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Control Methods for Efficiency Optimization of Electrical Drives-Present Trends and Perspectives

Invited Paper

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Abstract - The paper gives an overview of methods for efficiency optimization in electric drives. A historical overview of these method is given and in a more detailed actual trends are described through presented control models, simulation and experimental results. Possible directions for further research and the challenges in this field are also given in the paper.

Keywords - efficiency optimization; model based methods; search control; hybrid methods; fuzzy logic controller; artificial neural networks; energy storage

NOMENCLATURE

R_s, R_r	Resistance of stator and rotor winding
L_s, L_r	Self inductance of stator and rotor
L_m	Magnetizing inductance
P	Number of pole pairs
ϑ_s, ω_s	Rotor flux angle and angular speed
ϑ_m, ω_m	Rotor angle and angular speed
ω_r	Slip speed
s_m, L	Position
T_{em}	Electromagnetic torque
T_L	Load torque
Ψ_{sd}	Magnetizing flux
i_{sd}, i_{sq}	d and q component of stator current vector

I. INTRODUCTION

In the last 10 years, the use of electric drives has been increasing, from simple drives such as pumps, compressors, fans (heating, ventilation, air conditioning-HVAC), to high-performance servo drives which are characterized by fast response, precision and a wide range of regulated speed. Due to its simple control characteristics, for a long time the DC motor was irreplaceable in the controlled electrical drives. The relatively complex control algorithms and the need to calculate the rotate transformations made it impossible to use induction motor (IM) in servo applications. However, since the late of 1990s, the use of IM and permanent magnet synchronous motor (PMSM) in servo systems has been made possible by the use of digital systems such as microprocessors and microcontrollers, and modern power converters based on pulse-width modulation and space vector modulation [1-3]. Concept vector control, or direct torque control is generally used in IM and PMSM drives [4-7]. Also, in IM drives scalar control is also used.

It enables speed control of the by varying the supply frequency, so the ratio voltage per frequency (V/f) is constant. In this way, the torque characteristic of the motor is displaced and it is possible to regulate the rotor speed over a wide range of speeds. But with scalar control, torque cannot be directly controlled, so it is not applicable to high-performance electric drives. In high-performance drives, vector control and direct torque control are predominantly used. So, the torque and magnetizing flux can be directly controlled. The implementation of such control requires complex calculations in order to set torque and flux commands, and more complex control of the drive converter.

Very interesting research topic is efficiency improvement of electric motor drives. Considering that in industrialized countries, these drives consume more than of 2/3 of the total consumed electrical energy in industry, this issue becomes more relevant. This trend of energy efficiency improvement and the increasing presence of regulated electric drives in the industry have influenced the development of numerous methods for increasing efficiency in drives with an induction motor.

Electrical losses in an electric motor drive are calculated as the difference between the input power to the drive and the output power delivered to the mechanical subsystem. Function of these losses in the general case is a nonlinear and non-stationary function. It depends on several factors: frequency, heating, groove shape, power supply, etc. There are also additional losses, which cannot be predicted and calculated in advance. These are all reasons why optimization model should be non-linear and adaptive. In the recent years, in the implementation of such algorithms, fuzzy controllers, neural networks, or their integration in the form of neuro-fuzzy controllers have been increasingly used [8-11]. Their advantage in such applications is reflected in their non-linear structure and adaptive character. Also hybrid methods which combine different strategies for efficiency optimization become more interesting [12-16].

Today, there are a numerous number of strategies for efficiency improvement in electric motor drives. Regardless of the used method, the goal is unique; For the given operating conditions, determine the drive control so the drive operates with minimal losses. Algorithm should be fast and independent of the motor parameters variations.

Energy efficiency improvement in industrial processes is very significant in the field of horizontal and vertical

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transportation. So, there are significant opportunities for increasing efficiency in electric motor drives, since the movement of the controlled object is along a known trajectory. Examples are the various conveyors and elevator drives [17 - 26]. These drives often operate in generator mode, so there is considerable potential for energy recovery and storage. Although there is a significant number of the papers that addresses these issues, the problem has not been adequately solved and it is an open subject for research.

Organization of paper is as follows: Short description of power losses is given in second section. Review and comparison of different method for efficiency optimization are described in third section. Application of fuzzy controller and neural networks in methods for efficiency improvement of electric drives are presented in fourth section. Energy efficiency improvement in elevator drives and the possibility for energy recuperation and energy storage are given in the fifth section. Some results and interesting areas for further research are summarized in the conclusion.

