TRANSFORMERS

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Transformer Theory

1. ***Elementary theory*** given in Pars. **1** to **10** is developed from the viewpoint of a 3-phase three-leg concentric-cylindrical two-winding transformer, with the primary low-voltage winding next to the core and the secondary high-voltage winding outside the primary winding. This corresponds to a generator-step-up transformer of moderate kVA. Most of the information is also applicable to single-phase transformers with windings on two legs, 3-phase transformers with five-leg cores, transformers with the primary winding outside the secondary winding, three-winding transformers, substation transformers, etc.

2. ***Sinusoidal voltage*** is induced in windings by sinusoidal variation of flux,

$$E = 4.44 \times 10^{-8} a_c B f N \qquad (10\text{-}1)$$

where a_c = square inches cross section of core, B = lines per square inch peak flux density, E = rms volts, f = frequency in hertz, and N = number of turns in winding.

The induced voltage in the primary (excited) winding approximately balances the applied voltage. The induced voltage in the secondary (loaded) winding approximately supplies the terminal voltage for the load.

Voltage ratio is the ratio of number of turns ("turn ratio") in the respective windings. The rated open-circuit (no-load) terminal voltages are proportional to the turns in the windings, but under load the primary voltage usually must be somewhat higher than the rated value if rated secondary voltage is to be maintained, because of regulation effects.

3. ***Characteristics on Open Circuit.*** The core loss (no-load loss) of a power transformer may be obtained from an empirical design curve of watts per pound of core steel (Fig. 10-1). Such curves are established by plotting data obtained from transformers of similar construction. The basic loss level is determined by the grade of core steel used and is further influenced by the number and type of joints employed in construction of the core. Figure 10-1 applies for 9-mil-thick, M-3 grade steel in a single-phase core with 45° mitered joints. Loss for the same grade of steel in a three-phase core would usually be 5 to 10% higher.

Exciting current for a power transformer may be established from a similar empirical curve of exciting voltamperes per pound of core steel as given in Fig. 10-2. The steel grade and core construction are the same as for Fig. 10-1. The exciting current characteristic is influenced primarily by the number, type, and quality of the core joints, and only secondarily by the grade of steel. Because of the more complex joints in the 3-phase core, the exciting voltamperes will be approximately 50% higher than for the single-phase core.

4. ***Exciting current*** of a transformer contains many harmonic components because of the greatly varying permeability of the steel. For most purposes it is satisfactory to neglect the harmonics and assume a sinusoidal exciting current of the same effective value. This current may be regarded as composed of a core-loss component in phase with the induced voltage (90° ahead of the flux) and a magnetizing component in phase with the flux, as shown in Fig. 10-3.

Sometimes it is necessary to consider the harmonics of exciting current to avoid inductive interference with communication circuits. The harmonic content of the exciting current increases as the peak flux density is increased. Performance can be predicted by comparison with test data from previous designs using similar core steel and similar construction.

constant volts per hertz, i.e., voltage proportional to frequency and speed. The converter characteristics are shown in Fig. 20-19*b* and 19*c*. The $\pm V_d$ values are 1.35 times the line-line voltage on the ac side of each converter. For a given motor speed, frequency, and voltage, the firing angle of the rectifier is set at α_r to yield the required dc voltage V_l for the link. The firing angle of the inverter is set at α_i in the inverting quadrant of the converter so that the link voltage V_i matches the internal ac voltage generated by the motor at the given speed. Power flows from the rectifier at $V_r I_d$ into the inverter and the motor. The inverter firing signals are synchronized to the motor voltage. For decelerating the motor, the rectifier and inverter functions are reversed by shifting the firing angles. Power flows from the motor into the dc link and to the supply line.

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34. *References for Synchronous Motors*

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INDUCTION MACHINES

Theory of the Polyphase Inductor Motor[1]

35. *Principle of Operation.* An induction motor is simply an electric transformer whose magnetic circuit is separated by an air gap into two relatively movable portions, one carrying the primary and the other the secondary winding. Alternating current supplied to the primary winding from an electric power system induces an opposing current in the secondary winding, when the latter is short-circuited or closed through an external impedance. Relative motion between the primary and secondary structures is produced by the electromagnetic forces corresponding to the power thus transferred across the air gap by induction. The essential feature which distinguishes the induction machine from other types of electric motors is that the secondary currents are created solely by induction, as in a transformer, instead of being supplied by a dc exciter or other external power source, as in synchronous and dc machines.

