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Induction Motors with YY/Δ Connection Change for Efficiency and Power Factor Increasing at Partial Loads

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Abstract: It is established that there exists a significant possibility for energy savings, on the basis of application of induction motors with YY/Δ connection change proposed in this paper, especially for power to 30 kW. In connection Δ ($0.866U_n$), total losses and reactive loads are reduced to loads up to 75-85%. Benefits of such motors would be significant because more than 80% induction motors are light loaded (mean value ≤ 70%). In such manner one motor with two characteristics is attained, but that is better than to offer to the market two different motors, because only in exploitation it is possible to accurately select the one which is working with greater efficiency values in given conditions. However, at the motor with YY/Δ winding it is always possible, by selection of corresponding connection for (mean value) load measured in operation. Even, with connection change it is possible to adjust to load changes in future.

Moreover, at loads ≥30%, energy saving by induction motors with YY/Δ connection is greater than the one using induction motors with thyristor controllers. Induction motors YY/Δ connection application may be economical in cases where it is not recommended to use higher costs of energy efficiency of motors.

Keywords: Induction motors with YY/Δ connection change, partial loads, efficiency increasing, power factor increasing.

1 Introduction

Electrical motors consume around 55% of total consumed electrical energy and, thereof, induction motors account for 96% of energy consumption. Around 67% of this energy is used in induction motors with a rating below 55 kW, and it shows

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[1] that 85% of the energy loss is dissipated in these rating motors. Efficiency improvement of constant - speed drives, both constant-torque and variable-torque drives, is very important. It is usual that techniques for efficiency improvements of variable-torque drives are different from those of constant-speed and constant-torque applications. The latter is dealt with through optimization; it is very difficult to design and build a motor with high rating efficiency and rating power factor-it is shown [2] that higher efficiencies are associated with lower power factor. Especially, it is very difficult to design and build a drive operating at high efficiency and power factor over an entire range of loads, say from 25 - 100% of rated load (P_n), i.e. at partial load.

In appliances and commercial applications, where the torque required changes with load, attempts have been made with the thyristor/triac controllers. Such controllers are able to sense the torque of a drive and subsequently adjust the input voltage and current of three-phase induction motors. Motor losses during these light load periods are primarily iron-core losses. If these could be reduced during light load periods by reducing the voltage, the total energy employed might be reduced. It is an inherent characteristic of induction motors that the power factor is very low at light load and becomes much higher at full load. The controls of voltage by means of solid-state switching devices (thyristor, triac, transistors) are such that the current value needed to provide a certain torque is always minimal. But, induction motors with thyristor/triac controllers are non-linear load absorbing a non-sinusoidal current (current with harmonics) when supplied by sinusoidal voltage. The main effect of harmonics over power system can be summarized by just saying that these unnecessarily increase the current and power to be carried (fluctuating power), consequently worsening the power factor and causing additional losses in line conductor, transformer and the very motor supplied by thyristor/triac controllers. One of the obstacles to overcome in the design of such controller is the limitation of the total harmonic distortion of the current (THD_i) as imposed by standards IEEE 519 and IEC 1000-2-2.

The most important conclusions are given for motors with thyristor controllers [3]:

- When induction motor is supplied over the voltage regulator that is operated with purely sinusoidal voltage (ideal regulator), the total energy consumption is reduced at all loads $P < P_n$, by adjusting optimal voltage values for given loads.
- Three-phase thyristor controller with total harmonic distortion of current $THD_i \leq 25\%$, which is acceptable in IEEE-519, causes additional losses in motors and influences the motor current increasing.
- Induction motor with thyristor controllers can reduce power consumption

only at load $\leq$ 50-60% of rated load. However, complete driven power saving disappears just at load $P \geq$ 30-40% of rated load, and the drive losses increase because of the inherent losses of controllers.

- Power factor, as seen by the distribution system at the input of the pole transformer, does not improve because of the total current ($I^2_{rms(total)} = I_1^2 + \Sigma I_h^2$) formed by a fundamental component (I1) and a superposition of harmonics currents ($\Sigma I_h^2 = I_1^2 \times THD_i$, for $h \geq 2$), created by thyristor controllers.
- Some of controllers employ a ”soft-start” feature, reducing the peak starting current and eliminating the necessity for additional reduced-voltage or mechanical starters.

However, some of above mentioned imperfection might be entirely eliminated, and other imperfections might be diminished, as will be shown, with the solution proposed in this paper - induction motors with YY/Δ winding.

2 Efficiency at Partial Load of Motors

The typical the total losses dependence $P_\gamma(p)$ and motor efficiency dependence $\eta(p)$ are given by following equations:

$$P_\gamma(p,u) = P_0 + P_{\gamma P_n} p^2 \quad (1)$$

$$\eta = \frac{pP_n}{pP_n + P_0 + P_{\gamma P_n} p^2} \quad (2)$$

where $p = P/P_n$-the p.u. load power, P_0-no-load losses at $U = U_n$, and $P_{\gamma P_n}$ - load losses rated at rated condition.