II. DESCRIPTION OF POWER LOSSES IN ELECTRIC DRIVES

During the energy conversion in electrical motor drive, one part of input energy converts in power losses in the converter and the electrical motor. So, power losses in electrical drives consist of converter losses, and motor losses (copper losses, iron losses and other "secondary" losses). From the practical reasons these losses are described in d-q coordinative system.

Converter losses: Main constituents of converter losses in the typical electrical drive topology are the rectifier, DC link and inverter losses. Rectifier and DC link losses are proportional to output power and these losses are not dependant from the magnetization flux. The flux-dependent losses in converter are inverter losses. These are usually given by:

$$P_{INV} = R_{INV} \cdot i_s^2 = R_{INV} \cdot \left(i_{sd}^2 + i_{sq}^2 \right). \tag{1}$$

Motor losses: These losses consist of hysteresis and eddy current losses in the magnetic circuit (iron losses), losses in the stator and rotor conductors (copper losses) and stray losses. The main core losses can be modeled by

$$P_{Fe} = c_h \Psi_{sd}^2 \omega_e + c_e \Psi_{sd}^2 \omega_e^2 , \tag{2}$$

where c_h is hysteresis and c_e eddy current core loss coefficient.

Copper losses depend on the effective value of current through the stator and rotor windings and these can be expressed as:

$$p_{Cu} = R_s i_{sd}^2 + R_r i_{sq}^2 , \tag{3}$$

The total secondary losses (stray flux, skin effect and shaft stray losses) usually don't exceed few percent of the overall losses [3]. Therefore, these losses are usually omitted in the methods for efficiency optimization based on the loss model.

Based on previous consideration, total flux dependent losses in the drive can be given by the following expression:

$$P_\gamma = \left(R_{INV} + R_s \right) i_{sd}^2 + \left(R_{INV} + R_s + R_r \right) i_{sq}^2 + c_e \omega_e{}^2 \psi_{sd}^2 + c_h \omega_e \, \psi_{sd}^2 . \tag{4}$$

In the methods for efficiency optimization motor works with the flux which is less or equal to its nominal value. So we can suppose that during efficiency optimization procedure magnetization characteristic is linear. Based on expression (4) it can be concluded that losses in the electrical drive depend on the current in stator and rotor windings, electrical frequency and level of magnetization flux.

III. METHODS FOR EFFICIENCY OPTIMIZATION IN ELECTRICAL DRIVES

Efficiency optimization algorithms are based on the adjusting magnetization flux to drive load. In this way, at lower loads, magnetization flux is also lower so the balance between the copper losses and the iron losses is achieved and total losses are reduced.

Also, it should be taken into account that the reduction of the magnetization flux degrades the dynamic characteristics of the drive. If maximum drive performance is required, the flux should be at nominal level. This should be taken into account when methods for efficiency optimization are applied.

There are many methods for efficiency optimization in electrical drives and they are usually classified in 4 strategies [2]:

- Simple State Control (SSC) ,
- Loss Model Control (LMC) and
- Search Control (SC)

Also, there are methods which can't be classified in one strategy, but combine characteristics of two strategies. These methods are usually known as hybrid methods (HM).

A. Simple state control

The first strategy is based on the control of one of the variables in the drive. This variable must be measured or estimated and it is used in the feedback control of the drive. Slip frequency or power factor displacement are often used variables in this control strategy. This strategy is simple but gives good results only for a narrow set of working conditions. Also, it is sensitive to variations of motor parameters due to temperature changes and nonlinearity of the magnetic circuit.

B. Loss Model Control

A good feature of loss-based model methods is that they are fast and the optimal flux is determined directly from the model. Because of this, they are often applied, especially in electric drives that have faster dynamics. Taking into account expression for electromagnetic torque in steady-state:

$$T_{em} = \frac{3}{2} P \frac{L_m^2}{L_r} i_{sd} i_{sq} \,, \tag{5}$$

and expression (4), power losses can be expressed as a function of magnetization current i_{sd} and working conditions ω_e, T_{em}:

$$\begin{aligned} P_\gamma &= \left(R_{INV} + R_s + c_e \omega_e^2 L_m^2 + c_h \omega_e^2 L_m^2\right) i_{sd}^2 \\ &+ \left(R_{INV} + R_s + R_r\right) \frac{T_{em}^2}{\left(\frac{3}{2} p \frac{L_m^2}{L_r}\right)^2} \frac{1}{i_{sd}^2} \end{aligned} \,, \tag{6}$$

