Energy Efficiency in Electric Drives

Slobodan Mirchevski

Abstract—**In this paper a look at energy efficiency in electric drives is taken strongly through energy parameters - efficiency η and power factor k (in special case cos φ). Considering electric drive as system of working mashine, motor and power converter, the influence of components is evaluated. Induction motor, as the most used in industry, has been treated. The necessary of variable speed drives in dynamic states for reducing electrical losses by help of power converters is presented. The importance of energy efficiency in electric drives on improving technological process, consumed and paid electric energy and global problem of enviroment pollution is elaborated.**

Index Terms—**Adjustable Speed Electric Drives, Energy Efficiency, Induction Motor, Power Factor.**

I. Introduction

ENERGY efficiency is the basis of technical systems working. The first great question of this field was DC (T. Edison's practice) or AC system (N. Tesla's invention). And normally, the system with greater possibilities (bigger power, longer distances) and evidently lower losses won. Energy efficiency is always closely related with energy crisis in the world. In the past it has been temporary event, but these days it has become continuous and global problem because of environment pollution. The name has varied from energy saving in early 80-ties, through rational use of energy in 90-ties, to (till) energy efficiency now [16], [17], [18], [19], [20]. Electric drives account for approximately 65% of the electricity consumed by EU industry. Therefore electric drives have the great energy saving potential, technical (higher) and economic (lower) [1], [2], [3], [4], [5], [6].

The efficiency of an electric drive depends on more factors, including: motor efficiency, motor speed control, proper sizing, power supply quality, distribution losses, mechanical transmission, maintenance practices, end-use mechanical efficiency (pump, compressor, fan etc.). The energy efficiency has influence on the work of electric drive, its consumption and paying of electric energy (active, reactive), the working life etc. [21], [22], [23], [24], [25], [26].

Manuscript received 30 May 2012. Accepted for publication 10 June 2012. Some results of this paper were presented at the 16th International Symposium Power Electronics, Novi Sad, Serbia, October 26-28, 2012.

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DOI: 10.7251/ELS1216046M

What energy efficiency practice for? The answer is simple - because of getting high quality and cheaper products, lower production costs and reducing of global pollution.

How to realize energy efficiency in electric drives? The right way is with usage of better working machines, power convertors for getting variable speed to reduce power losses and energy efficient motors.

This paper strongly deals with energy efficiency in electric drives through energy parameters – efficiency η and power factor k (in special case with ideal supply without harmonics cos φ). In fact, efficiency and power factor are in close relation and therefore their product is also used as energy parameter. The working machine as a part of an electric drive is not treated, although it is (comprising its whole distribution ducting) with the greatest savings potential (125 billion kWh/year for EU-25, [4]). It is worth mentioning that pumps, compressors and fans are the most used loads (>60% of all installed working machines), fortunately with mainly centrifugal mechanical characteristics n(M) and the greatest savings potential by using power converters with simple and cheap control system. In this paper, the attention is focused on motor speed control with saving potential of 50 billion kWh/year for EU-25 and motor losses expressed through its efficiency and power factor k with saving potential of 27 billion kWh/year for EU-25, [4].

Low voltage squirrel cage induction motor is considered as "work horse" in industry. Because of its wide, dominant usage, over 65% in all installed drives [1], [8], [9], [20], [27] is taken into consideration.

II. Variable Speed Drive

Variable speed drives with help of power electronics converters are more effective way of improving drive energy efficiency with nearly double savings potential than HEM [4]. In Fig. 1 the losses during starting of induction motor with one speed winding (a), Dahlander's winding for two speeds in ratio 1:2 (b) and continuous changing of speed (c), are presented [9]. It is evident utility of speed control during drive starting, braking, reversing and speed changing.

Losses during starting and counter current braking (plugging) in no load regime (M_L=0) are expressed with eq. (1) and eq. (2)

$$A_{Cu_{2st}} = J\frac{\omega^2}{2} \tag{1}$$

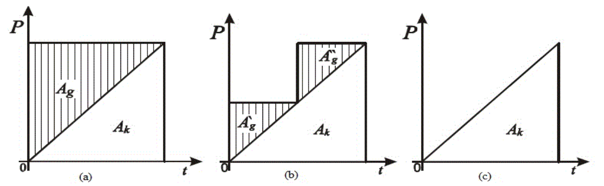

Fig. 1. Losses during starting (M_L=0) of IM with one speed winding (a) η=0,5; Dahlander's winding for two speeds in ratio 1:2 (b) η=0,75 and continuous changing of speed with ideal power converter neglecting losses (c) η=1. [9].

$$A_{Cu_{2br}} = 3J\frac{\omega^2}{2} \tag{2}$$

where A_{Cu2} [Ws] are copper losses in the rotor, J [kgm ^{2}] is the moment of inertia and ω [rad/s] is the angular speed. With load the situation becomes worse. It is clear that speed changing is the right solution for reducing losses in dynamic states.