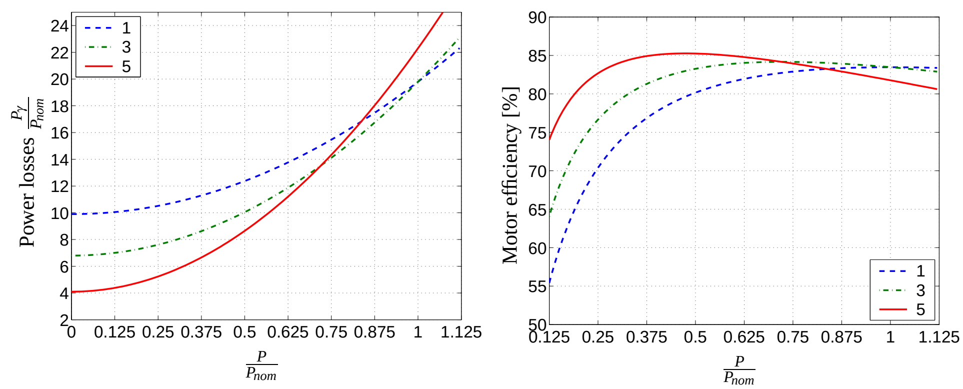
In Fig. 1(a) are total losses curves 1, 3 and 5, for three motors with quotient values $P_{0n}/P_{\gamma P_n}$, and in Fig 1b are given corresponding efficiency curves 1, 3 and 5, for the same three motors.

The analysis of the dependence (2) between the partial load efficiency and the values of components P_0 and $P_{\gamma P_n}$ losses leads to some interesting conclusions. It enables the designer to select motor parameters in order to obtain the desired variation of efficiency by load. One can impose the efficiency maximal values for full load (100%), or 75%, or maybe for 50% load. It is determined by the values of the P_0 and $P_{\gamma P_n}$ losses, or more precisely by P_0/P_{γ_n} values.

Most motors are over dimensioned for safety reason (and due to impossibility to evaluate the load value) and because of standard power ratings. This means that motors are usually used in the following range:

- 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).



(a) (b)

Fig. 1. (a) The total losses versus $P_\gamma/P_n = f(P/P_n)$, and (b) Efficiency curve $\eta = f(P/P_n)$, in relation to three P_0/P_{γ_n} values (in a per unit $P_n = 1$): $P_0/P_{\gamma_n} = 0.099/0.099$, $\eta_{max} = \eta_n$ (for $P = P_n = 100\%$) curve 1 - motor 1, $P_0/P_{\gamma_n} = 0.068/0.130$, $\eta_{max} = \eta_{75}$ (for $P/P_n = 75\%$), curve 3- motor 2, $P_0/P_{\gamma_n} = 0.041/0.182$, $\eta_{max} = \eta_{50}$ (for $P/P_n = 50\%$), curve 5-motor 3.

It is important that the efficiency at 50 and 75% rated load should be included in all manufacturers' information [4]. If we consider the efficiency curves shown in Fig. 2, we notice that 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 - motors curve 1 in relation to motors curves 3 and 5 in Fig. 1.

In Fig. 2 are given the efficiency curves for the mentioned motors 1, 3 and 5, with maximum values of efficiency, respectively, for 100%, 75% and 50% rated load. The difference in efficiency between the motors varies with iron losses change. Reducing the voltage could reduce the motor total losses and the total energy employed might be reduced.

3 Induction Motors with YY/Δ Connection Change

With the solution proposed in this paper - induction motors with winding for YY/Δ connection change, which is presented by Fig. 2 - are given an opportunity to significantly increase the efficiency values (η) in connection Δ (delta) at loads up to 70-85% (corresponds to curve 5 in the Fig. 1(b). Efficiency decreasing (curve 5 in the Fig. 1(b) will be avoided by connection change from Δ ("delta") to YY

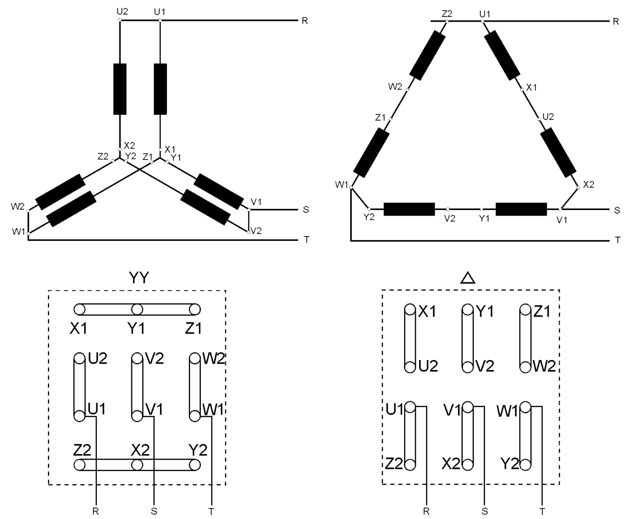


Fig. 2. Induction motors with YY/Δ connection change for efficiency and power factor increasing at partial loads

