieves a value of $2\phi_m$ due to which transformer draws a large exciting current. This is because the core gets into deep saturation region of magnetization. This large current drawn during transients is called inrush current.

5.13. What are the drawbacks of inrush current ?

Ans.
1. Unwanted tripping of relays.
2. Momentary large voltage drops.
3. Large humming due to magnetostriction of the core.

5.14. What are the effects of harmonic current in transformer ?

Ans.
1. Increased core loss.
2. Additional electrical (I^2R) loss swing to circulating currents.
3. Magnetic interference with commutation circuits and protective gear.

5.15. What is doubling effect ?

Ans. During transients, the core flux attains the maximum value of flux equal to $2\phi_m$ which is over twice the normal flux. This is known as doubling effect.

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B.Tech.
(SEM. III) ODD SEMESTER THEORY EXAMINATION, 2014-15
ELECTRO-MECHANICAL ENERGY CONVERSION-I

Time : 3 Hours **Max. Marks : 100**

1. Attempt any **four parts :** (5 × 4 = 20)

a. Explain how flow of energy takes place in electro-mechanical device ?

Ans. Refer Q. 1.3, Page 1–4B, Unit-1.

b. The magnetic flux density on the surface of an iron face is 1.6 T which is a typical saturation level value for ferromagnetic material. Find the force density on the iron face.

Ans. Refer Q. 1.12, Page 1–14B, Unit-1.

c. Derive the expression for magnetic torque and force developed in doubly excited system.

Ans.

A. Expression for magnetic torque, T_e :

1. A doubly-excited magnetic system has two independent sources of excitations.
2. The flux linkage equations for the two windings are

$$\lambda_1 = L_1 i_1 + M i_2 \quad ...(1)$$
$$\lambda_2 = L_2 i_2 + M i_1 \quad ...(2)$$

3. The instantaneous voltage equations for the two coils are

$$v_1 = R_1 i_1 + \frac{d\lambda_1}{dt} \quad ...(3)$$
$$v_2 = R_2 i_2 + \frac{d\lambda_2}{dt} \quad ...(4)$$

4. Substituting the values of λ_1 and λ_2 from eq. (1) and (2) in eq. (3) and (4), we get

$$v_1 = R_1 i_1 + \frac{d}{dt}(L_1 i_1) + \frac{d}{dt}(M i_2) \quad ...(5)$$
$$v_2 = R_2 i_2 + \frac{d}{dt}(L_2 i_2) + \frac{d}{dt}(M i_1) \quad ...(6)$$
$$v_1 = R_1 i_1 + L_1 \frac{di_1}{dt} + i_1 \frac{dL_1}{dt} + M \frac{di_2}{dt} + i_2 \frac{dM}{dt} \quad ...(7)$$
$$v_2 = R_2 i_2 + L_2 \frac{di_2}{dt} + i_2 \frac{dL_2}{dt} + M \frac{di_1}{dt} + i_1 \frac{dM}{dt} \quad ...(8)$$

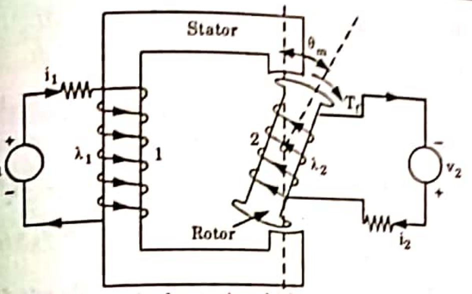


Fig. 1. Doubly excited rotational electromagnetic system.

5. Multiplying eq. (7) by i_1 and eq. (8) by i_2, we get

$$v_1 i_1 = R_1 i_1^2 + L_1 i_1 \frac{di_1}{dt} + i_1^2 \frac{dL_1}{dt} + i_1 M \frac{di_2}{dt} + i_1 i_2 \frac{dM}{dt} \quad ...(9)$$
$$v_2 i_2 = R_2 i_2^2 + L_2 i_2 \frac{di_2}{dt} + i_2^2 \frac{dL_2}{dt} + i_2 M \frac{di_1}{dt} + i_1 i_2 \frac{dM}{dt} \quad ...(10)$$

6. Eq. (9) and (10) are the power equations for the coils.
7. Integrating eq. (9) and (10) with respect to time and adding, we get

$$\int (v_1 i_1 + v_2 i_2)\, dt = \int (R_1 i_1^2 + R_2 i_2^2)\, dt + \int (L_1 i_1 di_1 + L_2 i_2 di_2 + i_1 M di_2 + 2 i_1 i_2 dM + i_1^2 dL_1 + i_2^2 dL_2 + i_2 M di_1) \quad ...(11)$$

Also, $$\begin{bmatrix} \text{Useful electrical} \\ \text{energy input} \end{bmatrix} = \int (v_1 i_1 + v_2 i_2)\, dt - \int (R_1 i_1^2 + R_2 i_2^2) dt \quad ...(12)$$

And, $$\begin{bmatrix} \text{Energy to field} \\ \text{storage in the} \\ \text{electrical system} \end{bmatrix} + \begin{bmatrix} \text{Electrical to} \\ \text{mechanical} \\ \text{energy} \end{bmatrix}$$
$$= \int (L_1 i_1 di_1 + L_2 i_2 di_2 + i_1 M di_2 + 2 i_1 i_2 dM + i_1^2 dL_1 + i_2^2 dL_2 + i_2 M di_1) \quad ...(13)$$

8. From eq. (13), we get

$$\int dW_{fe} = \int_0^{i_1} L_1 i_1 di_1 + \int_0^{i_2} L_2 i_2 di_2 + \int_0^{i_1, i_2} (i_2 M di_1 + i_1 M di_2)$$
$$[\text{Total } W_{fe}] = \frac{1}{2} L_1 i_1^2 + \frac{1}{2} L_2 i_2^2 + M i_1 i_2 \quad ...(14)$$