Putting $A = R_{INV} + R_s + c_e \omega_e^2 L_m^2 + c_h \omega_e L_m^2$ and $B = \left(R_{INV} + R_s + R_r\right) \frac{T_{em}^2}{\left(\frac{3}{2} p \frac{L_m^2}{L_r}\right)^2}$ from (6) expression for power losses can be given as follows:

$$P_\gamma = A i_{sd}^2 + \frac{B}{i_{sd}^2} \,. \tag{7}$$

Minimization of losses is calculated from the condition $\frac{\partial P_\gamma}{\partial i_{sd}} = 0$ which gives:

$$2 A i_{sd} - \frac{2B}{i_{sd}^3} = 0 \,. \tag{8}$$

Based on (8), the reference value of the magnetization current (i_{sd}^*), which gives minimal losses for the given working conditions is:

$$i_{sd}^* = \sqrt[4]{\frac{B}{A}}. \tag{9}$$

Block diagram of loss model control implemented in induction motor drive is presented in fig 1.

Based on loss model, and working conditions, values of control variables i^*_{sd} and i^*_{sq} are generated. The main drawback of the model is that it takes into account only the most significant sources of losses in the electric drive. Also, it is sensitive to parameter variations in the model especially due to changes in temperature and nonlinearity of the magnetic circuit. Beside all, this strategy is very popular. Control variables are generated fast and directly from loss model so this method can be use even in cases frequent change of working conditions.

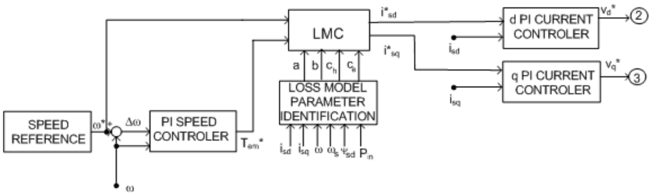

Fig. 1. Block diagram of loss model strategy implemented in induction motor drive.

C. Search Control

Application of SC methods is very simple. For two successive values of the i_{sd} current, power losses are determined as difference between input and output power of the drive:

$$P_\gamma(n) = P_{in}(n) - P_{out}(n). \tag{10}$$

$P_\gamma(n)$ is value of power losses in last sample (nT_s) , where T_s is sample time.

Sign of Δi_{sd} is maintained if power losses are reduced. Otherwise, the sign of Δi_{sd} is opposite in the next step:

$$i_{sd}(n) = i_{sd}(n-1) - \mathrm{sgn}\left(\Delta P_\gamma(n-1)\right) \Delta i_{sd} \,. \tag{11}$$

Value of Δi_{sd} is usually determined to be proportional of P_γ. It means if $P_\gamma(n)$ is greater, then $\Delta i_{sd}(n)$ is greater and vice versa. Block diagram of search control strategy is presented in fig.2.

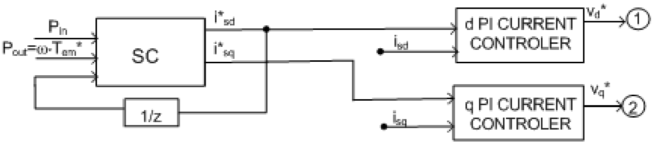

Fig. 2. Block diagram of search control strategy implemented in induction motor drive.

Search strategy methods have an important advantage compared to other strategies. These methods are not sensitive to parameter variations in the motor. Also, these methods are applicable universally to any motor. Besides all good characteristics of search strategy methods, there is an outstanding problem in their use. Flux convergence to the value which gives minimal losses can be slow for drives with higher dynamic requirements. Also, magnetization current oscillates in small steps around its optimal value it.

D. Hybrid Methods

Hybrid method usually combines characteristics of two optimization strategies SC and LMC [14-15]. It is an interesting solution and it is expected to be more used in the future. During transient process LMC is used, so fast flux changes and good dynamic performances are achieved. In a steady state search algorithm is applied. In that case parameter variations has not significant influence to method for efficiency optimization. Control diagram for the hybrid optimization method is presented in fig 3.

