

Analysis of Induction Motor Efficiency Class Change at Partial Load

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Abstract: Motors with efficiency high values can become inefficient than standard motors when they are lightly loaded. The calculation procedure for the estimation of any part load efficiency when two load points are given is presented in paper. Efficiency dependence is expressed in the form of $\eta = \eta_N \pm k(1 - \eta_N)$, where k is magnitude $k_P = f_1(P_0, P_{\gamma_N}, P/P_N)$, so that changes-deviations of efficiency values compared to rated value (η_N) would be explicitly expressed. Based on those deviations, energy efficiency class changes of observed motors are directly identified with load change. Efficiency curve for several motors, with typical shapes, are considered, especially for loads $P/P_N = 0.50 - 1.00$. These results are shown justification claim that efficiency values at 50% and 75% load shall be stated in the documentation. The users can then select the motor best suited for their application.

Keywords: Induction motors, estimation, efficiency, energy efficiency class, partial load efficiency, testing.

1 Introduction

MOST motor are over-dimensioned for safety reasons (and due to impossibility of evaluating the load value) and because of standard power ratings. This means that motors are usually used in the following range [1, 2]:

- About 50% rated load, for small motors (to 10 kW),
- 50-75% rated load, for medium motors (11-30 kW), and
- 75-100% rated load, for larger motors (37-100 kW).

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By this reason, the topic of part load efficiencies was considered in detail when is presented and considered the IEC projects, IEC 60034-30 and IEC 60034-31 [3, 4]. Some countries stated that they nominal efficiency for a given class motors be reached at 75% or 100%. Other countries requested the nominal efficiency to be reached at both 75% and 100% or even over the whole range from 60 to 100% [5]. As Serbian member of IEC WG 31, which is performed IEC 60034-30 and IEC 60034-31, Author these paper is presented a calculation procedure for the estimation of any part load efficiency, when they for two load points are given [5, 6]. This procedure is accepted in principle

Technically, the vast majority of motors (especially energy efficient motors) have at least the same if not a greater efficiency at 75% compared to 100%. With the exception of very small motors (typically 1.1 kW and lower) it would actually be more expensive for a manufacturer to design a motor a greater efficiency at 75% compared to 100%.

In order to simplify testing and harmonize with US procedures it was decided [3] to classify the motors according to their full load efficiency only. However, from 16 June 2011, the information about part load efficiencies (50% and 75%) shall be visibly displayed on the technical documentation of motors [7]. The users can then select the motor best suited for their application.

If we consider the efficiency curves shown in Fig. 1, we notice that the difference in efficiency between the motors varies with the load condition [6]. This means that a motor with a high rated efficiency does not guarantee a high efficiency at partial load. This is especially the case for motors with relatively high no-load losses - motors curve 1 and 2 in relation to motors curve 3.

2 Partial Load Efficiency

The typical motor efficiency dependence $\eta(p)$ is given by following equations

$$\eta = \frac{p}{p + p_0 + p_{\gamma p_n} p^2} \quad (1)$$

were are $p = P/P_n$ -the p.u. load power, P_0 -no-load losses at $U = U_n$ in p.u. $p_0 = P_0/P_n$ and $P_{\gamma p_n}$ -load losses at rated load, in p.u. $p_{\gamma p_n} = P_{\gamma p_n}/P_n$

The difference in efficiency between the motors varies with values of at ratio of no-load losses (P_0) to load losses in rated regime ($P_{\gamma p_n}$), the Fig.1

Total losses (a) and Efficiency (b) dependencies, from output power in p.u., i.e. from (P/P_n) values, varies for three (same) motors but with different number of turns per stator phase (W_s), -fig.2 [8].