9. If the transducer rotates, the rate of change of field energy with respect to time is given by differentiating eq. (14)

$$\frac{dW_{fe}}{dt} = \frac{1}{2} L_1 \frac{d}{dt} i_1^2 + \frac{1}{2} i_1^2 \frac{dL_1}{dt} + \frac{1}{2} L_2 \frac{di^2}{dt^2} + \frac{1}{2} i_2^2 \frac{dL_2}{dt} + i_1 i_2 \frac{dM}{dt} + i_1 M \frac{di_2}{dt} + i_2 M \frac{di_1}{dt}$$

$$\frac{dW_{fe}}{dt} = L_1 i_1 \frac{di_1}{dt} + \frac{1}{2} i_1^2 \frac{dL_1}{dt} + L_2 i_2 \frac{di_2}{dt} + \frac{1}{2} i_2^2 \frac{dL_2}{dt} + i_1 i_2 \frac{dM}{dt} + i_1 M \frac{di_2}{dt} + i_2 M \frac{di_1}{dt} \quad ...(15)$$

10. Integrating eq. (15) with respect to time

$$\int dW_{fe} = W_{fe} = \int\left(L_1 i_1 di_1 + \frac{1}{2} i_1^2 \, dL_1 + L_2 i_2 di_2 + \frac{1}{2} i_2^2 dL_2\right) + i_1 i_2 dM + i_1 M di_2 + i_2 M di_1 \quad ...(16)$$

$$W_{em} = \begin{bmatrix}\text{Electrical to} \\ \text{mechanical} \\ \text{energy}\end{bmatrix} = \int\left(\frac{1}{2} i_1^2 dL_1 + \frac{1}{2} i_2^2 dL_2 + i_1 i_2 dM\right) \quad ...(17)$$

11. Differentiating eq. (17) with respect to θ_m,

$$T_e = \frac{dW_{em}}{d\theta_m} = \frac{1}{2} i_1^2 \frac{dL_1}{d\theta_m} + \frac{1}{2} i_2^2 \frac{dL_2}{d\theta_m} + i_1 i_2 \frac{dM}{d\theta_m} \quad ...(18)$$

as only L_1, L_2 and M are dependent on θ_m.

12. Eq. (18) shows that torque is equal to the rate of increase of the field energy with respect to the displacement of constant currents.

B. Expression for magnetic force, F_e :

1. The differential electrical energy input dW_{elec}, from two energy sources is

$$dW_{elec} = i_1 d\lambda_1 + i_2 d\lambda_2$$

Here $\lambda_1 = L_1 i_1 + M_{12} i_2$

and $\lambda_2 = L_1 i_2 + M_{21} i_1$

Also $M_{12} = M_{21}$

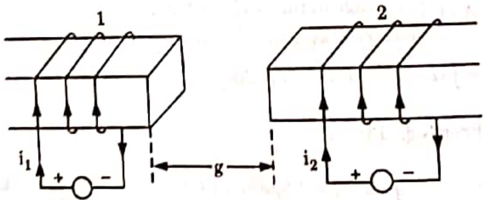


Fig. 2. Doubly excited linear magnetic system.

2. The magnitude of magnetic force f_e is given as

$$f_e = \frac{1}{2} i_1^2 \frac{dL_1}{dx} + \frac{1}{2} i_2^2 \frac{dL_2}{dx} + i_1 i_2 \frac{dM_{12}}{dx} \quad ...(19)$$

$$f_e = \frac{\partial W_{fld}}{\partial x}(i_1, i_2, x) \quad ...(20)$$

$$= \frac{\partial W_{fld}'}{\partial x}(i_1, i_2, x) \quad ...(21)$$

3. Eq. (19) and (21) reveals that the magnetic torque and forces act in such a direction as to tend to increase the field energy at constant currents.

d. Describe in detail account on energy stored in magnetic system.

Ans. Refer Q. 1.9, Page 1–10B, Unit-1.

e. Draw the circuit and explain the concept of a doubly excited magnetic system.

Ans.

1. A doubly-excited magnetic system is one which has two independent sources of excitations.
2. Fig. 3 illustrates a simple model of a doubly excited magnetic system. This model consists of stator iron, rotor iron and both are of the salient pole type.

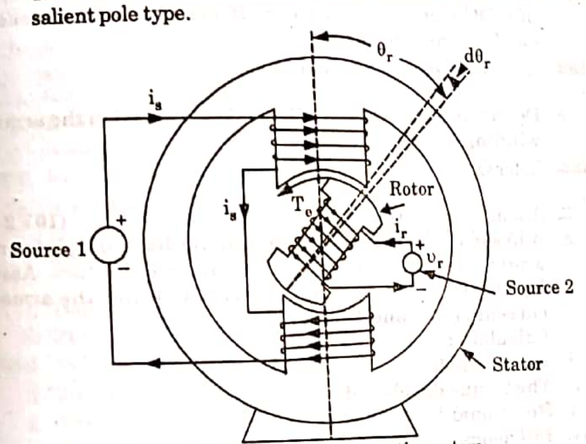


Fig. 3. Doubly-excited magnetic system.

3. The stator with N_s turns is energised from source 2. The mmfs produced by both the stator and rotor windings are in the same direction and magnetic torque T_e is in the anticlockwise direction.
4. Examples are synchronous machines, loudspeakers, tachometers, DC shunt machines etc.
5. The differential electrical energy input dW_{elec} from two energy sources 1 and 2, in Fig. 3, is
6. $dW_{elec} = i_s d\lambda_s + i_r d\lambda_r$

   Here λ_s and λ_r are the instantaneous total flux linkages of stator and rotor windings respectively.
7. λ_s and λ_r can be expressed in terms of self and mutual inductances.

$\therefore$ $\lambda_s = L_s i_s + M_{sr} i_r$

and $\lambda_r = L_r i_r + M_{rs} i_s$

where L_s = Self-inductance of stator winding

L_r = Self-inductance of rotor winding

and $M_{sr} = M_{rs}$ = Mutual inductance between stator and rotor windings.

f. Define energy and co-energy.

Ans. Refer Q. 1.5, Page 1–5B, Unit-1.

2. Attempt any two parts : **(10 × 2 = 20)**

a. Discuss in detail the phenomenon of commutation in DC machines and also explain the methods adopted to improve commutation.

Ans. Refer Q. 2.14, Page 2–16B, Unit-2.

b. Explain the effects of armature reaction on the operation of a DC machines. How the effects of armature reactions can be minimized ?

Ans. Refer Q. 2.10, Page 2–12B, Unit-2.

c. Derive an expression for the emf generated in the armature winding of a DC machine.