In hybrid methods block which determines steady state of the drive is usually used. So, for a steady state this block changes optimization control from LMC to SC and vice versa when working conditions are changed.

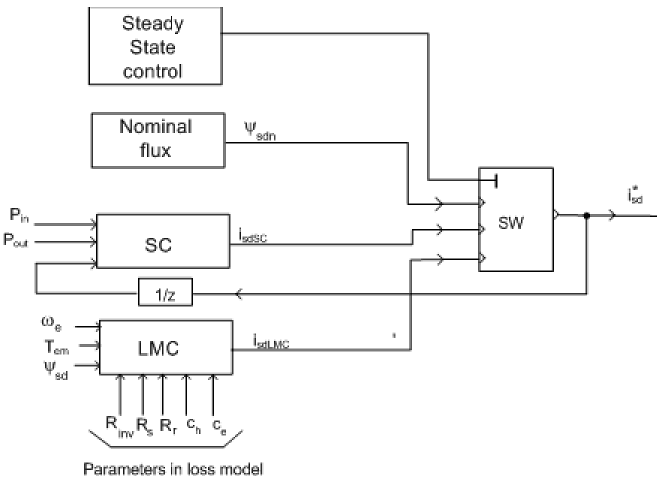

Fig. 3. Block diagram of hybrid control method implemented in induction motor drive.

IV. IMPLEMENTATION OF FUZZY LOGIC AND ARTIFICIAL NEURAL NETWORKS IN METHODS FOR ENERGY EFFICIENCY IMPROVEMENT OF ELECTRICAL DRIVES.

One of the outstanding problem in all methods for efficiency improvement is that they are sensitive to fast change of working condition. Reduction of the magnetization flux degrades the dynamic characteristics of the drive. This is presented in fig 4. For a step change of load torque speed drop is much more expressed when motor works with lower then for nominal flux. Speed response on the step change of load torque (from 0.5 p.u. to 1.1 p.u.) at t=25s, for nominal flux and when LMC method is applied, is presented in the fig. 4. That is reason why it is necessary maintain torque reserve in the methods for efficiency improvement, especially in the applications where output power changes are more frequent. The loss model is nonlinear. It is not possible to predict and take into account all the factors that affect to losses. Also, many parameters in the model are sensitive to parameter variations in drive due to temperature, saturation of the magnetic circuit, skin effect, etc. The reserve of the electromagnetic moment also should be taken into account. Based on this, it can be concluded that it is convenient to implement fuzzy controller in methods for efficiency improvement (fig. 5).

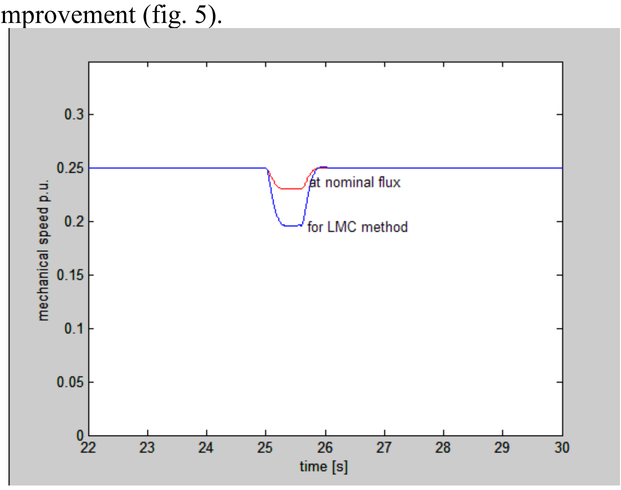

Fig. 4. Block diagram of hybrid control method implemented in induction motor drive.

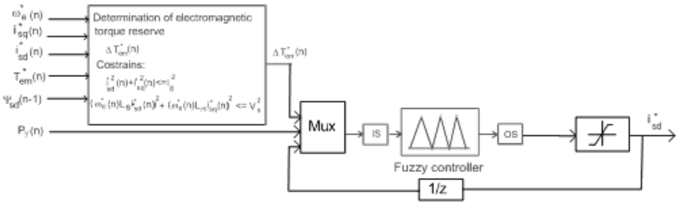

Fig. 5. Implementation of fuzzy controller in methods for efficiency optimization of electrical drives.

