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REACTIVE LOAD AND POWER FACTOR AT PARTIAL LOADS OF INDUCTION MOTOR

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Abstract: *Method for determination of reactive load nominal components, Q_0 and Q_{2N}, is presented. New expression for calculation component (in branch) loads (Q_{2N}), on the base motor catalogue dates (I_N, $\cos\varphi_N$, s_N, P_N, and T_b-breakdown torque), is found out. On the base Q_o and Q_{2N} values, reactive power (Q_{1p}) at any partial load $p=P/P_N$, and corresponding power factor values ($\cos\varphi_p$) are calculated. Though, for motor individual correction, the capacitor output should be approximatively 90% of no-load power, power factor obtainable with this correction $\cos\varphi=0.95\text{-}0.98 \geq 0.95$ (recommended final $\cos\varphi$), as it is shown. The effects of voltage variations on reactive loads components and power factor values at partial loads are analyzed.*

Key Words: ***Rreactive load, Power factor, Partial load, Induction motor.***

1. INTRODUCTION

The connected motor load in a facility is usually a major factor in determining the system power factor. Low system power factor results in increased losses in the distribution system. Induction motors inherently cause a lagging system power factor. The power factor of an induction motor decreases when the load decreases, as shown in Figure 1. Figure 2 indicates that rated load power factor increases with an increase in the horsepower rating of the motor. A number of induction motors, all operating at light load, can cause the electrical system to have a low power factor. The power factor of induction motors at rated load is less for low-speed motors than for high-speed motors as shown in Figure 2.

Power-factor-correction capacitors can be used to improve power factor of the electrical system. However, if they are used, they should be carefully selected and applied to avoid unsafe operating conditions. It is recommended that the motor manufacturer be consulted for the proper value of corrective capacitance. An analysis of the electrical system will indicate whether improvement in the power factor is needed and whether capacitors, synchronous motors, or other corrective measures should be used.

A small increase in voltage (≤ 10 percent) above rated voltage will decrease the power factor, and a small decrease in voltage (≤ 10 percent) below rated voltage will improve the power factor of an induction motor. The above-mentioned effects of voltage variations are larger as loads are smaller, i.e. these effects are greater at partial loads. However, other performance characteristics may be adversely affected by such a change in voltage and operation as close as possible to the nameplate voltage and horsepower rating is recommended.

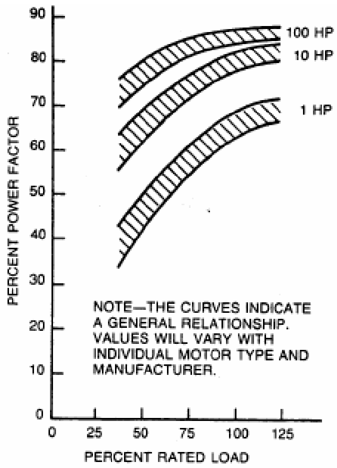

Fig. 1. *Typical power factor versus load curves for 4-pole three-phase Cage Induction motors [1]*

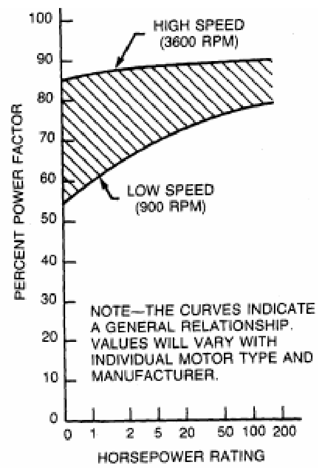

Fig. 2. *Typical full-load power factor versus for three-phase 60-hertz design B squirrel-cage induction motors*

2. DETERMINING OF POWER FACTOR AT PARTIAL LOAD

The required capacitor rating can be determined relatively easily and accurately from the power company's monthly invoice. Induction motors is the most wide spread contributor to reactive load in an industrial electric power system. An analysis of the electrical system will indicate in what manner improvement in the power factor is needed.

The power factor induction motors may be improved by connecting a capacitor directly across the motor terminals, i.e. by individual power factor correction. It has been stressed, that capacitors used for individual motor correction should not exceed the no-load reactive power (Q_0), or better $0.9Q_0$ values. The reason for this is to ensure that over-excitation of the motor cannot occur. For this reason and energetic analysis, calculation total reactive power ($Q_1= Q_0+Q_2$) at any partial load, and its components Q_0 and reactive power (in branch) of loads component (Q_2), is needed.