Ans. Refer Q. 2.3, Page 2–5B, Unit-2.

3. Attempt any two parts : (10 × 2 = 20)

a. A 15 kW, 250 V, 1200 rpm, shunt motor has 4 poles, 4 parallel armature paths and 900 armature conductors. Assume R_a = 0.2 Ω. At rated speed and rated output the armature current is 75 A and I_f = 1.5 A.

Calculate :

i. The flux/pole

ii. The torque developed

iii. Rotational losses

iv. Efficiency

v. The shaft load.

Ans. Refer Q. 3.20, Page 3–26B, Unit-3.

b. Derive an expression for the torque developed in the armature of a DC motor.

Ans. Refer Q. 2.4, Page 2–6B, Unit-2.

c. A 250 V DC shunt motor has a shunt field resistance of 200 Ω and an armature resistance of 0.3 Ω. For given load, motor runs at 1500 rpm drawing a current of 22 A from the supply. If a resistance of 150 Ω is added in series with the field winding, find the new armature current and the speed. Assume load torque constant and magnetization curve to be linear.

Ans. Refer Q. 3.6, Page 3–9B, Unit-3.

4. Attempt any two parts : (10 × 2 = 20)

a. The parameters of the equivalent circuit of a 150 kVA, 2400/240 V transformer are :

$R_1 = 0.2\ \Omega$, $R_2 = 2 \times 10^{-3}\ \Omega$, $X_1 = 0.45\ \Omega$,

$X_2 = 4.5 \times 10^{-3}\ \Omega$, $R_i = 10\ k\Omega$, $X_m = 1.6\ k\Omega$

(as seen from 2400 V side).

Calculate :

i. Open-circuit current, power and power factor when LV is excited at rated voltage.

ii. The voltage at which the HV should be excited to conduct a short-circuit test (LV shorted) with full-load current flowing. What is the input power and is power factor ?

Ans. Refer Q. 4.18, Page 4–20B, Unit-4.

b. A 500 kVA transformer has an efficiency of 95 % at full-load and also at 60 % of full-load; both at unity power factor.

i. Separate out the losses of the transformer.

ii. Determine the efficiency of the transformer at 3/4th full-load.

Ans. Refer Q. 4.14, Page 4–13B, Unit-4.

c. A 400/100 V, 10 kVA, 2-winding transformer is to be employed as an auto-transformer to supply a 400 V circuit from a 500 V source. When tested as a 2-winding transformer at rated load, 0.85 power factor lagging, its efficiency is 97 %.

i. Determine its kVA rating as an auto-transformer.

ii. Find its efficiency as an auto-transformer.

Ans. Refer Q. 4.24, Page 4–29B, Unit-4.

5. Attempt any two parts : (10 × 2 = 20)

a. Explain the operation of parallel transformer on no-load and also derive the expression for equal voltage ratios in division of load between transformers in parallel.

Ans. Refer Q. 5.18, Page 5–18B, Unit-5.

b. Describe in detail on phase conversion in transformer.

Ans.

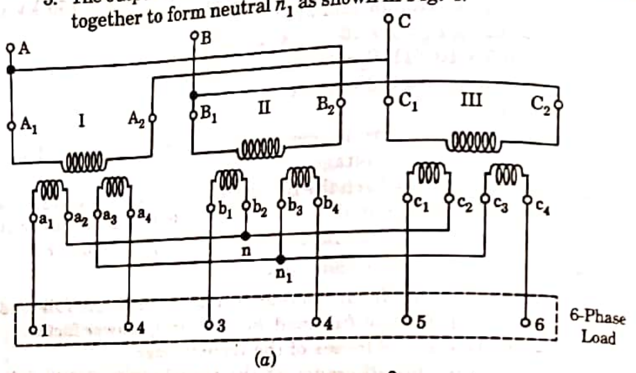
A. 3ϕ to 2ϕ conversion : Refer Q. 5.10, Page 5–12B, Unit-5.

B. 3ϕ to 6ϕ conversion : The following schemes of connections are commonly used for 3-phase to 6-phase transformation :

Double star :

1. For 3ϕ to 6ϕ transformation, three identical single-phase transformers are used.
2. Each transformer unit has its secondary winding split into two equal sections. The three primaries must be connected in delta.
3. One set of three secondary is connected in star and the other set is connected in reversed star.

4. The output terminals for one star are $a_1b_1c_1$ with $a_2b_2c_2$ connected together to form neutral n.
5. The output terminals for second star are $a_4b_4c_4$ with $a_3b_3c_3$ connected together to form neutral n_1 as shown in Fig. 4.



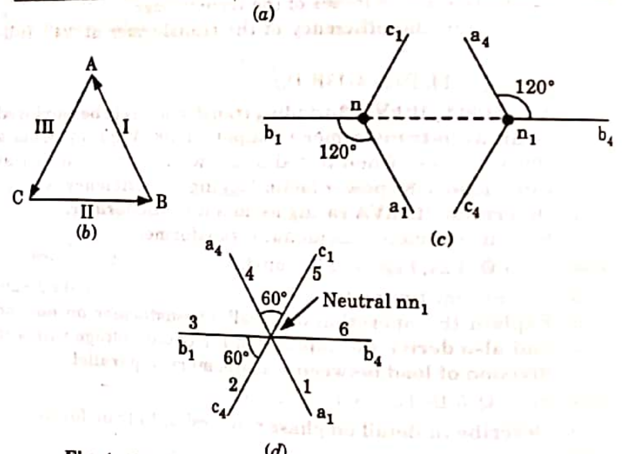


Fig. 4. 3φ to 6φ transformer : (a) Double star connection, (b) Phasor diagram of primary, (c) Phasor diagram of secondary, (d) Six-phase star connection.

c. What is meant by transformer inrush current ? Explain the effect of hysteresis and saturation during excitation phenomenon in transformers.

Ans. Refer Q. 4.13, Page 4–12B, Unit-4.

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B.Tech.
(SEM. III) THEORY EXAMINATION, 2015-16
ELECTRO-MECHANICAL ENERGY CONVERSION-I

Time : 3 Hours **Max. Marks : 100**

Note : Attempt all 3 Section.