Fuzzy controller can be applied for both SC and LMC methods. Based on electromagnetic torque reserve, last sample of the calculated power losses and magnetization current, new value of magnetization current is determined. Electromagnetic torque is determined based on maximum torque which can be achieved for the current flux level in the motor and taking into account constrains for current and voltage (fig. 5). Fuzzy set has 12 rules, 3 inputs and 1 output. Mamdani type of fuzzy inference and centroid defuzzification method are used. For the working condition presented in fig. 6. obtained speed response and power losses are presented in Figs. 7 and 8.

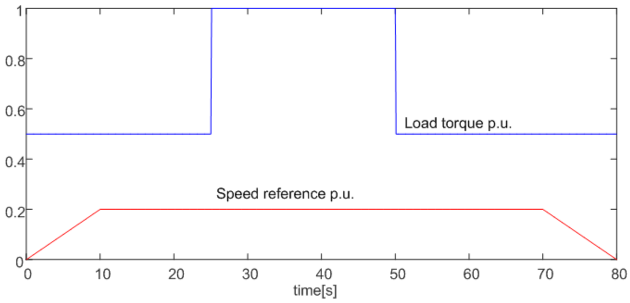

Fig. 6. Graph of mechanical speed and load torque reference.

Reference value of mechanical speed is set to 0.2 p.u. For low speed, drive is more sensitive to step change of load torque. So, control of electromagnetic torque is very important in efficiency optimization methods when drive works with low speed. It is obvious that electrical drive is more robust on the step change of load when electromagnetic torque reserve is included in method for efficiency improvement (fig. 7). But in this case the losses are slightly higher for low loads (fig. 8).

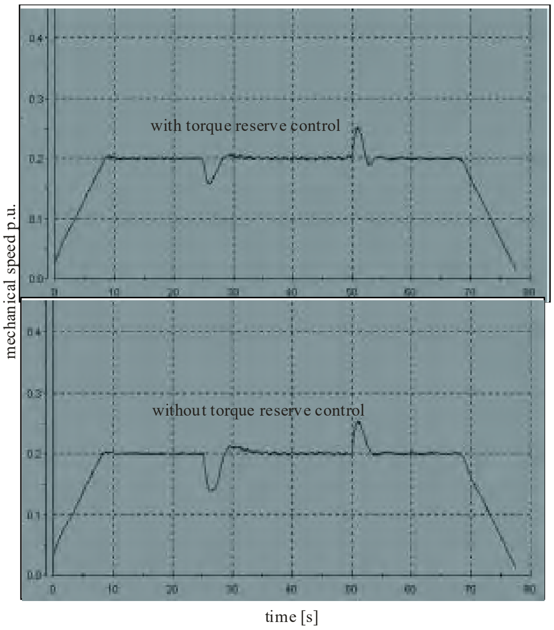

Fig. 7. Speed response for a given working conditions when LMC is applied with torque reserve and without torque reserve.

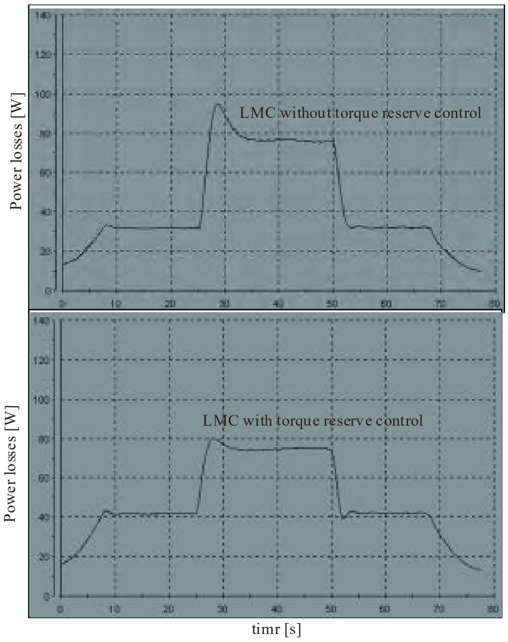

Fig. 8. Power losses for a given working conditions when LMC is applied with torque reserve and without torque reserve.

Therefore, it is necessary to maintain balance between efficiency optimization and torque reserve in order to keep good dynamic characteristics of electrical drive. More recently, neural networks have been used for faster SC methods and maintain electromagnetic torque reserve. The Hybrid method for efficiency optimization with ANN is shown in fig. 9.