Variable speed is obtained with frequency and voltage power converters, usually of indirect type with DC circuit, called voltage source inverters (VSI). Power electronics converters are also consumers of reactive energy, because of switches nonlinearity. So, in indirect frequency converters the rectifier consumes reactive power from the grid and reactive power is generated in the circuit of the inverter and the motor, because DC circuit does not cross reactive power. The solution of these problems is in using condenser banks and filters, passive or active. However, consumption of reactive and disturbance energy (according to DIN 40110) in power converters is neglected. Objectively this consumption exists and it is approximately a few percentage of the active energy consumption, without costs for condenser banks and filters.

In Fig. 2 [4] conventional pumping system (a) and energy efficient pumping system (b) are presented with their total efficiency 31% and 72%.

The greater initial investment is covered in short period with evident energy saving possibilities [18], [19], [20], [21], [22], [23], [24], [25,], [26], [30].

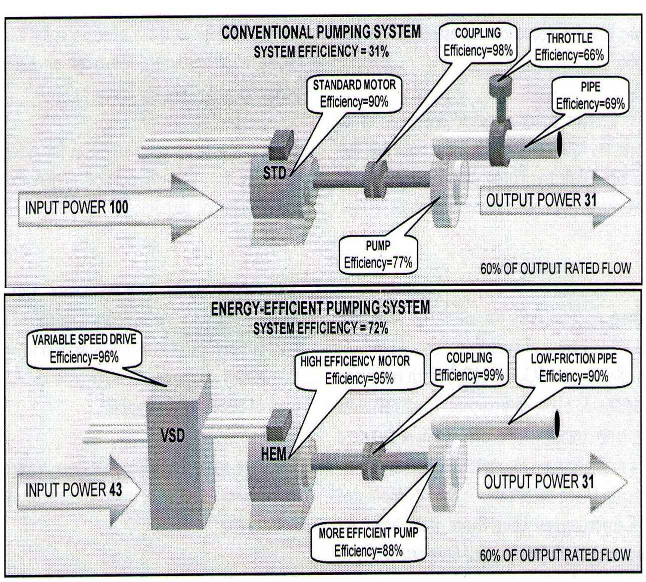

Fig. 2. Conventional pumping system 31% (a); Energy-efficient pumping system 72% (b), [4].

III. Induction Motor

The low voltage induction squirrel cage motor is superior to other types of motors because of its good technical characteristics (torque, current, overloading), smaller dimensions and mass, so as lower price. In the power range up to a 100 kW it is a serial product and standards already define the categories of motors with respect to their efficiency [7], [8], [27], [28], [31].

A. *Efficiency η*

The concept for increasing the efficiency of the motor is to reduce power losses and at the same time achieve all other required characteristics of the machine. The tendencies are directed towards standardization of the values of efficiency required in advance. The efficiency of electric motors can be improved by: a) Reducing the losses in the windings, which is done by increasing the cross-sectional area of the conductor or by improving the winding technique to reduce the length; b) Using better magnetic steel; c) Improving the aerodynamics of the motor; d) Improving manufacturing tolerances. Assuming that we have applied all the knowledge in machine design to reduce power losses in an induction motor (sizing of the air-gap, shape and number of slots, magnetic wedges, optimal choice of the cooling fan, squirrel-cage made of copper instead of aluminium etc.), the possibility of further reduction of losses is by increasing the motor size within reasonable limits (motor frame size, shaft height).

Using the scaling laws for design of electric machines [8], [9], the equation for efficiency η can be obtained

$$\eta = \frac{P}{P + k_{Cu1}a^{(2n\text{-}5)} + k_{Fe1}a^{(3\text{-}2n)} + P_{meh} + P_{dod}} \tag{3}$$

where P is the rated mechanical shaft power and P_g are the total losses in the motor which consist of the stator and rotor copper losses P_{Cu}, the iron losses P_{Fe}, the friction and windage losses P_{meh} and the additional losses $P_{dod} = 0{,}005\ P_1$ (P_1 is the electric power input from the grid) which are the four addends in the denominator of eq. 3. It is assumed that mechanical losses due to friction and windage will not change significantly due to increased dimensions.