Induction motors are classified as squirrel-cage motors and wound-rotor motors. The secondary windings on the rotors of squirrel-cage motors are assembled from conductor bars short-circuited by end rings or are cast in place from a conductive alloy. The secondary windings of wound-rotor motors are wound with discrete conductors with the same number of poles as the primary winding on the stator. The rotor windings are terminated on slip rings on the motor shaft. The windings can be short-circuited by brushes bearing on the slip rings, or they can be connected to resistors or solid-state converters for starting and speed control.

36. *Construction Features.* The normal structure of an induction motor consists of a cylindrical rotor carrying the secondary winding in slots on its outer periphery and an encircling annular core of laminated steel carrying the primary winding in slots on its inner periphery. The primary winding is commonly arranged for 3-phase power supply, with three sets of exactly similar multipolar coil groups spaced one-third of a pole pitch apart. The superposition of the three stationary, but alternating, magnetic fields produced by the 3-phase windings produces a

[1] P. L. Alger; *The Nature of Polyphase Induction Machines;* New York, John Wiley & Sons, Inc., 1951.

sinusoidally distributed magnetic field revolving in synchronism with the power-supply frequency, the time of travel of the field crest from one phase winding to the next being fixed by the time interval between the reaching of their crest values by the corresponding phase currents. The direction of rotation is fixed by the time sequence of the currents in successive phase belts and so many be reversed by reversing the connections of one phase of a 2- or 3-phase motor.

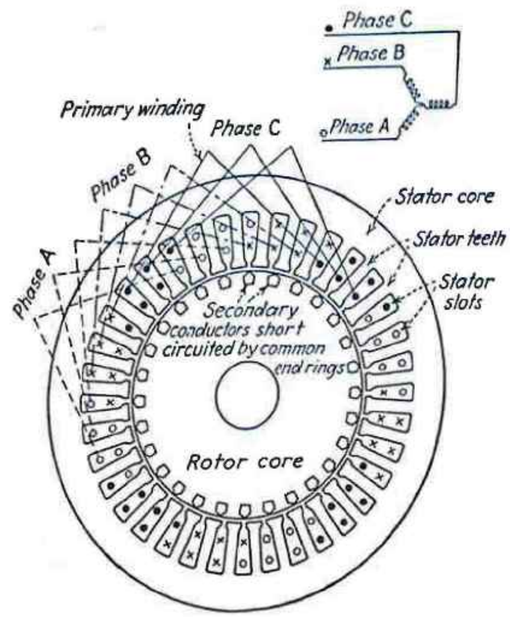

FIG. 20-20 Section of squirrel-cage induction motor, 3-phase, 4-pole, 8/9-pitch stator winding.

Figure 20-20 shows the cross section of a typical polyphase induction motor, having in this case a 3-phase 4-pole primary winding with 36 stator and 28 rotor slots. The primary winding is composed of 36 identical coils, each spanning 8 teeth, one less than the 9 teeth in one pole pitch. The winding is therefore said to have 8/9 pitch. As there are three primary slots per pole per phase, phase A comprises four equally spaced "phase belts," each consisting of three consecutive coils connected in series. Owing to the short pitch, the top and bottom coil sides of each phase overlap the next phase on either side. The rotor, or secondary, winding consists merely of 28 identical copper or cast-aluminum bars solidly connected to conducting end rings on each end, thus forming a "squirrel-cage" structure. Both rotor and stator cores are usually built on silicon-steel laminations, with partly closed slots, to obtain the greatest possible peripheral area for carrying magnetic flux across the air gap.

37. The Revolving Field. The key to understanding the induction motor is a thorough comprehension of the revolving magnetic field.

The rectangular wave in Fig. 20-21 represents the mmf, or field distribution, produced by a single full-pitch coil, carrying H At. The air gap between stator and rotor is assumed to be uniform, and the effects of slot openings are neglected. To calculate the resultant field produced by the entire winding, it is most convenient to analyze the field of each single coil into its space-harmonic components, as indicated in Fig. 20-21 or expressed by the following equation:

$$H(x) = \frac{4H}{\pi}\left(\sin x + \frac{1}{3}\sin 3x + \frac{1}{5}\sin 5x + \frac{1}{7}\sin 7x + \cdots\right) \qquad (20\text{-}8)$$

When two such fields produced by coils in adjacent slots are superposed, the two fundamental sine-wave components will be displaced by the slot angle θ, the third-harmonic components by the angle 3θ, the fifth harmonics by the angle 5θ, etc. Thus, the higher space-harmonic components in the resultant field are relatively much reduced as compared with the fundamen-

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AC DRIVES

153. ***General Theory of AC Drives.*** There are three basic types of ac machines—synchronous machines, wound-rotor induction machines, and squirrel-cage induction machines (see Table 20-20). Each of these machines is normally applied to a fixed-speed application. The speed of each is determined by the internal mechanical and electrical configuration (refer to Par. **154** and **155** for a detailed discussion). It can be displayed as

$$\text{Speed(rpm)} = \frac{120 \times \text{frequency (Hz)}}{\text{No. of poles}}$$

Except for special cases, the number of poles in a machine is fixed and the incoming line frequency is normally fixed. Therefore, except for slip in induction machines, a given ac motor operated on a given electrical network will operate at a single fixed speed.