Section – A

1. Attempt all parts of this section : (2 × 10 = 20)

a. Why is the wave winding useful for high voltage low current DC machines ?

Ans. Refer Q. 2.1, Page SQ–3B, Unit-2, Two Marks Questions.

b. How the back EMF does make the DC machine self-regulatory ?

Ans. Refer Q. 3.8, Page SQ–7B, Unit-3, Two Marks Questions.

c. How the direction of rotation of the DC shunt motor can be changed ?

Ans. Refer Q. 3.1, Page SQ–6B, Unit-3, Two Marks Questions.

d. Based on the principle of conservation of energy, write an energy balance equation of the motor.

Ans. Refer Q. 1.2, Page SQ–1B, Unit-1, Two Marks Questions.

e. State the phenomenon useful for the electromechanical energy conversion in rotating machines.

Ans. Refer Q. 1.4, Page SQ–2B, Unit-1, Two Marks Questions.

f. Give two applications of the DC shunt motor and DC compound generator.

Ans. Refer Q. 3.9, Page SQ–7B, Unit-3, Two Marks Questions.

g. How are the transformer losses affected by the power factor of the connected load ?

Ans. Refer Q. 4.7, Page SQ–11B, Unit-4, Two Marks Questions.

h. An auto-transformer has primary voltage V_1 and secondary voltage V_2, where $V_1 > V_2$. Calculate the fraction of power transferred inductively.

Ans. Refer Q. 4.3, Page SQ–9B, Unit-4, Two Marks Questions.

i. **If P_i and P_c represents iron loss and full-load ohmic loss, then find the fractional load at which the maximum power shall be transferred.**

Ans. Refer Q. 4.8, Page SQ–11B, Unit-4, Two Marks Questions.

j. **A 1000 kVA, 50 kV/40 kV single-phase auto-transformer is fully loaded. Find the current in the common section of the winding.**

Ans. Refer Q. 4.9, Page SQ–11B, Unit-4, Two Marks Questions.

Section – B

Attempt any five question from the following : (10 × 5 = 50)

2\. i. **Show that the torque in a doubly excited magnetic system is equal to the rate of increase of the field energy with respect to the displacement at constant currents.**

Ans. Refer Q. 1(c), Page SP–1B, Solved Paper 2014-15.

ii. **Show that in a linear magnetic system the energy and co-energy are represented by the same expression.**

Ans. Refer Q. 1.6, Page 1–6B, Unit-1.

3\. i. **Explain the commutator action in DC machines. Also describe the ways for achieving good commutation.**

Ans. Refer Q. 2.14, Page 2–16B, Unit-2.

ii. **A 4-pole DC shunt generator with wave connected armature has field and armature resistance of 90 Ω and 0.15 Ω. It supplies power to 25 lamps rated at 100 V, 60 W each, calculate the armature current and emf generated neglecting brush drop.**

Ans. Refer Q. 2.5, Page 2–7B, Unit-2.

4\. **Discuss the internal and external characteristics of the DC shunt generator. Also explain why the load characteristics of DC shunt generator have drooping more than that of separately excited generator ?**

Ans. Refer Q. 2.17, Page 2–20B, Unit-2.

5\. i. **Compare the speed torque characteristics of DC shunt, series and compound motor. Which machine is most suitable for traction purpose ?**

Ans. Refer Q. 3.3, Page 3–4B, Unit-3.

ii. **What are the advantages of the field flux control over armature circuit resistance control method employed for the speed control of DC motors ?**

Ans. Refer Q. 3.11, Page 3–14B, Unit-3.

6\. **Show that the VA rating of the auto-transformer is more than the corresponding two winding transformer. Show that in case of an auto-transformer**

$$\frac{\text{Inductively transferred power}}{\text{Total power}} = \frac{\text{High voltage} - \text{Low voltage}}{\text{High voltage}}$$

Ans. Refer Q. 4.22, Page 4–25B, Unit-4.

7\. **A 2300/220 V 500 kVA, 50 Hz distribution transformer has the core losses of 1600 W at rated voltage and copper loss 7.5 kW at full-load. During the day, it is loaded as follows :**

Load	0 %	20 %	50 %	80 %	100 %	125 %
Power Factor		0.7 lag	0.8 lag	0.9 lag	1	0.85 lag
Hours	2	4	4	5	7	2

Ans. Refer Q. 4.15, Page 4–14B, Unit-4.

8\. **Explain the back to back test for testing of the single-phase transformers. Also explain how the reading of the wattmeter recording the core losses remain unaffected when the low voltage is injected in the secondary series circuit ?**

Ans. Refer Q. 4.17, Page 4–18B, Unit-4.

9\. **An electrical machine has cylindrical stator and salient pole rotor. Justify the correctness of the following statement :**

i. **Reluctance torque is produced when exciting winding is on rotor.**

ii. **When stator and rotor both carry exciting winding electromagnetic as well as reluctance torque are produced.**

Ans. Refer Q. 1.14, Page 1–16B, Unit-1.

Section – C

Attempt any two questions of the following : (15 × 2 = 30)

10\. i. **Explain the conditions to be satisfied for the successful parallel operation of the single-phase transformers.**

ii. **Two single-phase transformers rated 1000 kVA and 500 kVA respectively are connected in parallel on both HV and LV sides. They have equal voltage rating of 11 kV/400 V and** their per unit impedances are $(0.02+ j0.07)\ \Omega$ and $(0.0025 + j0.0875)\ \Omega$ respectively. What is the largest value of the unity power factor load that can be delivered by the parallel combination at the rated voltage ?

Ans. Refer Q. 5.20, Page 5–22B, Unit-5.

11. i. **Explain the Hopkinson test for determining the efficiency of the DC shunt machine.**

ii. **A 50 kW, 250 V compound motor takes a current of 9 A running at no-load at rated voltage and rated speed. The shunt field current is 5 A. The resistance of the windings is as armature winding 0.1 Ω, series field 0.07 Ω, interpolar windings 0.03 Ω. The brush drop is 2 V. Determine the motor output and the efficiency of the motor when the intake is 155 A.**

Ans. Refer Q. 3.21, Page 3–27B, Unit-3.