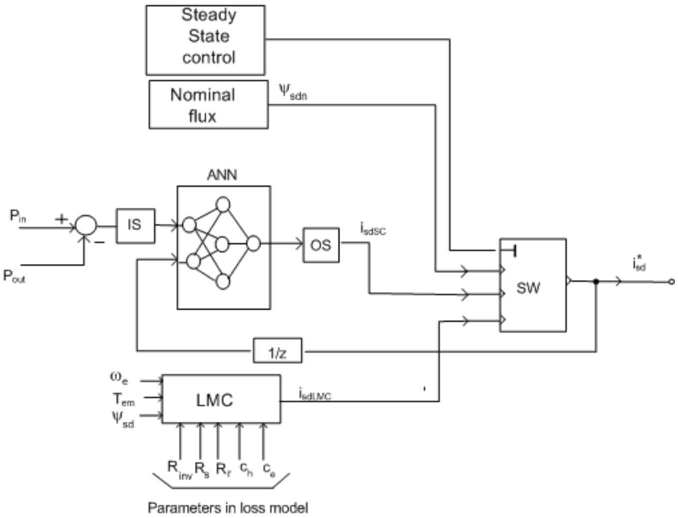

Fig. 9. Hybrid method for efficiency optimization with ANN.

ANN is used for the implementation of SC method in hybrid system for efficiency improvement. The neural network has 2 inputs, 1 output and 2 hidden layers with 7 and 5 neurons respectively. The transfer functions of the neurons in the hidden levels are sigmoidal (tansig) and the output level linear (purelin). The Levenberg-Marquardt method is used to train the network. The performance index target value is set to $5*10^{-4}$. The qualitative analysis of the network operation gives the dependence of the performance index and the mean-square error as a function of the learning epochs number. Also, for the defined working conditions of the drive (fig. 6), a trajectory of the current reference value i_{sdSC} was generated using a neural network (fig. 10), and the speed response and loss power for the nominal flux and for the hybrid method with ANN were compared and obtained results are presented in figs. 11 and 12 respectively.

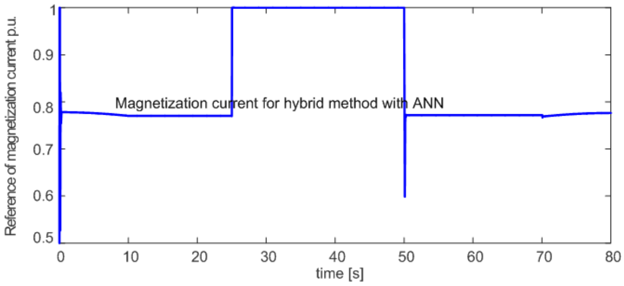

Fig. 10. Magnetization current generated in sc with ANN and for given working conditions presented in fig.6.

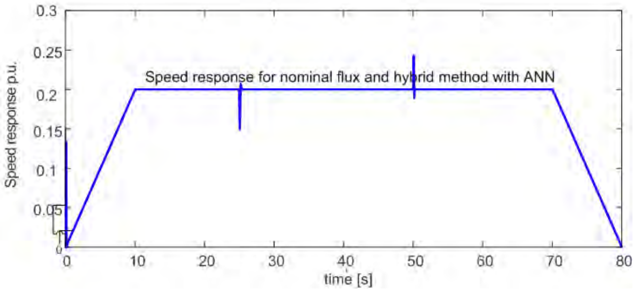

Fig. 11. Speed response for nominal flux and for hybrid method with ANN and for given working conditions presented in fig.6.

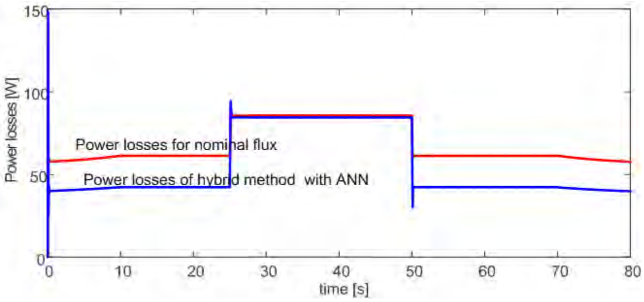

Fig. 12. Power losses for nominal flux and for hybrid method with ANN and for given working conditions presented in fig.6.

The obtained results show that the application of ANN in efficiency optimization is justified. Good results are achieved in maintaining good dynamics of the electric drive, but also in efficiency improvement.