("double star") at loads $\geq$ 70-85% (curve 3 in the Fig. 1(b). In such manner is attained one motor with two characteristics, but it is better than to offer to the market two different motors, because only in exploitation it is possible to accurately select the one which is working with greater efficiency values in given conditions. Naturally, with YY/Δ winding motor, by selection of corresponding connection, it is also possible; even with such load drive changes.

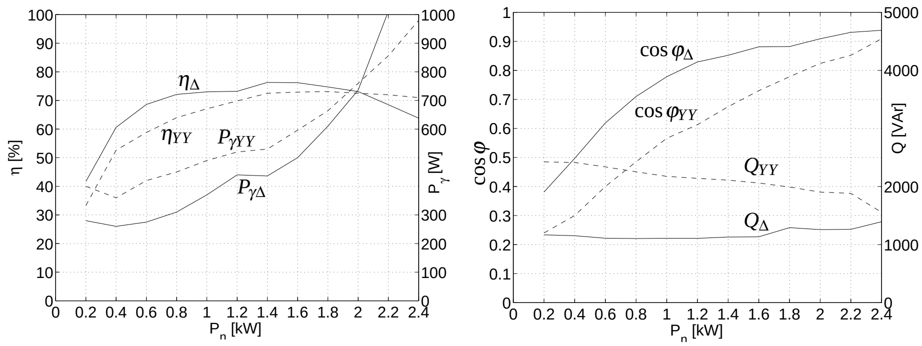
It is essential in the connection Δ ("delta") to reduce the voltage to 0.866 of, which is $P_0(u)$. The typical total losses dependence $P_\gamma(p,u)$ and efficiency depen-dence $\eta(p,u)$ are given by following equations:

$$P_\gamma(p,u) = P_0(u) + P_{\gamma P_n}\frac{p^2}{u^2} \tag{3}$$

$$\eta = \frac{pP_n}{pP_n + P_0(u) + P_{\gamma P_n}\frac{p^2}{u^2}} \tag{4}$$

where $u = U/U_n$ - the p.u. voltage values.

If, for example, the total losses dependence $P_\gamma(p,u)$ is given by curve 3 in Fig. 1(a) and efficiency dependence $\eta(p,u)$ is given by curve 3 in Fig. 1(b), when motor is in the connection YY ($U = U_n$), then, for the same motor in the connection Δ ($U = 0.866U_n$), the corresponding total losses dependence $P_\gamma(p,u)$ and efficiency dependence $\eta(p,u)$ may be given by curves 5 in Fig. 1(a) and Fig. 1(b). Using the above mentioned induction motor with the stator windings in Δ (delta), one can



(a) (b)

Fig. 3. (a) Efficiency (η) and power losses (P_γ), and (b) Factor power ($\cos\varphi$) and reactive load (Q) versus power output (P), for rewinding motor 1ZK 100 L-4, 2.2 kW: For winding in "YY" connection (corresponding to nominal voltage U_n), and For winding in "Δ" connection (corresponding to voltage value $0.866U_n$).

significantly improve efficiency values on the partial loads up to 75% (corresponds to curve 5 in the Fig. 1(b). It is interesting to notice that the power factor will be significantly improved - energetic effects due to reduced reactive power are equal to or greater than the effects due to reduced power total losses, and it significantly increases (duplicates) the total effects.

By testing 2.2 kW induction motors, which are rewound in order to make possible YY/Δ connection change of stator winding [5], the significant space for savings is discovered. In connection Δ ("delta"), which corresponds to reduced voltage value (0.866 U_n) on the half-phase winding, and under load from no-load (0%) up to 90%, the measured power losses are reduced by $\Delta p_{\gamma YY/\Delta}$ = 14 - 3% (u % P_{γ_n}) - Fig. 3(a), and reactive load (Q) is reduced by about one third, or around $\Delta Q = 25-30$ (% P_n) -Fig. 3(b). At load levels higher than 90% rated power, the motor is used in connection YY to avoid the increased power losses. When loads are variable, it is sufficient to choose connection of the motor on the base load mean value for a longer time (days or months), and then this connection change may be performed in the motor terminal box (Fig. 1), or by the breaker intended for this.