The variation of efficiency is a function of changes of linear dimensions a (max 2) and of the exponent n (0-2), according to scaling laws for specific magnetic load B=(0,4-1,2) [T] and specific electric load $\Gamma<3\ 10^6$ [A/mm^2]. Let assume that we have induction motor with following ratings 22 kW, 380 V, 50 Hz, $2p = 2$, $P_{Fe} = 597$ W, P_{Cu} =1098 W, P_{meh} = 870W, P_{dod}=110 W. Using eq. (3) we can obtain the curves in Fig. 3 which showing efficiency η as a function of changes of linear dimensions a and of the parameter n for the motor.

The electric energy saved due to increased efficiency of an electric motor can be calculated from

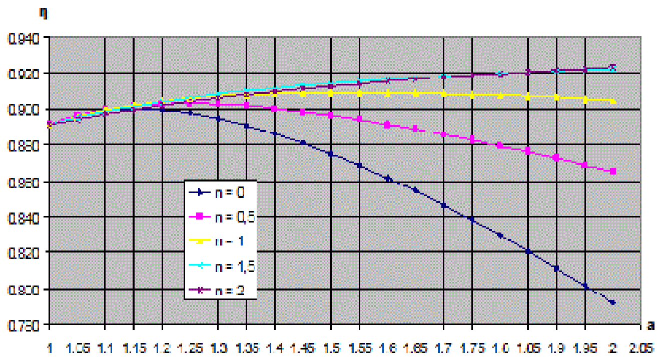

Fig. 3. Family of curves showing efficiency η as a function of changes of linear dimensions a and of the parameter n for the motor.

$$\Delta W_{year} = P_r\, t_r \left(\frac{1}{\eta_n} - \frac{1}{\eta_v} \right) \quad \text{kWh} \tag{4}$$

where ΔW_{year} is the annual energy savings in kWh, P_r is the actual power load in kW, t_r is the number of operating hours per year, η_n is the lower efficiency of the motor and η_v is the higher efficiency.

Let us consider a realistic case with presented motor. If dimensions are increased by 25% (a = 1,25), in Fig. 3 is shown that the efficiency can be increased at maximum from 0,89159 to 0,90611, i.e. by 1,452%. The annual energy savings thus obtained is 2016,6 kWh. If the exploitation period of the motor is 20 years, the total energy savings equals 40332 kWh. If the average price of electric energy is 0,05 EUR/kWh, the annual savings amounts to 100,83 EUR, and during exploitation period of 20 years it equals 2016,6 EUR.

Motors with improved efficiency are called "High Efficiency Motors" or HEM. Three energy efficiency classes are proposed, Fig. 4, [1], [3], [7], [8], [11], [12], [13], [27], [28], [31]. The fourth class IE4 - Super Premium as informative is also proposed. It is clear that better efficiency is result of greater dimensions (eq. 3) and therefore the price of HEM is greater. The range of payback on individual motors is between several months and several years [4].

In [29] the impact of different lubrication oils on electric motor energy consumption is given.

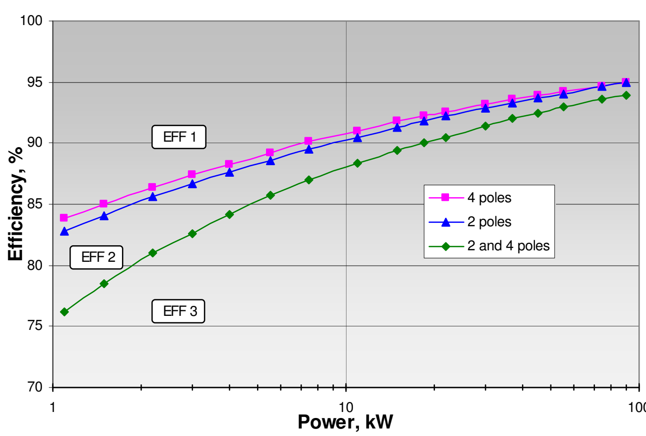

Fig. 4. Efficiency of induction motors according to EuroDEEM classification.

In [32] possibilities for enhancing reliability and efficiency are considered.

B. *Power factor k*

Reactive power is necessary for induction motor because of magnetization and maintaining the alternating magnetic field. Power factor is the ratio $k = P$[kW]/S [kVA] and it is different from $\cos\varphi$ because of harmonics. The equality is only for ideal sinusoidal supply or $\cos\varphi$ relates to basic harmonic. In Fig. 5 a) and b) $\cos\varphi(P)$ for $2p$ = 2, 4, 6 and P = (0-90) [kW] for induction motors according [11] and [15] are presented. In Table I the values of $\cos\varphi$ for different powers of catalogue and speeds of 3000 [min^{-1}], 1500 [min^{-1}] and 1000 [min^{-1}] are shown. Power factor k depends on ratio $\mu = Q$ [kVAr]/ P[kW], which is better to be lower [10].

$$\mu = Q/P = gp/D \tag{5}$$

where g [m] is air gap between stator and rotor, p is number of pair poles and D [m] is diameter of the stator. It is clear that machines with greater power and greater speed have greater power factor (Fig. 5).