If the line frequency supplying the motor can be adjusted, then the speed of the motor can also be adjusted. That is the basis for adjustable-speed drives for ac motors.

154. ***Application and Economics of Speed Control.*** As previously noted, ac motors provide the motive power for a wide array of industrial applications. Most of these involve a centrifugal type of load, e.g., fans, blowers, compressors, or pumps. The configuration of these devices is such that the torque required to turn them is proportional to the square of the speed. And the *power* required to turn them is proportional to the *cube* of the speed. The relationships

$$\text{Torque} \propto \text{rpm}^2$$

$$\text{Power} \propto \text{rpm}^2$$

is what makes adjustable-speed drives (ASDs) economically attractive.

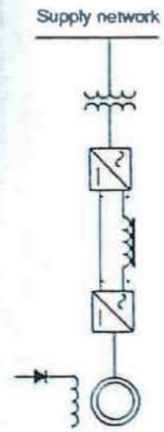
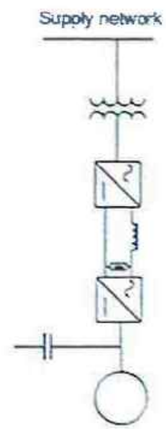
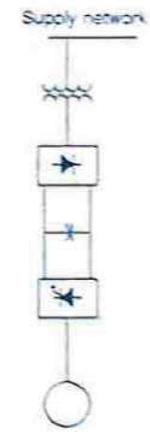
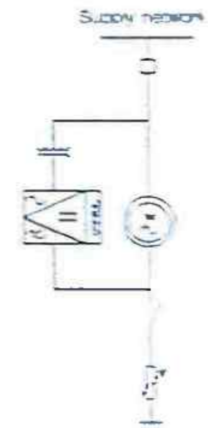
Most of these devices are part of a process which requires some degree of flow or pressure control. This is normally performed via mechanical throttling of the flow, e.g., inlet or outlet dampers, guide vanes, valves, or bypass systems. The net result of any of these methods is the consumption of excess energy required to overcome the pressure drop or bypass flow each creates.

However, efficient and precise control of the flow or pressure in a system can be obtained by directly controlling the speed of the device. This direct-speed control, coupled with the speed/power and speed/torque relationships shown above, results in an exceptionally efficient method of controlling the process. Several programs are commercially available to calculate energy savings and paybacks based on energy rates, operating profiles, internal rates of return, etc.

155. ***Power Semiconductor Devices.*** In order to supply an adjustable frequency to an ac motor, the incoming constant-frequency voltage or current must first be *rectified* to a dc current or voltage. This dc voltage or current is then *inverted* to an adjustable frequency output. This is accomplished by power semi-conductor devices.

These devices allow current to flow in only one direction. They act as electronic switches. Various types can be fired on and off at certain times in the cycle. This selected firing allows control of the resultant voltage or current.

TABLE 20-20 Basic Types of AC Machines

Drive system	LCI-fed synchronous motor	LCI-fed squirrel-cage induction motor	Voltage-source PWM inverter-fed squirrel-cage induction motor	Wound-rotor induction motor with slip-recovery converter
System one-line diagram				
Type of machine	Synchronous motor	Squirrel-cage induction motor	Squirrel-cage induction motor	Wound rotor induction motor
Typical power range	1000 to 100,000 hp	1000 to 20,000 hp	1000 to 10,000 hp	1000 to 20,000 hp
Maximum speed	7500 rpm (depending on power)	7500 rpm (depending on power)	7500 rpm (depending on power)	1800 rpm
Typical speed range	10 to 100%	50 to 100%	0 to 100%	50 to 95%
Significant properties and features	Simplest converter Single-motor drive Four-quadrant operation	Applicable to existing SCIMs Nearly sinusoidal motor voltage and current	High-power factor Good dynamic performance over entire speed range Low harmonic distortion	Suitable for retrofit to existing slip ring motor Very economical for small speed ranges Inherent bypass capability

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