4 Procedure for Determination of Energetic Effects Obtainable by YY/Δ Connection Change

For establishing of energetic effects obtainable by YY /Δ connection change can be used standard procedures recommended for determination of losses and efficiency of induction motors (IEEEE112, IEC 34-2, IEC 61972). The motor 1ZK 100 L-4, 2.2 kW (Fig. 3 and Fig. 4) was tested using standard IEEE 112 Method. The losses and efficiency were calculated using the measured input electrical power and measured output mechanical power using torque and speed, and analysis procedure described in IEEE 112-B. The Test Code includes six load points, ranging from $^1/_4$ to $1^1/_2$ times rated load. Although the method is very accurate, it is not suitable for field evaluation because it is associated with measuring the output mechanical power or torque. Obviously, this is impractical and costly, even for a rewinding workshop.

A simple and accurate method for determining of energetic effects obtainable by YY/Δ connection change of induction motor will be proposed and described in this article. With the stator winding connecting change, from YY to Δ, the voltage value on the half-phase winding to reduce from values $u = 1$ to $u = 0866$ (in p.u.), total losses changes. For this reason the procedure for determination of energetic effects obtainable by YY/Δ connection change is based on the dependencies power losses and reactive load from voltage values. As is shown, it is sufficient to measure:

- No-load losses at voltage nominal values (U_n) and voltage value $0.866U_n$ (corresponding "Δ" connection), and
- Load losses at nominal condition should be evaluated, and, on the basis of these data, then to determine motor total losses for all loads from 0-100% rating load, at nominal voltage (corresponding " YY "connection) and voltage value $0.866U_n$ (corresponding "Δ" connection). Energetic effects obtainable by YY/Δ connection change can be determined by this procedure in all desired cases.

4.1 Change (reducing) of power losses with YY/Δ connection change and characteristic load

Differences of the total losses values in YY connection ($P_{\gamma YY}$) and the total losses values in Δ connection ($P_{\gamma\Delta}$), are both calculated by equation (3), respectively for $u = 1$ and $u = 0.866$, for the same load $p = P/P_n$, represented in YY /Δ connection change effect in absolute values $\Delta P_{\gamma YY-\Delta} = P_{\gamma YY} - P_{\gamma\Delta}$ or in per unit values $\Delta p_{\gamma YY-\Delta} = \Delta P_{\gamma YY-\Delta}/P_{\gamma n}$, and are calculated by following equations:

$$\begin{aligned} \Delta P_{\gamma YY-\Delta} &= (P_{0YY} - P_{0\Delta}) - 0.33 P_\gamma p_n p^2 \\ \Delta p_{\gamma YY-\Delta} &= (p_{0YY} - p_{0\Delta}) - 0.33 p_{\gamma p_n} p^2 \end{aligned} \tag{5}$$

where $P_0(u) = P_{Cu0} + P_{Fe} + P_{fW}$ sum of the electric (copper) losses in the stator (P_{Cu0}), the core losses (P_{Fe}) and the friction and windage losses at no-load condition; $P_\gamma p = P_\gamma p_n p^2/u^2$ is load loss (component), depending on load ($p = P/P_n$)

and voltage ($u = U/U_n$), and it is proportional to load loss (component) at rated condition ($P_\gamma p_n = (P_{Cu1,n} - P_{Cuo}) + P_{Cu2,n} + P_{d,n}$).

Total losses changes reduce with load increasing, and become $\Delta P_{\gamma YY-\Delta} = 0$, at some characteristic load (P_{charac} or $p_{charac} = P_{chara}/P_n$), that is calculated by equations:

$$p_{charac} \approx \sqrt{\frac{P_{0YY} - P_{0\Delta}}{0.33P_{\gamma pn}}} \qquad p_{charac} \approx \sqrt{(p_{0YY} - p_{0\Delta})0.33p_{\gamma pn}} \tag{6}$$

Values P_{charac} calculated by (6), chiefly agree with measured values for motors from 1-100 kW [6]. Also, total losses changes (ΔP_γ or $\Delta p_\gamma = \Delta P_\gamma / P_{\gamma n}$), which are calculated by (5), agree with measured values for load $P \leq P_{charac}$. Only, at $P \geq 1.2P_{charac}$ or $P \geq 0.9P_n$, values calculation are somewhat lesser, because temperature increasing is greater (as $P_{\gamma\Delta} > P_{\gamma YY}$ for $P > P_{charac}$) - [6].