12. **Write short notes on :**

i. **Magnetisation characteristics for DC shunt generator.**

Ans. Refer Q. 2.18, Page 2–22B, Unit-2.

ii. **Three-phase to two-phase connection.**

Ans. Refer Q. 5.10, Page 5–12B, Unit-5.

iii. **Inrush current in transformers.**

Ans. Refer Q. 4.13, Page 4–12B, Unit-4.

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B.Tech.

(SEM. III) THEORY EXAMINATION, 2016-17
ELECTRO-MECHANICAL ENERGY CONVERSION-I

Time : 3 Hours **Max. Marks : 100**

Section – A

1. **Attempt all parts of the followings :** (2 × 10 = 20)

a. **Write the energy balance equation for motor action and draw power flow diagram.**

Ans. Refer Q. 1.2, Page SQ–1B, Unit-1, Two Marks Questions.

b. **What is back-emf in a DC motor ?**

Ans. Refer Q. 3.4, Page SQ–6B, Unit-3, Two Marks Questions.

c. **Define reactance voltage in commutation process.**

Ans. Refer Q. 2.5, Page SQ–4B, Unit-2, Two Marks Questions.

d. **What is the effect of frequency and supply voltage on iron losses ?**

Ans. Refer Q. 3.5, Page SQ–6B, Unit-3, Two Marks Questions.

e. **What are the effects of armature reaction ?**

Ans. Refer Q. 2.6, Page SQ–4B, Unit-2, Two Marks Questions.

f. **Differentiate between armature voltage control and flux control of DC shunt motor.**

Ans. Refer Q. 3.6, Page SQ–7B, Unit-3, Two Marks Questions.

g. **What is the need of tertiary winding in a 3ϕ transformer ?**

Ans. Refer Q. 5.1, Page SQ–13B, Unit-5, Two Marks Questions.

h. **Why short circuit test is performed on HV side of transformer ?**

Ans. Refer Q. 4.6, Page SQ–10B, Unit-4, Two Marks Questions.

i. **What is the need of starter while starting the DC motor ?**

Ans. Refer Q. 3.7, Page SQ–7B, Unit-3, Two Marks Questions.

j. **Define energy and co-energy.**

Ans. Refer Q. 1.3, Page SQ–2B, Unit-1, Two Marks Questions.

Section – B

Attempt any five questions of the followings : (10 × 5 = 50)

2. a. Derive an expression for reluctance torque in a rotating electrical machine.

Ans: Refer Q. 1.8, Page 1–8B, Unit-1.

b. Explain the various phenomenon happening in electromechanical energy conversion in rotating electrical machines.

Ans: Refer Q. 1.3, Page 1–4B, Unit-1.

3. What are various losses that occur in DC machines ? Also, derive the condition for maximum efficiency of a DC generator.

Ans: Refer Q. 3.14, Page 3–17B, Unit-3.

4. Draw the speed-torque characteristics of DC shunt, series and compound motors. A 200 V shunt motor has $R_a = 0.1\ \Omega$, $R_f = 240\ \Omega$ and rotational loss 236 W. On full-load the line current is 9.8 A with the motor running at 1450 rpm. Determine

a. The mechanical power developed.

b. The power output. **c. The load torque.**

d. The full-load efficiency.

Ans: Refer Q. 3.19, Page 3–25B, Unit-3.

5. Explain the procedure of O.C. and S.C. tests for a transformer. How different parameters of the transformer can be determined from these tests ?

Ans: Refer Q. 4.16, Page 4–16B, Unit-4.

6. A 500 kVA, 11/0.43 kV, 3ϕ delta/star connected transformer has on rated load. The H.V. copper loss of 2.5 kW and the L.V. loss of 2 kW and the total leakage reactance of 0.06 per unit. Find the ohmic values of the equivalent resistance and leakage reactance on the delta side.

Ans: Refer Q. 5.12, Page 5–13B, Unit-5.

7. a. Derive the relationship between magnetic field energy and co-energy for a singly-excited system.

Ans: Refer Q. 1.6, Page 1–6B, Unit-1.

b. Derive the emf equation for a DC generator.

Ans: Refer Q. 2.3, Page, 2–5B, Unit-2.

8. Two single-phase furnaces 1 and 2 are supplied at 80 V by means of a Scott connected transformer combination fed by a 3ϕ, 6600 V system. The voltage of furnace 1 is leading. Calculate the line currents on the 3ϕ side when the furnaces take 500 kW and 800 kW respectively

a. At unity pf.

b. Furnace 1 at unity pf and furnace 2 at 0.7 pf (lagging).

Ans: Refer Q. 5.13, Page 5–15B, Unit-5.

9. What do you mean by parallel operation of 3ϕ transformers ? Discuss the advantages and disadvantages of parallel operation of 3ϕ transformers.

Ans: Refer Q. 5.16, Page 5–17B, Unit-5.

Section-C

Attempt any two questions of the followings : (15 × 2 = 30)

10. Write short notes on the following :

a. 3ϕ to 2ϕ connection of transformers.

Ans: Refer Q. 5.10, Page 5–12B, Unit-5.

b. 3ϕ to 6ϕ connection of transformers.

Ans: Refer Q. 5(b), Page SP–6B, Solved Paper 2014-15.

11. A 4-pole series wound fan motor draws an armature current of 50 amps, when running at 2000 rpm on a 230 V DC supply with four field coils connected in series. The four field coils are then reconnected in two parallel groups of two coils in series. Assuming flux/pole to be proportional to the exciting current and load torque proportional to the square of the speed, find the new speed and armature current.

Ans: Refer Q. 3.12, Page 3–15B, Unit-3.

12. a. Discuss the following tests on DC machines :

i. Hopkinson's test.

Ans: Refer Q. 3.15, Page 3–18B, Unit-3.

ii. DC resistance test.

Ans: DC resistance test is done only for AC machine.

DC resistance test for induction motor :

1. The stator winding resistance is measured between any two terminals, using direct current.
2. This gives the resistance of two phases in series, which must be divided by 2 to obtain stator winding resistance per phase.
3. For greater accuracy, the resistance between three pairs of stator terminals is measured.

4. The average of these three values divided by 2 gives the resistance per phase.
5. Since the effective AC resistance is higher than the DC resistance, the latter is usually multiplied by a figure of about 1.25 to obtain the former.

b. Discuss the following test on 1ϕ transformers :
i. Sumpner's back-to-back test.
ii. Polarity test.