V. EFFICIENCY OPTIMIZATION IN ELEVATOR DRIVES, ENERGY RECUPERATION AND STORAGE

The standard topology of the indirect AC/AC converter controlled elevator drives, consists of a diode rectifier, DC link, and a three-phase PWM controlled inverter. Such topology has many drawbacks and does not allow bidirectional power flow and energy recuperation.

Elevator drives often work in generator mode, so it is convenient object for efficiency optimization improvement and energy recuperation and storage. In that case units for energy storage are necessary. Usually, supercapacitors are used, due to fast charging and discharging. In this application converters which provide bidirectional power flow, and appropriate control units which automatically control the working are required. These applications must not affect to elevator ride, jerk, speed, positioning and the comfort of passengers.

One concept of efficient elevator drive with the unit for energy storage is shown in fig. 13 [22]. It consists of two tree phase back to back converters and a digitally controlled switch unit. Three phase power supply is connected with the voltage oriented control (VOC) PWM rectifier. This rectifier obtain good control of DC voltage and phase control between input voltage and current (PF≈1) (fig.13). Total harmonic distortion of input current is low. This rectifier is connected to unit switch over DC link from one side and three phase inverter from the other side. Space Vector Modulation (SVM) technique is used for inverter control. Such topology provide possibilities for the implementation of advanced control strategies like VC or SVM. The basic parameters are monitored on the storage unit; DC voltage, charging /discharging current and the capacity, i.e. state of charge (SOC), status of the main supply and the working mode of elevator motor (motor, generator).

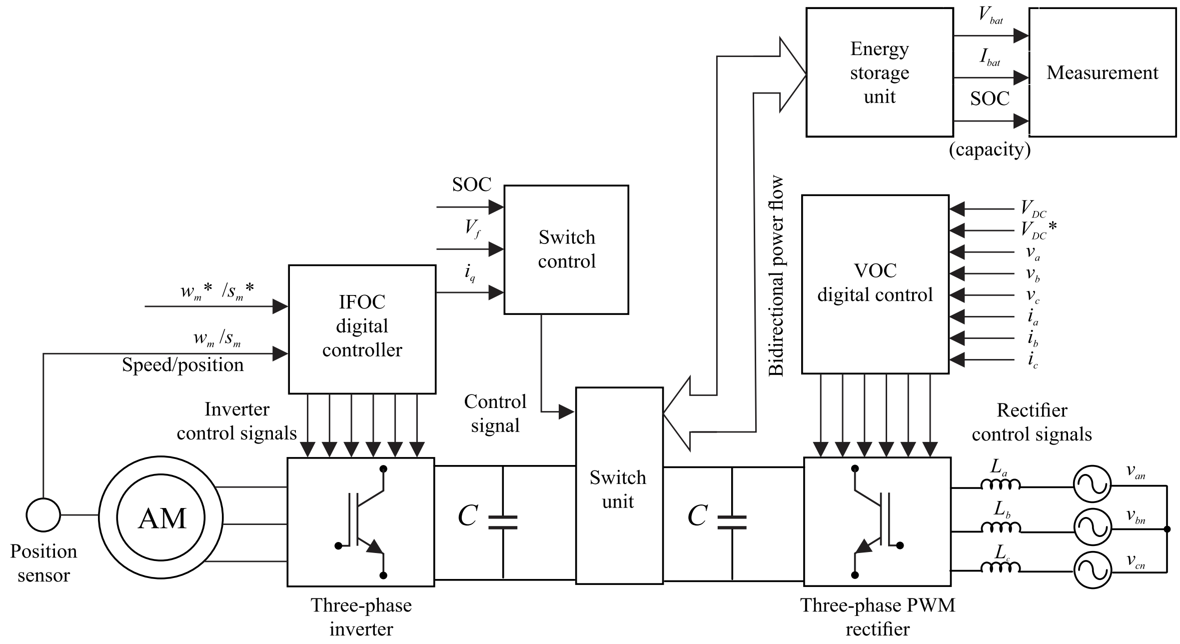

Fig. 13. One concept of elevator drive with the energy storage unit [22].

If the motor works in the generator mode and the storage unit is not full, switch is turned so the storage unit is charged with the regulated current (fig. 15). In the case of a main power failure, storage unit is used as auxiliary power supply. This process is fast and automatically realized (Fig. 16). Any changes in the operation mode are fast and from the standpoint of the elevator user seamlessly.