It should be note that power factor is mainly less than 0,9. It means that condenser banks are needed or reactive energy must be paid. In any case, there are certainly costs for reactive energy.

IV. Conclusion

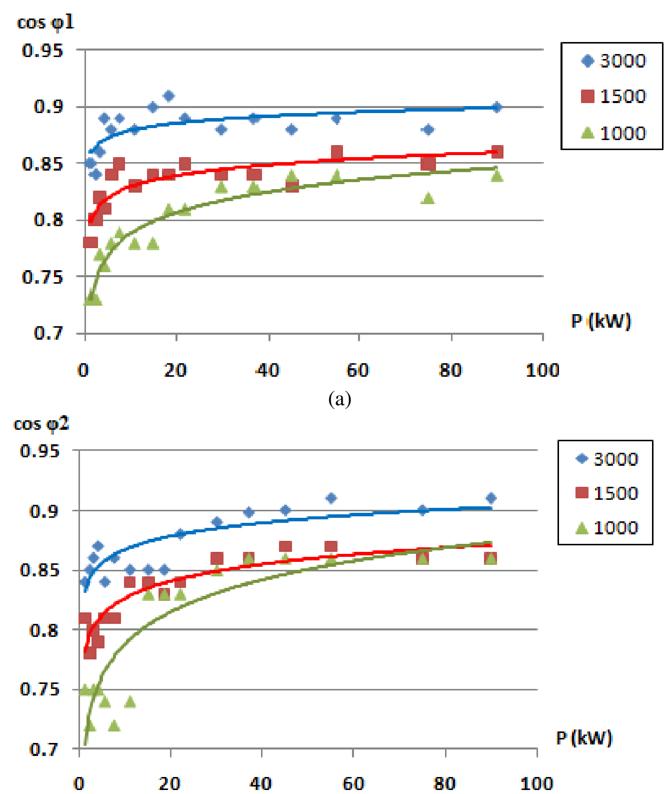

Fig. 5. Power factor ($\cos\varphi$) of fully loaded IM in function of power for different speeds: (a) – ABB ($\cos\varphi 1$), (b) – SIEMENS ($\cos\varphi 2$).

TABLE I
VALUES OF COSΦ IN FUNCTION OF POWER FOR DIFFERENT SPEEDS
(1 – ABB; 2 – SIEMENS)

$n[min^{-1}]$ / P[kW]		1.1	3	5.5	11	15	22	30	45	55	75	90
3000	cos φ1	0.85	0.86	0.88	0.88	0.90	0.89	0.88	0.88	0.89	0.88	0.90
	cos φ2	0.84	0.86	0.84	0.85	0.85	0.88	0.89	0.90	0.91	0.90	0.91
1500	cos φ1	0.78	0.82	0.84	0.83	0.84	0.85	0.84	0.83	0.86	0.85	0.86
	cos φ2	0.81	0.80	0.81	0.84	0.84	0.84	0.86	0.87	0.87	0.86	0.86
1000	cos φ1	0.73	0.77	0.78	0.78	0.78	0.81	0.83	0.84	0.84	0.82	0.84
	cos φ2	0.75	0.75	0.74	0.74	0.83	0.83	0.85	0.86	0.86	0.86	0.86

The cost of electric energy during the exploitation period of the motor can be from 100 to 200 larger than the price of the motor [8].

Reactive and disturbance energy cannot be neglected in considerations in energy efficiency, as it is usually done.

Electric drives have great saving potential with total 202 billion kWh/year, equvalent to a reduction of 10 billion EUR per year in operating costs for industry. It would also create the following additional benefits:

- a saving of 5-10 billion EUR per year in operation costs for industry through reduced maintenance and improved operations (EU-25),
- a saving of 6 billion EUR per year in reduced environmental costs (EU-25),
- a reduction of 100 million tonne of CO_2 equivalent emissions, or approximately 30% of the EU's Kyoto target of 336 million CO_2 eq. (EU-25),
- a 45 GW reduction in the need for new power plant over the next 20 years (EU-25),
- a 6% reductions in EU's energy imports (EU-25), [4].

To achieve this a 4 year (2008-2012) package of measures is suggested, investing 400 million EUR in the electric drives market [4].

The package of measures should include stimulation of industry through national governments solutions and financial support for wide education and training possibilities in universities and industry.

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