The Simplified Circle Diagram

Author: E.E. Kimberly

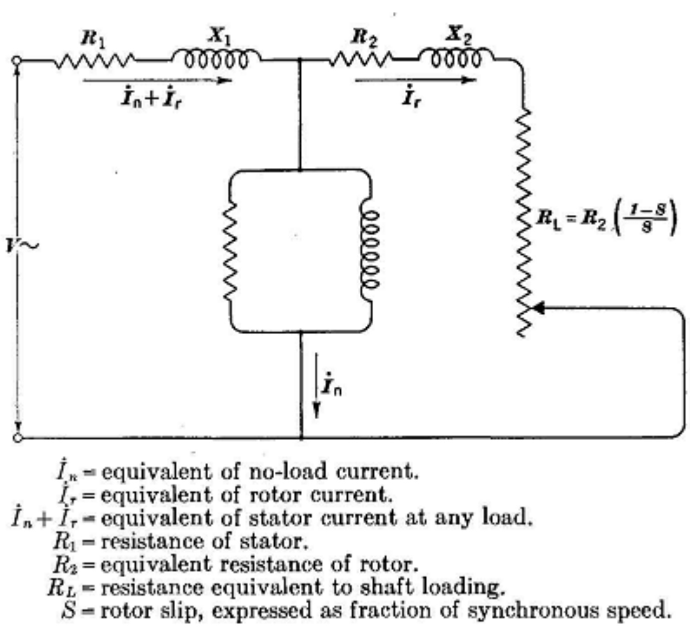

Fig. 18-13. Three-Phase Induction-Motor Equivalent Circuit

In Fig. 18-13 the power in the resistor RL corresponds to the power output of the motor shaft. The powers in R_1 and R_2 correspond to the power losses in the stator and rot or, respectively, which cause their temperatures to rise. The reactances X_1 and X_2 correspond to the leakage reactances of the stator and rotor, respectively. The parallel circuit carrying current In carries the equivalent no-load current of the motor, and the losses in it corresponding to the windage, friction, and iron losses (and some stator PR loss) are assumed constant regardless of speed. The current In is the no-load current and lags the applied voltage

$$\frac{V}{\sqrt{3}}$$

per phase by the constant angle θn, as shown in Fig. 18-14.

The current Ir corresponds to the rotor current, and in Fig. 18-14 it is shown added vectorially to In to complete the line current In+ Ir. It is 4 Principles of Alternating Current Machinery, by R. R. Lawrence. McGraw-Hill Book Co.

assumed that the effective resistance of the rotor (and therefore of R_2) is constant. However, the rotor-circuit reactance is constant (as its effect is viewed through the line terminals), and the effective resistance R_2 + RL decreases as the load increases. The current IT describes a locus which is a circle whose diameter lies along AGE. Point C on the locus corresponds to the condition when RL is reduced to zero in Fig. 18-13, and corresponds to the condition of blocked rotor or standstill in the motor.

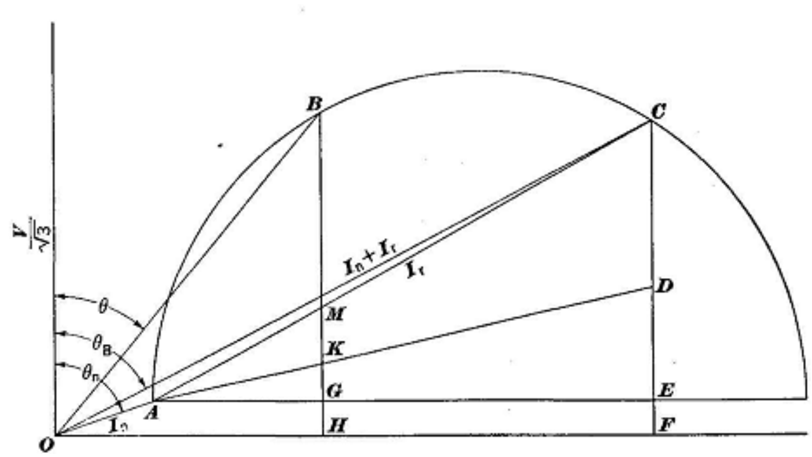

Fig. 18-14. Simplified Circle Diagram of Motor With Low-Resistance Rotor

The most obvious usefulness of the circle diagram is its help in determining the speed-torque characteristics of a motor without the necessity of loading it. The diagram cannot be used with accuracy for a rotor (particularly the double-deck rotor) whose effective resistance changes with change in speed. The circle diagram is drawn with "per phase" values. The motor may always be assumed to be Y-connected. As the motor load changes, the point B of the circle diagram in Fig. 18-14 moves along the circular locus between A and C.