On the base

- Catalogue dates for rated load I_N, $\cos\varphi_N$, s_N, P_N, and
- T_b-breakdown torque expressed as a per unit vale of the rated torque $T_N=1$,

first are determined total reactive power (Q_{1N}) and its component (in branch) load (Q_{2N}), both at rated load, and no-load reactive power (Q_0), i.e.:

$$Q_{1N} = \frac{P_N}{\eta_N} \cdot \frac{\cos\varphi}{\sqrt{1-\cos^2\varphi}} \qquad (1)$$

$$Q_{2N} = (0.5/T_b) \cdot P_N \qquad (2)$$

$$Q_0 = Q_{1N} - Q_{2N} \qquad (3)$$

On the base Q_o and Q_{2N} values, reactive power (Q_{1p}) at any partial load $p=P/P_N$, and corresponding power factor values ($\cos\varphi_p$) are calculated:

$$Q_{1p} = Q_0 + Q_{2N} \cdot p^2 \qquad (4)$$

$$\cos\varphi_p = \frac{P_{1p}}{\sqrt{{P_{1p}}^2 + {Q_{1p}}^2}} \qquad (5)$$

where:
$P_{1p}=(p+ p_0+ p_{LN}\cdot p^2)\cdot P_N$ –active power input at any partial load $p=P/P_N$.

Values obtained by (2) are little a bit higher from the amount of reactive loads growth from no-load to full load, in absolute values (ΔQ_N) or per unit ($\Delta q_N= \Delta Q_N/P_N$), because of reactive power reduction on magnetization branch ($\Delta q_{mN} =(0.01\text{-}0.16)q_{0N}$) for the nominal regime in order to no-load regime, Table I.

Table 1. *Values $\Delta q_N= \Delta Q_N/P_{1n}$ for induction motors*

Motor Power	$\Delta q_N= \Delta Q_N/P_N$
0.25÷ 3 kW	0.16-0.10
4 ÷ 7.5 kW	0.10-0.06
11÷ 30 kW	0.06-0.02
37÷ 100 kW	0.02-0.01

For motors rated ≤3kW, $Q_{1n}\approx Q_o$ [2], because$Q_{2n}\approx\Delta Q_{\mu n}$.

Equation (2) is obtained by expressions (6) and (7a) getting from the equivalent Γ-circuit of induction machine [2]:

- for rated load condition

$$I_{2Qn} / I_{2Pn} = (\sigma_1 X_1 + {\sigma_1}^2 X_2)/({\sigma_1}^2 R_2 / s_n) \qquad (6)$$

- for condition when input power is a maximum ($P_1=P_{1,max}$):

$$P_{max} / P_N = (R_2 / s_N)/(2(\sigma_1 X_1 + {\sigma_1}^2 X_2)) \qquad (7)$$

and, for condition when electromagnetic torque is a maximum ($T=T_b\approx P_{max}/P_N$), equation (8) is, approximate, valid:

$$T_b \approx (R_2 / s_N)/(2(\sigma_1 X_1 + {\sigma_1}^2 X_2)) \qquad (8)$$

NOTE: By complete analysis getting from the equivalent Γ-circuit of induction machine, which is given in chapter 7. APPENDIX, it is obtain

$$Q_{2N} = (0.99 \div 1.03) \cdot (0.5/T_b) \cdot P_N \qquad (9)$$

where are coefficient values from 0.99-1.03, respectively, for motors with rated slip $s_N=0.03\div0.01$. By (9), it will be proved that (2) from [2], is sufficient accurate.

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3. POWER FACTOR OBTAINABLE VALUES WITH INDIVIDUAL CORRECTION MOTORS

The power factor of an induction motors may be improved by connecting capacitors directly across the motor terminals, or alternatively by connecting a capacitor to the lines supplying the motor. The practice of connecting capacitors a cross the starter of an induction motor and switched the motor and capacitor as one unit is now universally established, and this individual correction of motors is to be recommended.

Care should be taken in deciding the kvar rating of the capacitor in relation to the magnetizing *kvar* of the induction motors. If the rating is too high, damage may result to both motor and capacitor. Namely, as the motor, while still revolving after disconnection from the supply, may act as a generator by self-excitation and produce a voltage higher the supply voltage. If the motor is switched on again before the speed has fallen to about 80% of the normal running speed, the high voltage will be superimposed on the supply circuits and there may be a risk of damaging other types of equipment. As a general rule the correct size of capacitors for individual correction motor should have a *kvar* rating not exceeding 90% of the normal no-load kVA of the machine [3].

. Though, for motor individual correction, the capacitor output should be approximatively 90% of no-load power, power factor obtainable with this correction cosφ=0.95-0.98 ≥ 0.95 (recommended final cosφ), as it is shown.