Ans. Refer Q. 4.17, Page 4–18B, Unit-4.

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B.Tech.

(SEM. IV) EVEN SEMESTER THEORY EXAMINATION, 2017-18

ELECTRICAL MACHINES-I

Time : 3 Hours **Max. Marks : 70**

Note : 1. Attempt all Section. If required any missing data; then choose suitably.

SECTION-A

1. Attempt all questions on brief : (2 × 7 = 14)

a. Explain with the help of an example why in an electrical machine the number of stator poles should be equal to the number of rotor poles.

Ans. Number of stator pole and rotor pole should be equal for the generation of torque since with distinct stator and rotor poles, the rotor torque is zero as there is no magnetic coupling.

b. Explain Faraday's laws of electromagnetic induction and Lenz's law.

Ans. Refer Q. 4.4, Page SQ–10B, Unit-4, Two Marks Questions.

c. Explain why equalizer connections are used in lap-winding and dummy coils are sometimes used in wave-windings.

Ans. Refer Q. 2.2, Page SQ–3B, Unit-2, Two Marks Questions.

d. Explain why a DC motor should not be started direct-on-line.

Ans. Refer Q. 3.3, Page SQ–6B, Unit-3, Two Marks Questions.

e. Describe how a DC machine is to be maintained for a long satisfactory performance.

Ans. Refer Q. 2.3, Page SQ–3B, Unit-2, Two Marks Questions.

f. Explain the function of a commutator in a DC machine for motoring and generating action.

Ans. Refer Q. 2.4, Page SQ–3B, Unit-2, Two Marks Questions.

g. State why the core of a transformer should be made up of magnetic material.

Ans. Refer Q. 4.5, Page SQ–10B, Unit-4, Two Marks Questions.

SECTION-B

2. Attempt any three of the following : (7 × 3 = 21)

a. **The magnetic flux density on the surface of an iron face is 1.6 T which is a typical saturation level value of ferromagnetic material. Find the force density on the iron face.**

Ans. Refer Q. 1.12, Page 1–14B, Unit-1.

b. **Derive the EMF equation and torque equation for DC machines.**

Ans. Refer Q. 2.4, Page 2–6B, Unit-2.

c. **A 250 kW, 400 V, 6-pole DC generator has 720 lap wound conductors. It is given a brush lead of 2.5 angular degrees (mech.) from the geometric neutral. Calculate the cross and demagnetizing turns per pole. Neglect the shunt field current.**

Ans. Refer Q. 2.11, Page 2–13B, Unit-2.

d. **A transformer on no-load has a core loss of 50 W, draws a current of 2 A (rms) and has an induced emf of 230 V (rms). Determine the no-load power factor, core-loss current and magnetizing current. Also calculate the no-load circuit parameters of the transformer. Neglect winding resistance and leakage flux.**

Ans. Refer Q. 4.19, Page 4–21B, Unit-4.

e. **A 20 kVA, 50 Hz, 2000/200 V distribution transformer has a leakage impedance of $0.42 + j0.52\ \Omega$ in the HV winding and $0.004 + j0.05$ in the LV winding. When seen from the LV side, the shunt branch admittance Y_0 is $(0.002 - j0.015)$ ℧ (at rated voltage and frequency). Draw the equivalent circuit referred to**

i. **HV side**

ii. **LV side**

Indicating all impedances on the circuit.

Ans. Refer Q. 5.21, Page 5–23B, Unit-5.

SECTION-C

3. Attempt any one part of the following : (7 × 1 = 7)

a. **Find an expression for the force per unit area between the plates of a parallel plate condenser in terms of the electric field intensity. Use both the energy and coenergy methods. Find the value of the force per unit area when $E = 3 \times 10^6$ V/m, the breakdown strength of air.**

Ans. Refer Q. 1.10, Page 1–11B, Unit-1.

b. **Derive an expression for dynamical equations of electromechanical systems.**

Ans. Refer Q. 1.11, Page 1–13B, Unit-1.

4. Attempt any one part of the following : (7 × 1 = 7)

a. **The following test results were obtained while Hopkinson's test was performed on two similar DC shunt machines :**
Supply voltage = 250 V,
Field current of motor = 2 A,
Field current of generator = 2.5 A,
Armature current of generator = 60 A,
Current taken by the two armatures from supply = 15 A,
Resistance of each armature circuit = 0.2 Ω.
Calculate the efficiency of the motor and generator under these conditions of load.

Ans. Refer Q. 3.18, Page 3–25B, Unit-3.

b. **Explain the efficiency testing of DC machines in detail.**

Ans. Refer Q. 3.15, Page 3–18B, Unit-3.

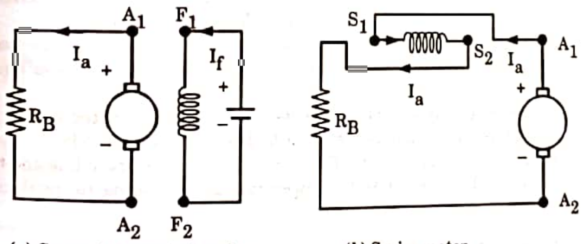
5. Attempt any one part of the following : (7 × 1 = 7)

a. **Explain the plugging, dynamic braking and regenerative braking of DC machines in detail.**

Ans.

A. **Plugging :**

1. For plugging, the supply voltage of a separately excited motor is reversed so that it assists the back emf in forcing armature current in reverse direction as shown in Fig. 1.



(a) Separately excited motor (b) Series motor

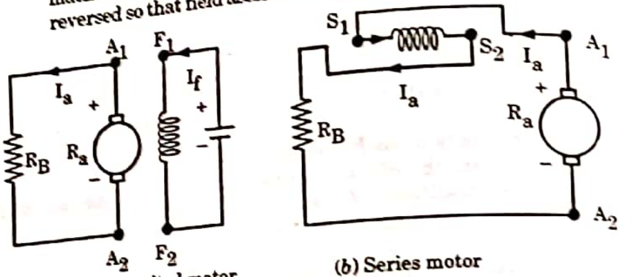
Fig. 1. Plugging operation of DC motors.