4.2 Reducing of Reactive loads with YY /Δ connection change

Reactive loads reducing is the result no-load reactive current reducing, and lower increasing reactive component of rotor current (load arm current). This reducing ($\Delta Q_{YY-\Delta}$ or $\Delta q_{YY-\Delta} = \Delta Q_{YY-\Delta}/P_n$), is calculated by equations:

$$\Delta Q_{YY-\Delta} \approx (Q_{0YY} - Q_{0\Delta}) - 0.33Q_{2n}p^2 \qquad \Delta q_{YY-\Delta} \approx (q_{0YY} - q_{0\Delta}) - 0.33q_{2n}p^2 \tag{7}$$

Reactive load corresponding values $Q_{0,YY}$ and $Q_{0,\Delta}$ determine by of no- load test, with voltage rating (U_n) and voltage reducing ($0.866U_n$). Reactive power in load arm Q_{2n} and q_{2n}, in rating condition (P_n, U_n), calculated by equations:

$$Q_{2n} = 0.5P_n/m_{max} \qquad q_{2n} = 0.5/m_{max} \tag{8}$$

where $m_{max} = M_{max}/M_n$- breakdown torque values in p.u. Values $\Delta Q_{YY-\Delta}$, calculated by (8), agree with measured values for motors from 1-100 kW, for load from 0-100 % of rated power [6].

4.3 More accurate calculation of power losses change ($\Delta P_{\gamma YY-\Delta}$) with YY/Δ connection change at load $P > P_{charac}$

As is shown by measurement, power losses values change ($\Delta P_{\gamma YY-\Delta}$), at load $P > P_{charac}$, are greater than values calculated by equation (5) and (5a), and even more so as load values become greater. Namely, at load $P > P_{charac}$, in Δ connection $P_{\gamma\Delta} > P_{\gamma YY}$, and motor temperature is additionally increased ($\Delta T_{YY-\Delta} > 0$). For that reason, load losses are additionally increased. These load losses increasing ($\Delta P_{\gamma,\Delta T}$) is suitable to express by $0.33 P_\gamma p_n p^2$ load loss component, i.e.

$$\begin{aligned} \Delta P_{\gamma\Delta T} &= (0,24 \div 0,32)(p^2 - p_{charac} 0.33 P_{\gamma pn} p^2, \quad p \geq p_{charac} \\ \Delta p_{\gamma\Delta T} &= (0,24 \div 0,32)(p^2 - p_{charac} 0.33 p_{\gamma pn} p^2, \quad p \geq p_{charac} \end{aligned} \tag{9}$$

Coefficient numerical values in equations (9), as it is shown by analysis [6], are in interval from 0.24÷0.32, i.e. coefficient $K_{\gamma,\Delta T} = 0.24 \div 0.32$, if increasing temperature is $75 \div 100$K at rating condition. Beside load losses increasing mentioned ($\Delta P_{\gamma,\Delta T}$), and in addition to increasing of load losses, it is proved that this increasing takes rise from:

- Greater increasing of motor current than given coefficient 1.155 ($i_{1\Delta}/i_{1YY} > 1/0.866 = 1.155$), by reason of greater increasing of emf than given coefficient $0.886 - e_{1\Delta}/e_{1YY} < e_{10\Delta}/e_{10YY} = 0,866$, and
- Lower increasing of core losses with load increasing in Δ connection, than in YY connection, because motor is less saturated in Δ connection (voltage $0.866 U_n$).

Quantitative analyses show that these total increasing (including and $\Delta P_{\gamma,\Delta T}$, in region loads $p > p_{charac}$, can be taken into account, by increasing of coefficient values in equation (9), with (0.24÷0.32) to the value 0.5, i.e. the equation for determining of additional increasing total values of losses ($\delta\Delta P_{\gamma YY-\Delta}$ and $\delta\Delta p_{\gamma YY-\Delta}$) is:

$$\begin{aligned} \delta\Delta P_{\gamma YY-\Delta} &= 0.5(p^2 - p_{charac}) 0.33 P_{\gamma,pn} p^2, \quad p \geq p_{charac} \\ \delta\Delta P_{\gamma YY-\Delta} &= 0.5(p^2 - p_{charac}) 0.33 p_{\gamma,pn} p^2, \quad p \geq p_{charac} \end{aligned} \tag{10}$$

It proved to be that, for load $p > p_{charac}$, total losses changes (ΔP_γ or $\Delta p_\gamma = \Delta P_\gamma / P_{\gamma n}$) ought to be calculated by equations:

$$\begin{aligned} \Delta P_{\gamma YY-\Delta} &= (P_{0YY} - P_{0\Delta}) - 0.33 P_{\gamma pn} p^2 (1 + 0.5(p^2 - p^2_{charac})), p \geq p_{charac} \\ \Delta p_{\gamma YY-\Delta} &= (p_{0YY} - p_{0\Delta}) - 0.33 p_{\gamma pn} p^2 (1 + 0.5(p^2 - p^2_{charac})), p \geq p_{charac} \end{aligned} \tag{11}$$

By coefficient $1 + 0.5(p^2 - p_{charac}) > 1$, in the second article of equations (11), it takes into account additional increasing of losses in region loads $p_{pcharac}$, that is not taken into account in equations (5) and (5a). It proved that so determined losses increasing are greater, than the one determined by equation (5):

- About 2 -3%, for load 85-90%,
- About 5 -6%, for rating load (100%), and

- About 9 -10%, for load 112%.