4. DEPEENDENCY OF REAACTIVE LOADS ON VOLTAGE VALUES

In order to ascertain reactive loads Q(u) dependency, it is necessary to determine no-load reactive power versus voltage, in absolute ($Q_0(u)$) values and per unit ($q_0(u)=Q_0/P_N$), for the load range from no-load to full load, as in ($q_0(u)=Q_0/P_N$), for the load range from no-load to full load:

$$Q_0(u) = \sqrt{3} \cdot U_0 I_0 \tag{10}$$

$$q_0(u) = Q_0(u) / P_N \tag{11}$$

Values of reactive loads nominal components, Q_{2N} and q_{2n}, are being calculated from the (2) and (10), and of T_b-breakdown torque expressed as a per unit vale of the rated torque T_N=1, and their values are little a bit higher from the amount of reactive loads growth from no-load to full load, in absolute values (ΔQ_N) or per unit ($\Delta q_N = \Delta Q_N/P_{1N}$), because of reactive power reduction on magnetization branch (Δq_{mN} =(0.01-0.10)q_{0N}) for the nominal regime in order to no-load regime. Total reactive load is calculated (in absolute values and per unit) as: as in ($q_0(u)=Q_0/P_N$), for the load range from no-load to full load:

$$Q_1(u) = Q_0(u) + Q_{2N}(u) \cdot p^2 / u^2 \tag{12}$$

$$q_1(u) = q_0(u) + q_{2N}(u) \cdot p^2 / u^2 \tag{12a}$$

For motors of power ≤3kW, $Q_{1N} \approx Q_0$ [2], because $Q_{2N} \approx \Delta Q_{mN}$, so $Q_1(u) \approx Q_0(u)$ and $q_1(u) \approx q_0(u)$.

Expressions (12) and (12a) are commonly in use. Instead of Q_{2N} and q_{2N}, ΔQ_N and Δq_N can be used if they are known or they can be calculated ($\Delta Q_N = Q_{1N} - Q_{0N}$). For the calculation of dependency according to expressions (2) and (12), it is necessary to know:

- no-load characteristic $I_0(u)$, $Q_0(u)$, for the analyzed voltage range
- motor catalogue data: nominal power (P_N), nominal current (I_N), efficiency (η), power factor (cosφ), slip (s_N) and the quotient of maximum and nominal torque (T_b), and Q_{2N} are calculated.

5. CONCLUSION

In this paper is proved any important conclusions.

1. By complete analysis getting from the equivalent Γ-circuit of induction machine, which will be given in full paper, it is obtain

$$Q_{2N} = (0.99 \div 1.03) \cdot (0.5 / T_b) \cdot P_N \tag{13}$$

where are coefficient values from 0.99-1.03, respectively, for motors with rated slip s_N=0.03÷0.01. By (9), it will be proved that (2) from [2], is sufficient accurate.

2. Though, for motor individual correction, the capacitor output should be $Q_C \leq Q_0$ (motor no-load power), power factor obtainable with correction cosφ=0.95-0.98≥0.95 (recommended final power cosφ), at motor load from 75-100%.

3. The effects of voltage variations on reactive loads components (Q_0 and Q_{2N}) and power factor values at partial loads are analyzed.

6. REFERENCES

[1] NEMA MG10, *Energy Management Guide For Selection and Use of Fixed Frequency Medium AC Squirrel-Cage Polyphase Induction Motors.*

[2] M.Kostić, *"Determination of Γ-scheme parameters and energetic characteristics of Induction motors on the base catalogue dates"*, "Technics", separate Electrical Engineering 3/2000, pp. 12E-18E (On Serbian).

[3] T. Longland, *"Power capacitor handbook",* printed in Great Britain, London, 1984.

7. APPENDIX

Equation (2) is completely derived in this Appendix.

$$Q_{2N} = (0.5 / T_b) \cdot P_N$$

1. Electromagnetic power ($P_{em,N}$) **at rated load**, i.e. at slip $s=s_N$, can be expressed as following:

$$P_{em,N} = T_{em,N} \cdot \Omega_1 = I_2^2 \cdot \sigma^2 R_r / s_n = \frac{U_1^2 \cdot \sigma^2 R_r / s_n}{(\sigma R_s + \sigma^2 R_r)^2 + (\sigma X_s + \sigma^2 R_r / s_n)^2} \tag{A-1}$$

For motors with power within the range of 1÷200kW, values for s_N are 0.05÷0.01, respectively, and therefore: $\sigma_1^2 R_r/s_N = (20 \div 100) \cdot \sigma_1 R_s$, $(\sigma_1 X_s + \sigma_1^2 X_r) \approx 0.20 \cdot \sigma_1^2 R_r/s_m$

$$P_{em,N} = M_{em,N} \cdot \Omega_1 = I_2^2 \cdot \sigma^2 R_r / s_N \approx \frac{U_1^2 \cdot \sigma^2 R_r / s_N}{(1.15 \div 1.05) \cdot (\sigma^2 R_r / s_N)^2} = \frac{U_1^2}{(1.15 \div 1.05) \cdot (\sigma^2 R_r / s_N)} \tag{A-2}$$