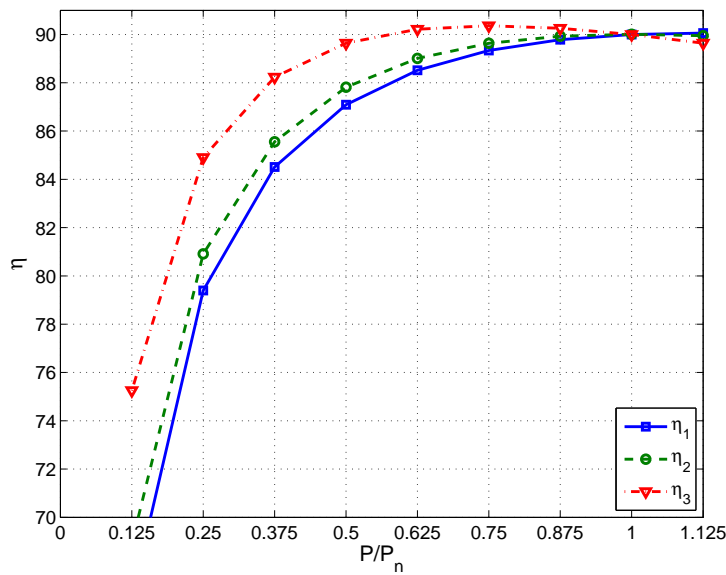


Fig. 1. Efficiency curve $\eta = f(P/P_n)$, in relation to three $P_0/P_{\gamma n}$ values (in a per unit $P_n = 1$): $(P_0/P_{\gamma P_n})_1 = 0.0618/0.0493 = 1.25$, $\eta_{max} = \eta_{112}$ for $P/P_n = 112\%$, curve η_1 , $(P_0/P_{\gamma P_n})_2 = 0.0555/0.0555 = 1.00$, $\gamma_{max} = \gamma_n$, for $P = P_n = 100\%$, curve η_2 , $(P_0/P_{\gamma P_n})_3 = 0.0400/0.0711 = 0.56$, $\eta_{max} = \eta_{75}$ for $P = P_n = 75\%$, curve η_3 .

Motor 1 ($W_s = 1.15W_{s3}$) with smallest light-load (and the greatest full-load) total losses, Fig.2a, and with greatest light-load (and the smallest full-load) efficiency, Fig.2b.

Motor 3 ($W_{s3} = W_s$) with smallest full-load (and greatest the light-load) total losses, Fig.2a, and with greatest full-load (and the smallest light-load) efficiency, Fig.2b.

Motor 2 ($W_{s2} = 1.09W_{s3}$) total losses and efficiency dependencies are between Motor 1 and 3, Fig.2a and 2b.

3 Energy Efficiency Motors and Partial Load Efficiency

3.1 Efficiency Classes of Three Phase Induction Motors

Three energy efficiency classes are proposed, IE1, IE2 and IE3 [4]. The 60 Hz efficiency values for class IE3 (premium) and IE2 (high) were taken from existing NEMA Premium and EPACT tables [9]. The 50 Hz values of class IE1 (standard) and IE2 (high) are similar to the existing CEMEP-EU *eff2* and *eff1* [10]. However the values have been adjusted to take the different test procedure into account

