

# General Theory of Multiple-Cage Induction Motors

S. S. L. CHANG  
ASSOCIATE AIEE

**P**OWER COMPANIES are usually particular about the starting current and running power factor of an induction motor. However, induction-motor manufacturers cannot possibly supply a motor much better in these respects than the present National Electrical Manufacturers' Association Design C standards, even though ideal materials should be discovered in the future.

Both the primary resistance and the saturation effect on leakage reactance are neglected in this analysis. While the first assumption can be fulfilled only with idealized material, it is a close enough approximation in motors of 20 horsepower or above. Under the assumptions, the motor can be analyzed with the help of a well-known theorem which states that as soon as the imaginary component of a physical network function is known for all values of frequency, the real component is totally determined up to an additive constant. In this case, the input reactive volt-amperes is the real component; the torque in synchronous watts the imaginary component; the slip corresponds to frequency; and the magnetizing current is the additive constant.

Figure 1 shows the assumed torque as a function of slip. Figures 2 and 3 show the full-load power factor and starting kilovolt-amperes per horsepower as functions of full-load slip and  $k_{r\infty}$ . The basic leakage factor  $k_{r\infty}$  is defined as  $1 - X_a/X_b$  where  $X_a$  is the leakage reactance not including the slot leakage of inner cages and  $X_b$  is the total reactance. Since no special configuration or multiplicity of rotor slots is assumed, the result indicates that the best obtainable start-

ing current and full-load power factor are fixed as soon as the full-load slip is chosen. Since the value of  $k_{r\infty}$  is not influenced by the selection of inner cage dimensions, altering the inner cage design would not improve the starting current and power factor without lowering the torque curve in general or in part. Real improvements can be accom-

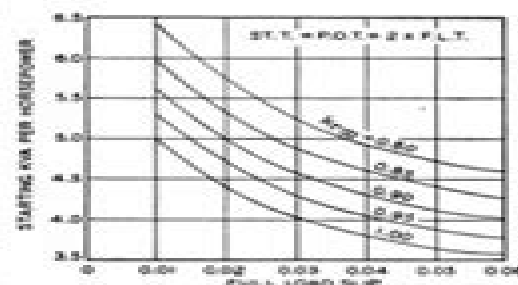


Figure 3. Starting kilovolt-amperes per horsepower of a constant-torque motor as a function of full-load slip and  $k_{r\infty}$ .



Figure 1. The speed-torque curve of a constant-torque motor.

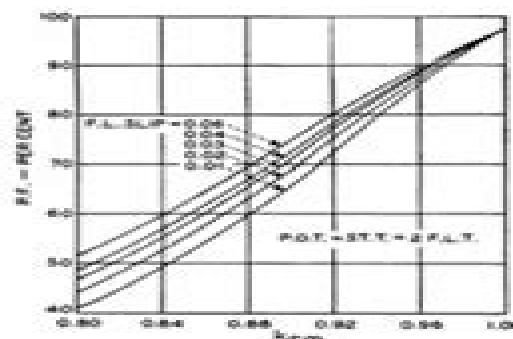


Figure 2. Power factor of a constant-torque motor as a function of full-load slip and  $k_{r\infty}$ .

plished only by measures which increase  $k_{r\infty}$ , such as reducing the air gap, increasing the number of stator slots, and so forth. All of these measures have practical limitations.

The theory also provides a guide for designing rotor laminations. Let  $X_a$  be the total leakage reactance at no load,  $R_a$  be the rotor resistance of the outermost cage only, and  $R_b$  be the rotor resistance with all cages in parallel.  $X_a$ ,  $R_a$ , and  $R_b$  are determined by equations 1, 2, and 3.

$$\frac{X_a}{X_b} = \frac{1}{s} \left( 2.57 + \ln \frac{s}{s_m} \right) \quad (1)$$

$$\frac{R_a}{X_b} = \frac{X_a}{X_b} \frac{s}{2} \quad (2)$$

$$\frac{R_b}{X_b} = \frac{X_a}{X_b} \frac{s_m}{s} \quad (3)$$

In these equations,  $s_m$  is the slip at maximum torque point and is about equal to 3.73 times the full-load slip;  $s_2$  is the slip at which the torque tapers off. The value of  $s_2$  is usually in the range of 1.5 to 2.5. The value of  $s_2$  is chosen to compromise the full-load power factor and starting current. Both are lower for higher value of  $s_2$  and conversely.

The values of  $R_a$  and  $R_b$  determine the total slot area and the slot area of the outermost cage, respectively.  $X_a$  determines the combined slot constant of the inner cages. Though all these conditions do not completely determine the slot shape, they are more than a starting point.

Digest of paper 49-238, "General Theory of Multiple-Cage Induction Motors," recommended by the AIEE Committee on Rotating Machinery and approved by the AIEE Technical Program Committee for presentation at the AIEE Fall General Meeting, Cincinnati, Ohio, October 17-21, 1949. Published in AIEE Transactions, volume 68, 1949, part 2, pages 1139-43.

S. S. L. Chang is with Robins and Myers, Inc., Springfield, Ohio.

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