2. Regime with maximum input power, i.e. at $s=s_m$, accrues when resistance $(\sigma_1 X_s + \sigma_1^2 X_r)$ and reactance in load branch $(\sigma_1 R_s + \sigma_1^2 R_r/s_m)$ are equal, i.e. $(\sigma_1 R_s + \sigma_1^2 R_r/s_m) = (\sigma_1 X_s + \sigma_1^2 X_r)$, and when the load branch impedance is $Z_{2,m} = \sqrt{2}(\sigma_1 X_s + \sigma_1^2 X_r)$. Corresponding electromagnetic power ($P_{em,m}$), power on the resistance $\sigma_1^2 R_r/s_m$ is:

$$P_{em,m} = T_{em,Pm} \cdot \Omega_1 = I_2^2 \cdot \sigma^2 R_r / s_m = \frac{U_1^2 \cdot \sigma^2 R_r / s_m}{2(\sigma X_s + \sigma^2 X_r)^2} \qquad \text{(A-3)}$$

Since for motors with power within the range of 1÷200kW, values for corresponding slip are $s_m =$ 0.25÷0.05, respectively, the skin effect in the bars of the squirrel-cage is minor (the depth of penetration $\delta_r(s_m f_1) \geq h_r$ -the bar height), so it is $\sigma_1^2 R_r/s_m$ =(5÷20) $\sigma_1 R_s$. Consequently it is

$$\sigma^2 R_r / s_m = (0.8 \div 0.95) \cdot (\sigma R_s + \sigma^2 R_r / s_m) = (0.8 \div 0.95) \cdot (\sigma X_s + \sigma^2 X_r) \qquad \text{(A-4)}$$

and the electromagnetic power ($P_{em,m}$), in the regime with maximum input power, is

$$P_{em,m} = T_{em,m} \cdot \Omega_1 = I_2^2 \cdot \sigma^2 R_r / s_m \approx \frac{U_1^2 \cdot (0.8 \div 0.95) \cdot (\sigma X_s + \sigma^2 X_r)}{2(\sigma X_s + \sigma^2 X_r)^2} = \frac{U_1^2 \cdot (0.8 \div 0.95)}{2(\sigma X_s + \sigma^2 X_r)} \qquad \text{(A5)}$$

3. If $\sigma_1^2 R_r/s_n$ is expressed from (A-1), and $(\sigma_1 X_s + \sigma_1^2 X_r)$ is expressed from (A-2), then it is:

$$\sigma^2 R_s + \sigma^2 R_r / s_N = \frac{U_1^2}{T_{em,N} \cdot \Omega_1 (1.15 \div 1.05)} \qquad \text{(A-6)}$$

$$\sigma X_s + \sigma^2 X_r = \frac{U_1^2 \cdot (0.8 \div 0.95)}{2 T_{em,Pn} \cdot \Omega_1} \qquad \text{(A-7)}$$

On the base of (A-6) and (A-7), it is given

$$\frac{\sigma X_s + \sigma^2 X_r}{\sigma^2 R_s + \sigma^2 R_r / s_n} = \frac{T_{em,N}}{2 T_{em,m}} \cdot (0.8 \div 0.95) \cdot (1.15 \div 1.05) \qquad \text{(A-8)}$$

Reactive power in the load branch of Γ-circuit, under rated condition, Q_{2N}, can be expressed in terms of the electromagnetic power ($P_{em,N}$), i.e:

$$Q_{2N} = P_{em,N} \cdot \frac{\sigma X_s + \sigma^2 X_r}{\sigma^2 R_s + \sigma^2 R_r / s_N} \qquad \text{(A-9)}$$

Since the relation between the electromagnetic power ($P_{em,N}$) and the rating power (P_N) is:

$$P_{em,N} = P_N \cdot \frac{\sigma^2 R_s + \sigma^2 R_r / s_N}{(\sigma^2 R_r / s_N)} \cdot \frac{1}{1 - s_N} \qquad \text{(A-10)}$$

then on the base of equations (A-7)-(A-10), it follows:

$$Q_{2N} = P_N \cdot \frac{T_{em,n}}{2 T_{em,m}} \cdot \frac{(0.8 \div 0.95) \cdot (1.15 \div 1.05)}{0.95 \div 0.99} = \frac{T_{em,n}}{2 T_{em,m}} \cdot (0.98 \div 1.01) \qquad \text{(A-11)}$$

Since the maximum torque (T_b), which is catalogue data, is greater up to 2% from mentioned torque ($T_{em,m}$) in the regime with maximum input power, i.e. $T_b \leq 1.02 T_{em,m}$, it might be concluded that the equation (9) represents **sufficiently accurate and simple expression for calculating the rating component of reactive power in load branch (Q_{2N}) in terms of the rating power (P_N), i.e.**:

$$Q_{2N} = (0.5 / T_b) \cdot P_N$$