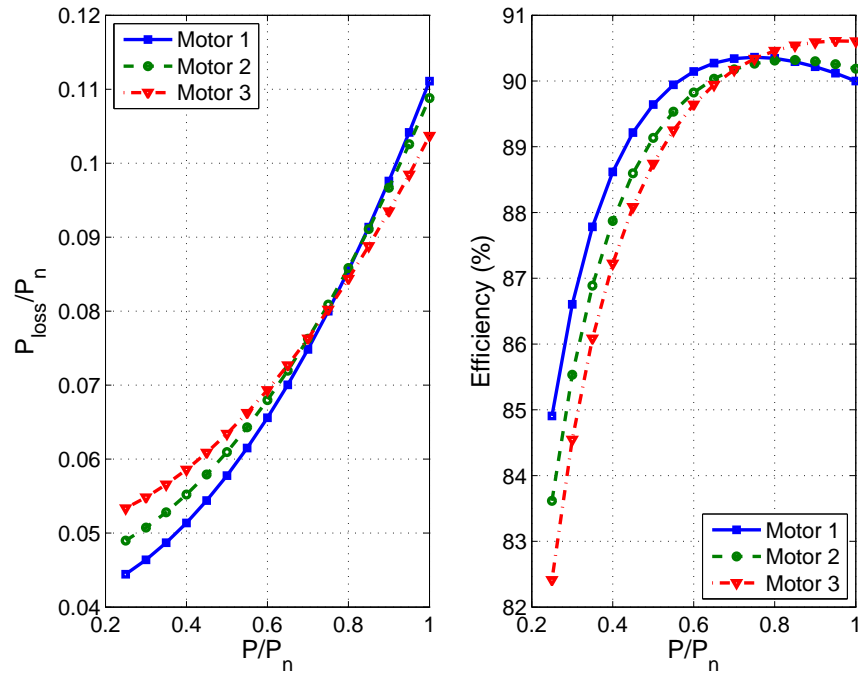


Fig. 2. Total losses (a) and Efficiency (b) dependencies, for three motors with different number of turns per stator phase (W_s).

(CEMP: additional load losses PLL flat 0.5% of input power; this standard determined from tested in accordance with IEC 60034-2-1 [11]. The 50 Hz efficiency values for class IE3 (premium) are newly designated. On average the IE3 motors have less energy losses 15%-20% than IE2 motors (Fig.3), [12].

Efficiency guide lines have been prepared to assist users in making the decision whether to spend additional money to purchase higher efficiency class motor for a new installation. The assumption is made that the purchased motor will be capitalized. The annual energy savings are calculated by the following equation [9]:

$$W_1 = p_L P_N \left(\frac{100}{E_A} - \frac{100}{E_B} \right) N \quad (2)$$

where W_1 is annual energy savings kWh/year, P_N is rated output power (kW), $p_L = P_L/P_N$ is related load of motor, E_B is lower motor efficiency %, E_A is higher motor efficiency %, and N is annual hour's operation h/year.

The calculated N h/years values, for full load ($P_L/P_N = 1$) and $3/4$ load ($P_L/P_N = 0.75$) and electricity price 0.10 Euro/kWh, are given in [12], for SIEMENS motors [13].

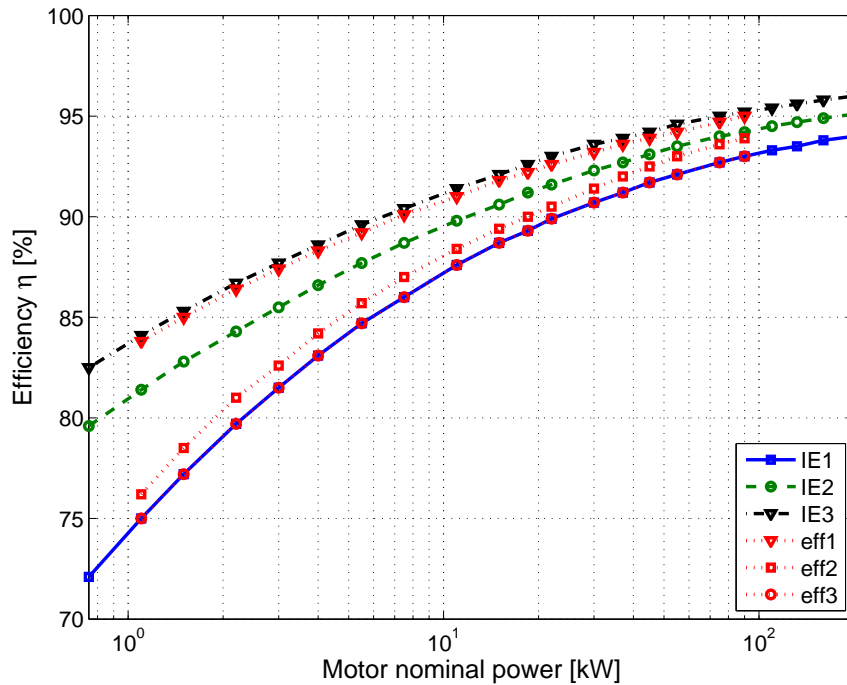


Fig. 3. Comparative Survey of efficiency rated values for classes IE1, IE2, IE3 [2] and eff1, eff2, eff3 [12].