These results show that losses increasing ought to be calculated by equations (11) and (11a), instead of calculation by equations (5) and (5a). At loads $p < p_{charac}$, values $\Delta p_{\gamma\Delta-YY} < 0$ and $\Delta T_{\Delta-YY} < 0$, and coefficient values $K_{\gamma,\Delta T}$ are negative, i.e. $K_{\gamma,\Delta T} = -(0.24 \div 0.32)$. With this are approximately compensated the other two (above mentioned) losses increasing, and additional increasing of losses changes $\delta\Delta P_{\gamma YY-\Delta} \approx 0$. By means of which is proved that total losses changes (ΔP_γ or $\Delta p_\gamma = \Delta P_\gamma / P_{\gamma n}$) ought to be calculated by equations (5) and (5a), for load $p < p_{charac}$.

On the basis of measurement results, for motors of powers 2.2 kW, 5.5 kW, 18.5 kW and 45 kW, it is established that calculation values $\Delta P_{\gamma YY-\Delta}$, by equation (11), are approximately equal to corresponding measured values. It means that complete proposed and described procedure is characterized with the high accuracy.

5 Classification Motors with YY/Δ Connecting Change on the Base Energy Effects

As in Δ connection total load losses are reduced ($\Delta P_{\gamma,YY-\Delta} > 0$) for load region $p \leq p_{charac}$, the characteristical load (p_{charac}) is an essential performance for production and application of motors with winding for YY/Δ connection. The second criterion is the percentage of motors working in exploitation with loads $p \leq p_{charac}$. By equation (6a) one can conclude that values p_{charac} are greater, for greater values of no-load loss reducing ($\Delta p_{YY-\Delta} = p_{0YY} - p_0$). Reducing of the values ($p_{0YY} - p_{0\Delta}$) is a consequence of decreasing of the core losses (P_{Fe}) and the electric (copper) losses in the stator (P_{Cu0}) "Δ" connection, i.e. $p_{0YY} - p_{0\Delta} = (p_{Fe} + p_{Cu0})_{YY} - (p_{Fe} + p_{Cu0})_\Delta$. On the basis of investigation of a large number of motors from 1-100 kW [6], it is established that there are values region ($p_{0YY} - p_{0\Delta}$) and p_{charac}:

- $p_{0YY} - p_{0\Delta}$= 0.12-0.14 and p_{charac} = 0.75-0.80, for small motors (from 1.1-7.5 kW) and 2p= 4,
- $p_{0YY} - p_{0\Delta}$= 0.10-0.12 and p_{charac}= 0.70-0.75, for medium motors (from 11-30 kW) and 2p= 4, and
- $p_{0YY} - p_{0\Delta}$= 0.08-0.10 and p_{charac}= 0.65-0.68, for greater motors (from 37-90 kW) and 2p= 4.

Total losses reducing $\Delta p_{\gamma,YY-\Delta}$ is calculated by equations (5a) and (11a), for motors representing, respectively, small, medium and greater power. In such a manner the calculating values, for loads region: 0; 12.5; 25; 37.5; 50; 62.5; 75; 87.5; 100 and 112.5 (%), are given in Table 1.

Table 1. Total losses change with YY/Δ connection change, for motors represent, respectively: small, medium and greater power

Loads P/P_n (%)	0	12.5	25.0	37.5	50.0	62.5	75.0	87.5	100.0	112.5
Motors rating power	Total losses values p_γ (in % $P_{\gamma n}$)									
1.1-7.5 kW, p_{charac}=78%	36.0	37.0	40.0	45.0	52.0	61.0	72.0	85.0	100.0	117.0
11- 30 kW, p_{charac}=73%	37.0	38.0	40.9	46.0	52.8	61.6	72.4	85.2	100.0	116.8
37-90 kW, p_{charac}=67%	40.0	40.9	43.7	48.4	55.0	63.4	73.8	85.9	100.0	116.0
Total losses reducing $\Delta p_{\gamma YY-\Delta} = P_{\gamma YY} - P_{\gamma\Delta}$ (in % $P_{\gamma n}$)										
1.1-7.5 kW, p_{charac}=78 %	13.0	12.7	11.7	10.0	7.7	4.7	1.0	-4.9	-12.9	-22.9
11- 30 kW, p_{charac}=73 %	11.5	11.2	10.8	8.5	6.2	3.2	-0.8	-6.5	-15.2	-24.8
37-90 kW, p_{charac}=67 %	9.0	8.7	7.7	6.0	3.8	0.8	-3.5	-9.6	17.8	-28.4
Total losses reducing $\Delta p_{\gamma YY-\Delta} = P_{\gamma YY} - P_{\gamma\Delta}$ (in % P_γ)										
1.1-7.5 kW, p_{charac}=78 %	36.1	27.0	30.0	23.6	16.1	8.9	1.4	-5.0	-14.7	-19.5
11- 30 kW, p_{charac}=73 %	31.1	29.5	26.4	18.5	11.7	5.2	-1.1	-7.6	-15.2	-21.2
37-90 kW, p_{charac}=67 %	22.5	21.3	17.6	12.4	6.9	1.3	-4.7	-11.2	-17.8	-24.4
Total losses reducing $\Delta p_{\gamma YY-\Delta} = P_{\gamma YY} - P_{\gamma\Delta}$ (in % P_γ)										
1.1-7.5 kW, p_{charac}=78 %	2.57	2.51	2.31	1.98	1.52	0.93	0.20	-1.0	-2.55	-4.62
11-30 kW, p_{charac}=73 %	1.48	1.44	1.39	1.09	0.80	0.41	-0.10	-0.8	-1.96	-2.80
37-90 kW, p_{charac}=67 %	0.75	0.73	0.64	0.50	0.32	0.07	-0.29	-0.8	-1.48	-2.37