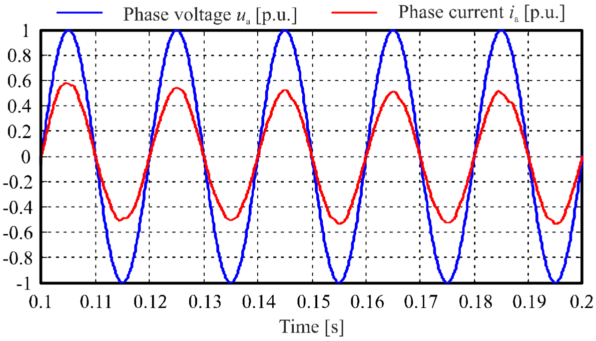

Fig. 14. Input phase voltage and current of PWM rectifier in elevator drive.

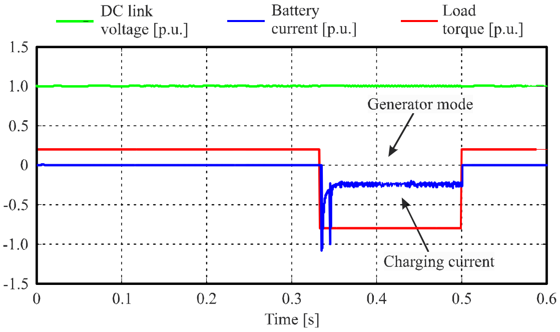

Fig. 15. Charge of energy storage unit in generator mode of elevator drive [22].

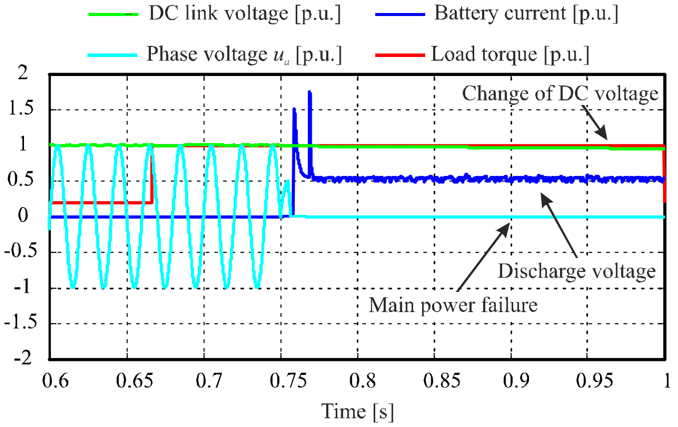

Fig. 16. Discharge of energy storage unit in a case of main power failure [22].

Studies and measurements on such elevator drive in the elevator operation show that the concept is interesting and it gives good results. Also, load perturbations or changes in operating modes have no effect on maintenance of the elevators' performance. Beside the step change of load and changes in operating modes, the elevator keeps defined speed and motion trajectories.

VI. CONCLUSIONS

The paper describes some of the interesting topics related to efficiency optimization of electric drives.

Based on content presented in the paper, the following conclusions can be drawn:

1. Controlled electric drives are suitable for implementation of methods for energy efficiency improvement.
2. In many HVAC applications it is possible to apply simple methods for efficiency y improvement, whose implementation is purely software.
3. In applications where speed and torque change more frequently, methods based on loss model and search algorithms may be used.
4. Hybrid methods, which combine the merits of loss-model based methods and search algorithms are also become more popular (fig. 3).
5. Elements of artificial intelligence, neural networks and fuzzy logic are increasingly used in methods for efficiency optimization and improve characteristics of these methods (figs. 7, 8, 10-12)

6 Horizontal and vertical transport systems are also of interest from the standpoint of energy efficiency. In addition to increasing efficiency in motor mode, it enables energy recovery and storage in generator mode. A model of one elevator system with the elements for efficiency improvement and energy storage is also presented in the paper (figs. 14-16).

APPENDIX

U_n = Δ220/Y380 V I_n = 3.6/2.1 A
P_n = 0.75 kW cosφ = 0.72
n_n = 1390 rpm f_n = 50 Hz
R_s = 10 Ω R_r = 6.3 Ω
$L_{\gamma s}$ = 43.067 mH $L_{\gamma r}$ = 40.107 mH
L_{mn} = 0.4212 H J_m = 0.00442 kgm^2

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