Technically, the vast majority of motors (especially energy efficient motors) have at least the same if not a greater efficiency at 75% compared to 100%. With the exception of very small motors (typically 1.1 kW and lower) it would actually be more expensive for a manufacturer to design a motor a lower efficiency at 75% compared to 100% [14].

Testing of part load efficiencies is a critical issue for manufacturers. In current practice all catalogue values for part load efficiencies are taken from the test of full load efficiency. Therefore they are obtained at an operating temperature related to full load instead of part loads. Since part load temperatures are generally lower, the part load efficiencies obtained by this practice are generally worse than in reality (so there is no problem for the user).

However when partly load efficiencies became a mandatory requirement [7], the tests had to be carried out on the base of standard procedures [11, 15]. This would require a significant amount of extra work and cost, as it is shown by series of IEEE 112A performance tests were conducted in 1999 and 2000 by Motor Systems Resource Facility (MSRF), [16]. That author suggests a similar series of performance tests for motor partial load efficiency. Apart from part load there are

many other practical factors which influence the actual efficiency in the field, like voltage drops, ambient temperature deviations, harmonic voltage distortions, etc. Determination of stray-load losses is especially complicated [16].

This author presented a calculation procedure for the estimation of any part load efficiency when two load points are given [6]. This procedure is accepted, in principle, and included into a new document "Guide for energy efficient usage of electrical motors and variable speed drives" [4].

3.2 Calculation of partial load efficiency

It is usually that the efficiency values:

- $\eta_{4/4} = \eta_N$ i.e. at 100% rated load ($P/P_N = 4/4$),
- $\eta_{3/4}$ i.e. at 75% rated load ($P/P_N = 3/4$),

be included in manufacturers' information [13].

If, the η_N and $\eta_{3/4}$ (or η_{P/P_n}) values are given, it is able to determine corresponding total losses components, load losses component at rated load ($P_{\gamma N}$), and no-load losses (P_0):

$$P_{\gamma P_n} = \frac{P_{\gamma N} - P_{\gamma, (P/P_n)}}{1 - \left(\frac{P}{P_N}\right)^2} \quad (3)$$

$$P_0 = P_{\gamma N} - P_{\gamma, (P/P_n)} \quad (4)$$

where is total losses at rated load ($P_{\gamma N}$) calculated by equation (10)

$$P_{\lambda N} = \frac{1 - \eta_n}{\eta_n} P_N \quad (5)$$

On the base P_0 and $P_{\gamma P_n}$ values, partial load demanded values η_{P/P_n} determine by equation(1).

By given procedure, on the base efficiency values for P_n ($\eta_{4/4} = \eta_N$) and $3/4 P_n$ ($\eta_{3/4}$) for squirrel-cage motors 1LA and 1LG efficiency classes *eff1* and *eff2* [13], from 1.1kW to 200 kW, calculation of efficiency values for $1/2 P_n$ ($\eta_{1/2}$) is performed. In such manner are obtained efficiency dependencies from output power - $\eta(P/P_n)$.

3.3 Changes of motors efficiency class at partial loads

Efficiency dependence $\eta = \eta_i(P/P_n)$ is given in Fig.3, for four motors (7.5 kW, $2p = 2$) with the same rated efficiency value $\eta_n = 90.1\%$ (Fig. 4). The efficiency dependence differs more, the greater the difference in ratio values of $P_0/P_{\gamma P_n}$. Namely, the smaller the losses ratio values $P_0/P_{\gamma P_n}$:

- the bigger the maximum efficiency values, i.e. $\eta_{4max} > \eta_{3max} > \eta_{2max} > \eta_{1max} = \eta_n$, and they are achieved at smaller values of relative loads P/P_n (Fig. 4), and
- the lower the minimum load values at which efficiency values $\eta_i(P/P_n) \geq \eta_n$, i.e. those motors may work in a wider load range with $\eta_i(P/P_n) \geq \eta_n$ (Fig. 4).