Before the circle diagram can be drawn, three tests must be made and the following data obtained:

1. Resistance of stator (hot) between line and neutral.

2. Current, voltage, and power per phase when running at no load.

3. Current, voltage, and power per phase when rotor is at standstill with applied voltage reduced.

From the circle diagram, the line current, speed, power factor, power input, power output, efficiency, and torque may be found and identified as follows:

I_n = no-load current per phase;

OC = current per phase with rotor blocked and full voltage on stator;

OB = line current in amperes for any chosen load;

$\frac{MK}{BK}$ = slip as a fraction of synchronous speed;

Speed = synchronous speed minus the slip, in rpm;

$\cos\theta$ = power factor;

$\frac{BH \times V}{\sqrt{3}}$ = power input per phase;

$\frac{BM \times V}{\sqrt{3}}$ = power output per phase at shaft;

$\frac{BM}{BH} \times 100$ = efficiency in per cent;

$$\text{Internal torque} = \frac{BK \times \frac{V}{\sqrt{3}} \times 33{,}000}{746 \times 2\pi \times \text{synch. speed in rpm}} \times 3 \qquad (18\text{–}1)$$

This torque is the total torque produced in the rotor, and is measurable directly in pound-feet only at standstill. The horsepower output per

$$P = \frac{BM \times \frac{V}{\sqrt{3}}}{746} \qquad (18\text{–}2)$$

phase is

Example 18-1. - Give instructions for obtaining necessary data for construction of the circle diagram and for determination of the speed-torque curve of a three-phase squirrel-cage induction motor 7 1/2 hp, 1200 rpm, 220 volts, 60 cycle.

Solution. - 1. Lock the rotor to prevent turning, and apply about one-fourth of the rated voltage to the stator terminals until the temperature of the stator frame rises 40 deg C by thermometer reading.

2. Measure the terminal-to-terminal d-c resistance between any two stator terminals. As a check, measure the resistance in the other two possible circuits of the stator also.

3. Apply a 3-phase voltage of about one-half of the rated voltage to the stator with the rotor locked. Measure quickly the current per terminal, the applied voltage, and the power input.

4. Release the rotor, and apply the rated voltage. Measure the current, voltage, and power with, the motor running at no load.

Example 18-2. - Construct the circle diagram and determine the starting torque of the motor of Example 18-1, on the basis of the following data:

1. Temperature of room, 22 C. Temperature of motor, 62 C.

2. I = 26.5 amp, V = 22.1 volts by d-c between terminals.

3. I - 28.0 amp, V = 109 volts, P = 4066 watts with rotor locked.

4. I = 7.2 amp, V = 224 volts, P = 400 watts at no load.

Solution. - From the data in item No. 4 the no-load power factor is

$$PF = \frac{400}{\sqrt{3} \times 224 \times 7.2} = 0.143 = 14.3\%$$

In Fig. 18-15 lay out 7.07 amp at an angle θ lagging the phase voltage

$$\frac{220}{\sqrt{3}}$$

and to some convenient scale. Note that the circle diagram is to be constructed on the basis of the rated motor voltage of 220 volts, although the actual test voltage was 224. A scale of 1/16 in. = 1 amp is used in Fig. 18-15. In this case,

$$\theta_n = \cos^{-1} 0.143 = 81°47'$$

The locked-rotor current from the data in item No. 3 is 28 amp at 109 volts. At 220 volts it is

$$28 \times \frac{220}{109} = 56.5 \text{ amp}$$

The power factor of the blocked-rotor current is

$$PF = \frac{4066}{\sqrt{3} \times 109 \times 28} = 0.77 \text{ or } 77.0\%$$

Next, lay out 56.5 amp at θB = cos-1 0.77 = 39°38'.

Draw the arc of a circle that passes through points A and C and has its center on AE or AE extended.

The line CF represents the component of the phase current which is in phase with the phase voltage when the rotor is locked with the rated voltage applied. Its length is therefore indicative of the power input per phase. Of the power input per phase, the portion DE is indicative of the added power PR per phase of the stator. The line-to-line resistance is

$$R_{L-L} = \frac{V}{I} = \frac{22.1}{26.5} = 0.834 \text{ ohm}$$

Since the stator is assumed to be Y-connected, the resistance per phase is

$$R_p = \frac{0.834}{2} = 0.417 \text{ ohm}$$

The resistance of a stator to alternating current is greater than that to direct current, and the d-c resistance should be multiplied by a conversion factor. The a-c resistance is greater than the d-c resistance because, when alternating current flows in the stator conductors, the current distribution across the conductor section is not uniform and the accompanying iron losses appear to be caused by an added series resistance. Furthermore, this factor helps to correct for some of the approximations permitted in the simplified circle diagram. Judgment in choice of this factor is based on performance of similar motors; and, depending largely on the type of rotor used, the factor may have any value between about 1.1 and 1.4.

A conversion factor of 1.4 should be satisfactory for the purpose of this example. Hence, the corrected resistance per phase is

When the rotor is locked,

$$0.417 \times 1.4 = 0.584 \text{ ohm}$$

$$I^2R = 56.5^2 \times 0.584 = 1860 \text{ watts per phase}$$

$$I = \frac{1860}{\frac{220}{\sqrt{3}}} = 14.6 \text{ amp}$$

This is the component DE of CEt and so the point D is determined. The component CD is, by measurement on Fig. 18-15, 27.1 amp. The power per phase corresponding to CD is

Since

$$\text{hp} = \frac{2\pi NT}{33{,}000},$$

$$T = \frac{\text{hp} \times 33{,}000}{2\pi \times 1200} = \frac{\frac{3450}{746} \times 33{,}000}{2\pi \times 1200} = 20.3 \text{ lb-ft per phase}$$

$$T = 20.3 \times 3 = 60.9 \text{ lb-ft for three phases}$$

$$27.1 \times \frac{220}{\sqrt{3}} = 3450 \text{ watts}$$

From Fig. 18 - 15 it is apparent that under no condition of speed will CD, and hence the torque of this motor, be larger than at standstill. Therefore, the motor has a high-resistance rotor.