2. A resistance R_B is also connected in series with armature to limit current.

3. For plugging of series motor, armature alone is reversed.
4. Plugging gives fast braking due to high average torque, even with one section of braking resistance R_B.

B. Dynamic Braking :

1. In dynamic braking, motor armature is disconnected from the source and connected across resistance R_B.
2. The generated energy is dissipated in R_B and R_a. Since, the series machine works as a self-excited generator, the field connection is reversed so that field assists the residual magnetism.



(a) Separately excited motor (b) Series motor

Fig. 2. Dynamic braking of DC motors.

C. Regenerative Braking :

1. In regenerative braking, generated energy is supplied to the source. For this to happen following condition should be satisfied :
$$E > V \text{ and negative } I_a$$
2. Field flux cannot be increased substantially beyond rated value because of saturation. Therefore
$$E = K_e \phi \omega_m$$
and
$$E > V \text{ and negative } I_a$$
3. For a source of fixed voltage of rated value regenerative braking is possible only for speeds higher than rated speed and with a variable voltage source, it is also possible below rated speed.
4. The regenerative braking is possible only when, there are loads connected to the line and they are in need of power more or equal to regenerated power.
5. When the capacity of loads is less than the regenerated power, all the regenerated power will not be absorbed by the loads.
6. The remaining power will be supplied to capacitors in line and the line voltage will rise to dangerous values leading to insulation breakdown.

b. A 400 V series motor has total armature resistance of 0.25 Ω. When running at 1200 rpm it draws a current of 25 A. When a regulating resistance of 2.75 Ω is included in the armature circuit, it draws a current of 15 A. Find the speed and ratio of the two mechanical outputs. Assume that the flux with 15 A is 70 % of that with 25 A.

Ans. Refer Q. 3.13, Page 3-16B, Unit-3.

6. Attempt any one part of the following : (7 × 1 = 7)

a. Explain the potential transformer, current transformer audio-frequency transformer and grounding transformer.

Ans.

A. Potential transformers :

1. It is basically a step down transformer.
2. These are used for measurement of high voltages by means of low range voltmeters or for energizing the potential coils of wattmeters, energy meters.
3. The primary winding of the transformer is connected across the line carrying the voltage to be measured that the voltage circuit is connected across the secondary winding.

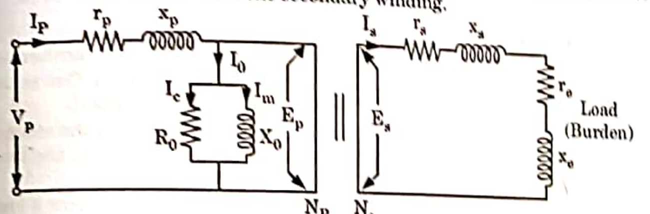


Fig. 3. Equivalent circuit of potential transformer.

B. Current transformer :

1. These transformers are basically step up transformers, *i.e.*, stepping up a voltage from primary to secondary. Thus the current reduces from primary to secondary.
2. So from current point of view, these are step down transformers, stepping down the current value considerably from primary to secondary. So that measurement can be done.

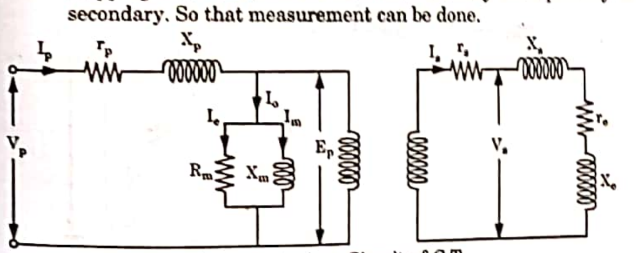


Fig. 4. Equivalent Circuit of C.T.

C. Audio frequency transformer :

1. It is used at the output stage of audio frequency electronic amplifier for matching the load to the output impedance of the power amplifier stage.

2. Here the load is fixed but the frequency is variable over a band (audio, 20 Hz to 20 kHz), the response being the ratio V_2/V_1.
3. The corresponding phase angle (angle of V_2 w.r.t V_1) is called phase response. A small angle is acceptable.
4. The transformer is used in electronic circuits (control, communication, measurement etc.) for stepping up the voltage or impedance matching.

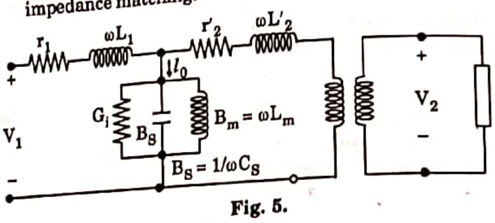


Fig. 5.

D. Grounding transformer :

1. Earthing (Grounding) transformer is three-limbed type transformer having two equally proportioned windings on each limb. One set of windings is connected in star to provide the neutral point.
2. The other ends of this set of windings are connected to the second set of windings so that the directions of the currents in the two windings on each limb are opposite to each other.
3. With this arrangement of windings the transformer offers a low impedance path to the flow of zero phase sequence currents under system fault conditions since the only magnetic flux which results from the zero sequence currents is the leakage flux about each winding section.

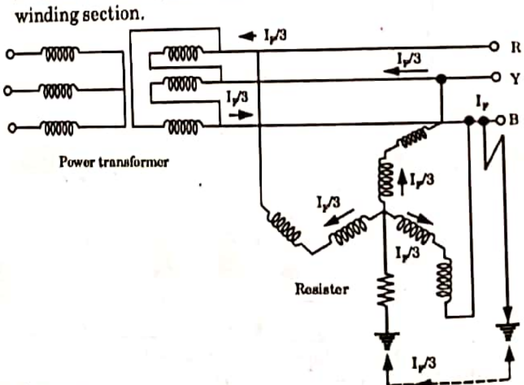


Fig. 6. System neutral grounded through an earthing transformer.

b. Two 1-phase furnaces *A* and *B* are supplied at 100 V by means of a Scott-connected transformer combination from a

3-phase 6600 V system. The voltage of furnace *A* is leading. Calculate the line currents on the 3-phase side, when the furnace *A* takes 400 kW at 0.707 pf lagging and *B* takes 800 kW at unity pf.

Ans. Refer Q. 5.14, Page 5–16B, Unit-5.