These given motors (7.5 kW, 2p=2) belongs to following efficiency class [3]:
These given motors (7.5 kW, 2p = 2) belongs to following efficiency class [3]:

- Standard efficiency class (IE1), if $86.0\% \leq \eta_n < 88.1\%$,
- High efficiency class (IE2), if $88.1\% \leq \eta_n < 90.1\%$, and
- Premium efficiency class (IE3), if $\eta_n \geq 90.1\%$.

As $\eta_n = 90.1\% \geq 90.1\%$, all considered motors corresponding efficiency class *IE3-Premim efficiency class*. These motors differ in values of efficiency in the area of relative loads of motor $P/P_n = 0 - 1.125$, particularly in region $P/P_n \leq 0.50$. This is consequence mater of fact that those motors differ in values of at ratio of no-load losses (P_0) to load losses in rated regime ($P_{\gamma P_n}$), Fig. 3.

It is interesting to determine the values of efficiency at load $P/P_n = 0.50$ (η_{50}), and establish corresponding *efficiency class at given load (50%)*, for given motors 1, 2, 3 and 4 (Fig. 4):

- Motor 1 corresponding Standard efficiency class IE1, as $\eta_1(0.5) = 87.1\% < 88.1\%$,
- Motor 2 corresponding Standard efficiency class IE1, as $\eta_2(0.5) = 87.8\% < 88.1\%$,
- Motor 3 corresponding High efficiency class IE2, as $\eta_3(0.5) = 89.6\% < 90.1\%$, and
- Motor 4 corresponding Premium efficiency class IE3, as $\eta_4(0.5) = 90.8\% \geq 90.1\%$.

Therefore motor 4 (curve 1 in Fig. 4), already at a load of $p = P/P_n = 0.50$, works with efficiency which corresponds to the motor whose energy efficiency class is lower by 2 row (i.e. efficiency class IE1), while the motor 3 works with efficiency class IE2 (lower by 1 row). Only motors 1 and 2 to be work with designated efficiency class IE3, i.e. they would maintain their energy class, and at 50% load. On the base alike analysis, or by Fig. 4, one can to conclusion that at a load of $p = P/P_n = 0.75$, motors 1 and 2 work with efficiency which corresponds to the efficiency class IE2, while the motor 3 and 4 work with declared efficiency class IE3.

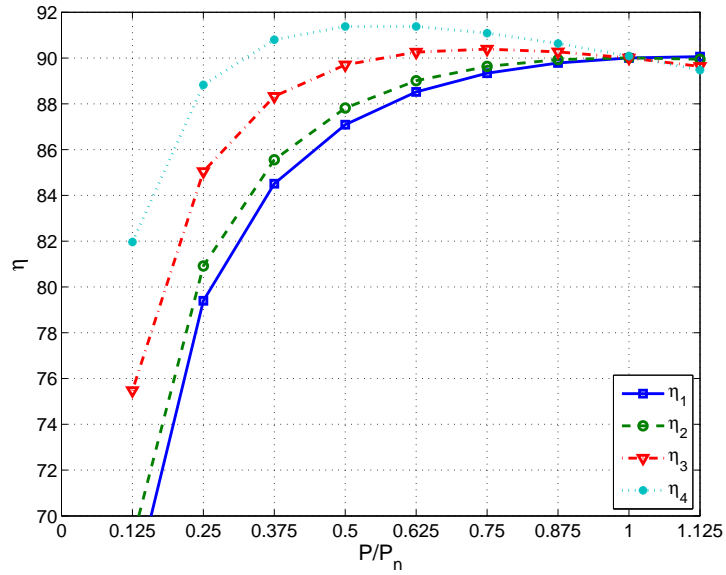


Fig. 4. Efficiency dependences $\eta = \eta_i(P/P_n)$, for 4 motors with the same rated efficiency values $\eta_n = 90.1\%$: these motors differ in values of ratio of no-load losses (P_0) to load losses in rated regime ($P_{\gamma P_n}$).