Reactive loads reducing $\Delta_{qYY-\Delta}$ are calculated by equations (7a), for motors representing small, medium and greater power, respectively. In such a manner the calculating values, for loads region: 0; 12.5; 25; 37.5; 50; 62.5; 75; 87.5; 100 and 112.5 (%), are given in Table 2.

Table 2. Reactive load reducing with YY/Δ connection change, for motors small, medium and greater power

Loads P/P_n (%)	0	12.5	25.0	37.5	50.0	62.5	75.0	87.5	100.0	112.5
Motors rating power	Reactive load values Q (in % P_n)									
1.1-7.5 kW, $p_{charac} = 78$ %	75,0	73,7	73,2	73,2	73,7	74,9	76,6	78,9	81,7	85,1
11- 30 kW, $p_{charac} = 73$ %	62,0	61,6	61,8	62,7	64,1	66,2	69,0	72,3	76,3	80,9
37-90 kW, $p_{charac} = 67$ %	50,0	50,0	50,7	52,1	55,3	57,1	60,7	65,0	70,0	75,7
Reactive load reducing $\Delta Q_{YY-\Delta} = Q_{\gamma YY} - Q_{\gamma\Delta}$ (in % Q_n)										
1.1-7.5 kW, $p_{charac} = 78$ %	34,5	33,5	32,3	30,8	29,3	27,3	25,1	22,6	20,1	14,4
11- 30 kW, $p_{charac} = 73$ %	33,0	32,4	31,6	30,4	30,0	27,3	25,3	23,1	20,6	17,7
37-90 kW, $p_{charac} = 67$ %	22,9	22,4	21,6	20,4	19,0	17,3	15,0	12,6	9,7	6,4
Reactive load reducing $\Delta Q_{YY-\Delta} = Q_{\gamma YY} - Q_{\gamma\Delta}$ (in % P_n)										
1.1-7.5 kW, $p_{charac} = 78$ %	28,2	27,4	26,4	25,2	23,9	22,3	20,5	18,5	16,4	11,8
11-30 kW, $p_{charac} = 73$ %	25,2	24,7	24,1	23,2	22,1	20,8	19,3	17,6	15,7	13,5
37-90 kW, $p_{charac} = 67$ %	16,0	15,7	15,1	14,3	13,3	12,1	10,5	8,8	6,8	4,5

In Fig. 4, in order to illustrate better, dependencies of total losses ($P_\gamma\% = P_\gamma/P_{\gamma,n}\%$) and reactive loads ($Q\% = Q/Q_n\%$), are shown as corresponding changes of total losses $\Delta P_{\gamma YY-\Delta}\% = P_{\gamma YY} - P_{\gamma\Delta}(\%)$ and changes of reactive loads $\Delta Q_{YY-\Delta}\% = Q_{YY} - Q_\Delta(\%)$, with YY/Δ connection change, respectively, for motors (a) small, (b)