7. Attempt any one part of the following : (7 × 1 = 7)

a. Explain the parallel operation of transformers in detail.

Ans. Refer Q. 5.18, Page 5–18B, Unit-5.

b. A 500 kVA transformer has an efficiency of 95 % at full load and also at 60 % of full load; both at unity power factor

i. Separate out the losses of the transformer

ii. Determine the efficiency of the transformer at 3/4th full load.

Ans. Refer Q. 4.14, Page 4–13B, Unit-4.

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B.Tech.

(SEM. IV) EVEN SEMESTER THEORY EXAMINATION, 2018-19

ELECTRICAL MACHINES-I

Time : 3 Hours **Max. Marks : 70**

Note : 1. Attempt all Section. If required any missing data; then choose suitably.

SECTION-A

1. Attempt all questions on brief : **(2 × 7 = 14)**

a. **Write the energy balance equation for the generator and motor.**

Ans. Refer Q. 1.2, Page SQ–1B, Unit-1, Two Marks Questions.

b. **Why is the wave winding useful for high voltage low current DC machines ?**

Ans. Refer Q. 2.1, Page SQ–3B, Unit-2, Two Marks Questions.

c. **Write voltage equation of DC motor.**

Ans. Refer Q. 3.1, Page SQ–6B, Unit-3, Two Marks Questions.

d. **How the direction of rotation of the DC shunt motor can be changed ?**

Ans. Refer Q. 3.2, Page SQ–6B, Unit-3, Two Marks Questions.

e. **Draw phasor diagram of transformer at no load condition.**

Ans. Refer Q. 4.1, Page SQ–9B, Unit-4, Two Marks Questions.

f. **How are the transformer losses affected by the power factor of the connected load ?**

Ans. Refer Q. 4.2, Page SQ–9B, Unit-4, Two Marks Questions.

g. **An auto transformer has primary voltage V_1 and secondary voltage V_2, where $V_1 > V_2$. Calculate the fraction of power transferred inductively.**

Ans. Refer Q. 4.3, Page SQ–9B, Unit-4, Two Marks Questions.

SECTION-B

2. Attempt any three of the following : **(7 × 3 = 21)**

a. **Derive an expression for reluctance torque in rotating electrical machines.**

Ans. Refer Q. 1.8, Page 1–8B, Unit-1.

b. **Explain commutator action in DC machines. Also descri[be] two ways of achieving good commutation and compar[e] them.**

Ans. Refer Q. 2.14, Page 2–16B, Unit-2.

c. **Describe a 3-point starter using a neat diagram. Compar[e] and distinguish it with a four point starter.**

Ans. Refer Q. 3.5, Page 3–7B, Unit-3.

d. **Show that the VA rating of the auto-transformer is mor[e] than the corresponding two winding transformer. Deriv[e] an expression for copper saving in case of auto-transforme[r].**

Ans. Refer Q. 4.23, Page 4–27B, Unit-4.

e. **Two transformers having equal voltage ratio are operate[d] in parallel. Obtain expressions for the maximum possibl[e] kVA loading of the two transformers in parallel. Stat[e] assumptions made if any. Also write the condition require[d] for parallel operation of two transformer.**

Ans. Refer Q. 5.18, Page 5–18B, Unit-5.

SECTION-C

3. Attempt any one part of the following : **(7 × 1 = 7)**

a. **Define energy and co-energy. What is the significance of co-energy ? Show that the field energy in a linear magnetic system is given by $W_f = \frac{1}{2}Li^2 = \frac{1}{2}\psi i = \frac{1}{2L}\psi^2$.**

Ans. Refer Q. 1.7, Page 1–7B, Unit-1.

b. **Derive an expression for the torque in a doubly excited system having salient pole type of stator as well as rotor.**

Ans. Refer Q. 1(c), Page SP–1B, Solved Paper (2014-15).

4. Attempt any one part of the following : **(7 × 1 = 7)**

a. **Discuss the internal and external characteristics of the DC shunt generator. Also explain why the load characteristics of DC shunt generator have drooping more than that of separately excited generator.**

Ans. Refer Q. 2.17, Page 2–20B, Unit-2.

b. **Calculate the number of conductor on each pole piece required in a compensating winding for a 4-pole, lap wound DC armature containing 136 conductors. The pole arc to pole pitch ratio is 0.9. The compensating winding carries full armature current.**

Ans. Refer Q. 2.8, Page 2–10B, Unit-2.

5. Attempt any one part of the following : (7 × 1 = 7)

a. **A 240 V, 25 kW shunt motor has a maximum efficiency of 90 % and a speed of 800 rpm, when delivering 80 % of its rated output. The resistance of its shunt field is 200 Ω. Determine the efficiency and speed when the motor draws a current of 68 A from mains.**

Ans. Refer Q. 3.16, Page 3–22B, Unit-3.

b. **Describe Swinburne's test in detail with its advantages and disadvantages.**

Ans. Refer Q. 3.15, Page 3–18B, Unit-3.

6. Attempt any one part of the following : (7 × 1 = 7)

a. **Define voltage regulation in transformer. A 20 kVA, 2500/500 V, single phase transformer has the following parameters :**
HV side : $r_1 = 8\ \Omega, x_1 = 17\ \Omega$
LV side : $r_1 = 0.3\ \Omega, x_1 = 0.7\ \Omega$
Find the voltage regulation at full load for a power factor of 0.8 lagging.

Ans. Refer Q. 4.20, Page 4–22B, Unit-4.

b. **Explain the procedure of OC and SC tests for a transformer. How different parameters of the transformer can be determined from these tests ?**

Ans. Refer Q. 4.16, Page 4–16B, Unit-4.

7. Attempt any one part of the following : (7 × 1 = 7)

a. **With a neat diagram, explain how a balanced three-phase supply can be converted to balance two-phase supply using transformer.**

Ans. Refer Q. 5.10, Page 5–12B, Unit-5.

b. **A 500 kVA, 11/0.43 kV, 3 phase delta/star connected transformer has on rated load. The HV copper loss of 2.5 kW and the LV loss of 2 kW and the total leakage reactance of 0.08 per unit. Find the ohmic values of the equivalent resistance and leakage reactance on the delta side.**

Ans. Refer Q. 5.22, Page 5–24B, Unit-5.

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