As it is important to know the efficiency values $\eta(P/P_n = 0.5)$, for motors working (or it may be assumed that they will often or frequently work) at loads of around 50%, and this information about part load efficiencies (50% and 75%) shall be visibly displayed on the technical documentation of motors from 16 June 2011 [7]. The users can then select the motor best suited for their application.

4 Calculation and Analysis of Efficiency Deviation with Load Change to Rated [6]

Based on performed analyses, it may be seen that the efficiency value of motor, at certain load, depends on the rated efficiency value, losses ratio $P_0/P_{\gamma P_n}$ and relative loads (P/P_n). From expression:

$$\frac{P_{\gamma}(p)}{P_{\gamma n}} = \frac{\frac{1 - \eta(p)}{\eta(p)} P}{\frac{1 - \eta_n}{\eta_n} P_n} \quad (6)$$

is obtained

$$\frac{1 - \eta(p)}{1 - \eta_n} = \frac{\eta(p)}{\eta_n} \frac{P_n}{P} \frac{P_\gamma(p)}{P_{\gamma_n}} \quad (7)$$

For observed values relations $\eta(p)/\eta_n \leq 1 \pm 10\%$, equation (7) is transferred to an approximate dependence (8)

$$\frac{1 - \eta(p)}{1 - \eta_n} \approx \frac{P_n}{P} \frac{P_\gamma(p)}{P_{\gamma_n}} \quad (8)$$

From equation (8) is obtained the expression (9)

$$\eta(p) \approx 1 - (1 - \eta_n) \frac{P_n}{P} \frac{P_\gamma(p)}{P_{\gamma_n}} \quad (9)$$

This, for our analyses, can be written in form (10)

$$\eta(p) \approx \eta_n \pm (1 - \eta_n) \left[1\mu \frac{P_n}{P} \frac{P_\gamma(p)}{P_{\gamma_n}} \right] \quad (10)$$

In calculations by expression (10), first is calculated the expression value $(P_n/P)(P_{\gamma_n}(p)/P_\gamma)$ for all given motors and given values of relative loads P/P_n .

It is sometimes appropriate to express efficiency values in the form of $\eta = \eta_n \pm k(1 - \eta_n)$, based on expression (10), so that changes-deviations of efficiency values compared to rated value (η_n) would be explicitly expressed. Based on those deviations, energy efficiency class changes of observed motors are directly identified with load change. In that form $\eta = \eta_n \pm k(1 - \eta_n)$ are certain efficiency values of motors 1, 2, 3,4 and 5, for loads $P/P_n = 0.50 - 1.00$, and given in Table 1.

Efficiency values in Table 1 are approximate, as they are calculated by approximate expression (10). They are somewhat bigger, compared to more accurate values, when $\eta(p) > \eta_n$, and somewhat smaller when $\eta(p) < \eta_n$. But those deviations are more prominent only in somewhat bigger relations $\eta(p)/\eta_n$, i.e. at lower loads (P/P_n). This proves that the approximate expression (10) is sufficiently accurate for determining the ratio of efficiency deviations to rated value.

On the base procedure, calculation efficiency dependencies is performed, for squirrel-cage motors from 1.1kW to 200 kW, efficiency class's eff1 and eff2, types 1LA and 1LG [13], for 1500 rpm and 3000 rpm. These results show that:

- criterion $\eta_{50\%} \geq \eta_{N,eff1(IE2)}$ and $\eta_{50\%} \geq \eta_{N,eff2(IE3)}$, is satisfied for 32 of 84 motors total, and
- criterion $\eta_{50\%} \geq \eta_{N,eff1(IE2)} - 0.05(100 - \eta_{N,eff1(IE2)})$ and $\eta_{50\%} \geq \eta_{N,IE3} - 0.05(100 - \eta_{N,IE3})$ is satisfied for 63 of 84 total.