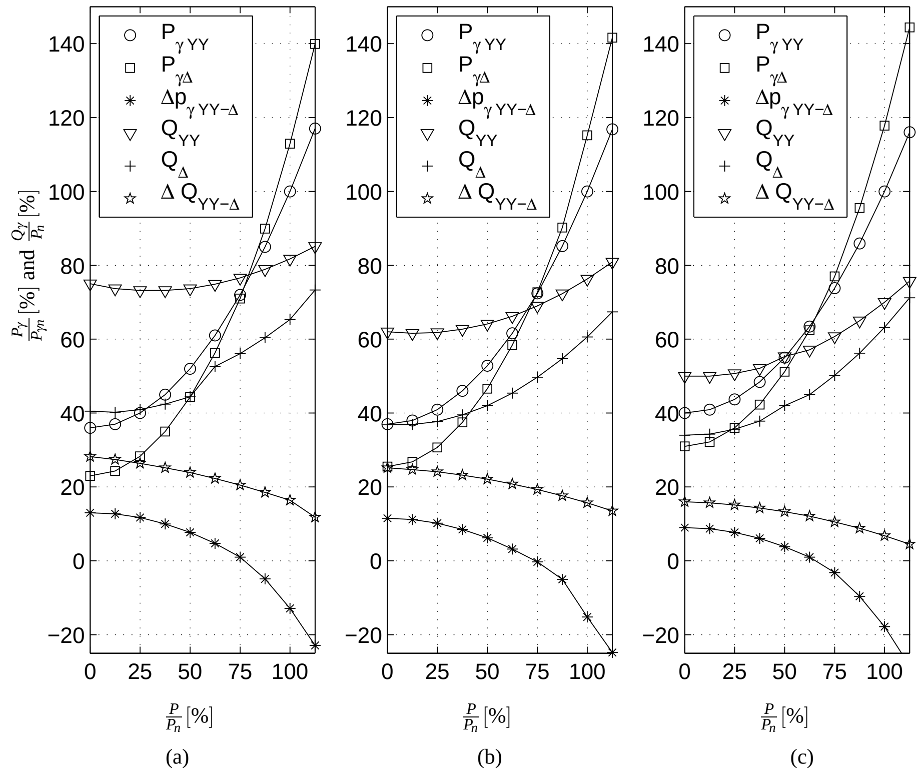


Fig. 4. Dependencies of total losses ($P_\gamma\% = P_\gamma/P_{\gamma,n}\%$) and reactive loads ($Q\% = Q/Q_n\%$), as a corresponding changes of total losses $\Delta P_{\gamma YY-\Delta}\% = P_{\gamma YY} - P_{\gamma\Delta}(\%)$ and reactive loads $\Delta Q_{YY-\Delta}\% = Q_{YY} - Q_\Delta(\%)$, with YY/Δ connection change, for motors (a) small, (b) medium and (c) greater power.

medium and (c) greater power.

6 Power Range for Application of Motors with YY/Δ Reconnecting Winding

Results of our investigation given in tables 1 and 2, as well as those illustrated in Fig. 4, show the total losses and reactive load versus power output load, for both motor connections, YY (”double star”) connection and connection Δ (”delta”) connection. For all motors with presented results, Δ (”delta”) connection appears more efficient, as follows:

- For motors up to 30 kW, at loads up to 75 - 8 5%, and
- For motors from 37-90 kW, at loads up to 65 - 7 5%,

Greater values refer to the cases when reactive energy cost exists, and (or) to the motors with greater core losses, for example rewinding motors.

As analysis shows, motors for general-purpose are usually used, with probability $\geq$95 %, at following loads:

- Motors from 1-7.5 kW, at the load range 37.5-50-62.5-75% of rated power,
- Motors from 11-30 kW, at the load range 50-62.5-75-87.5% of rated power, and
- Motors from 37-100 kW, at the load range 62.5-75-87.5-100 % of rated power.

This means that, in order to reduce energetic cost:

- Over 80 % of motors from 1-7.5 kW, could be used in Δ ("delta") connection,
- Over 60 % of motors from 11-30 kW, could be used in Δ ("delta") connection, and
- Only about 20-30 % of motors from 37-100 kW, could be used in Δ ("delta") connection.

On the base of that, it is concluded that application of these motors would be very useful, and therefore, production of motors from 1-30 kW with reconnected (in terminal box) YY/Δ winding may certainly be proposed.

7 Conclusion

On account of our investigation [6], the results of which are presented in this paper, it is confirmed that there are significant possibilities for energy savings by means of proposed induction motors with YY/Δ reconnecting winding, especially for small and medium power (1-30 kW) motors. As more than 80% induction motors are light loaded ($\leq$70%), in Δ ("delta") connection, stator half-phase winding voltage is reduced to $0.866U_n$ values, and total losses and reactive load are reduced. It is sufficient to choose one of two possible connections, YY ("double star") connection or Δ ("delta") connection, on the base load mean value determined for longer time (days or months). Connection change may be performed in the motor terminal box, or by a special breaker intended for this. Already, at loads $\geq$ 30%, energy saving by induction motors with YY/Δ connection is greater than with application of induction motors with Thyristor/Triac controllers [6]. Application of (standard) induction motors eff3 classes of efficiency levels with YY/Δ connection may be economical, even in cases when [7] applications of higher costs of energy efficiency of motors is not economically justified:

- eff2 motors (at loads $\leq$60 % and with $\leq$2000 hours annually),

- eff1 motors (at loads $\leq$60 % and with $\leq$4000 hours annually).

It can be particularly economically justified to make YY/Δ winding when performing the rewinding of a damaged motor.

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