All these results and analysis confirm justification claim that efficiency values at 50% and 75% load shall be stated in the documentation [6].

Table 1. Induction motor efficiency vales in the form of $\eta = \eta_n \pm k(1 - \eta_n)$, based on expression (10), for proposed criterion various [5]. In bold are marked target (criterion) values. Nominal values (η_N) for corresponding classes motors listed in clause 5.3.2-5.3.2 [1]

| P/P_n | 0.5 | 0.625 | 0.750 | 0.875 | 1.000 |
|---|-----------------------------|-----------------------------|------------------------------|-----------------------------|-----------------------------|
| 1. Official Criterion ($\eta_{4/4} \geq \eta_N$) [3] Considered alternative ($\eta_N = \eta_{max}$) | $\eta_N - 0.25(1 - \eta_N)$ | $\eta_N - 0.10(1 - \eta_N)$ | $\eta_N - 0.045(1 - \eta_N)$ | $\eta_N - 0.01(1 - \eta_N)$ | η_N |
| 2. Criterion $\eta_{4/4}$ and $\eta_{3/4} \geq \eta_N$ Considered alternative $\eta_N = \eta_{3/4}$ | $\eta_N - 0.12(1 - \eta_N)$ | $\eta_N - 0.04(1 - \eta_N)$ | η_N | $\eta_N - 0.25(1 - \eta_N)$ | η_N |
| 3a. Proposed Criterion $\eta_{3/4} \geq \eta_N$ Considered alternative $\eta_N = \eta_{max}$ | $\eta_N - 0.07(1 - \eta_N)$ | $\eta_N - 0.01(1 - \eta_N)$ | η_N | $\eta_N - 0.01(1 - \eta_N)$ | $\eta_N - 0.03(1 - \eta_N)$ |
| 3b. Proposed Criterion $\eta_{3/4} = \eta_{max}$ and $\eta_{1/2} \geq \eta_N - 0.05(1 - \eta_N)$ | $\eta_N - 0.05(1 - \eta_N)$ | $\eta_N - 0.01(1 - \eta_N)$ | $\eta_N - 0.02(1 - \eta_N)$ | $\eta_N - 0.01(1 - \eta_N)$ | $\eta_N - 0.01(1 - \eta_N)$ |
| 3c. Proposed Criterion Serbian $\eta_{1/2} \geq \eta_N$ and $\eta_{3/4} = \eta_{max}$ | η_N | $\eta_N - 0.05(1 - \eta_N)$ | $\eta_N - 0.07(1 - \eta_N)$ | $\eta_N - 0.06(1 - \eta_N)$ | $\eta_N - 0.03(1 - \eta_N)$ |
| 3d. Proposed Criterion $\eta_{34} = \eta_N + 0.05(1 - \eta_N)$ and $\eta_{3/4} = \eta_{max}$ | $\eta_N - 0.02(1 - \eta_N)$ | $\eta_N - 0.04(1 - \eta_N)$ | $\eta_N - 0.05(1 - \eta_N)$ | $\eta_N - 0.04(1 - \eta_N)$ | $\eta_N - 0.01(1 - \eta_N)$ |

5 Conclusion

The difference in efficiency between the motors varies with the load condition. This means that a motor with a high rated efficiency does not guarantee a high efficiency at partial load. This is especially the case for motors with relatively high no-load losses.

Calculation procedure for the estimation of any part load efficiency when two load points are given is presented in this paper. On base these calculation, the users can then select the motor best suited for their application. Efficiency curve for several motors, with typical shapes, is considered clime, especially, for loads $P/P_N = 0.50-1.00$. These results are shown justification claim that the information about part load efficiencies (50% and 75%) shall be visibly displayed on the technical documentation of motors [6], from June 16, 2011. Fortunately, the vast majority of motors (especially energy efficient motors) have at least the same if not greater efficiency at 75% compared to 100%.

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