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REVIEW OF METHODS FOR ENERGY-EFFICIENCY IMPROVEMENT IN INDUCTION MACHINES

Purpose. To present a comprehensive analysis of domestic and foreign experience regarding the existing optimization techniques in the problems of the power losses minimization in electromechanical systems with an induction machine for reduction of the total electricity consumed from the grid.

Methodology. A detailed study of the developments in the field of efficiency optimization of three-phase induction machines through optimal control and design techniques has been done. Special attention is given to vector-controlled systems. Sustainable development of a few trends was traced in this domain. The reference value of the field-generating current is an additional degree of freedom in the mathematical model of the investigated system. It influences the magnetic flux linkage dynamics and mechanical torque equations. Hence, the implemented model allows for a comparative analysis of different approaches to ensure minimum energy consumption with an adequate intensity of transients.

Findings. Among numerous control techniques, simple state control, loss model-based control and search control efficiency optimization algorithms have been highlighted. The simulation example on efficiency optimization of an asynchronous machine was performed in the framework of an indirect field-oriented control system considering the stepped trajectory of load torque, which is possible as a result of mechanical perturbation or when the motor performs complex speed profiles or counteracts shock loads.

Originality. The rigorous review indicates that existing optimization algorithms in conventional still can be used for induction motor drive applications. However, some existing problems in achieving the best control were not summarized. Accordingly, for the first time, this review provides suggestions for the future research and development of dynamic energy-efficient control in induction motors.

Practical value. The three-phase induction motor drives are a nonlinear system that is tough to describe precisely theoretically due to their sudden changes in conditions of operation mode and parameter variation. Thus, advanced algorithms are needed to enhance their performance in addition to effective hardware solutions. The suggested alternative solution will hopefully lead to increased efforts toward the development of advanced control systems for future applications.

Keywords: *induction machine, energy efficiency, optimization algorithms, dynamic operation, predictive control*

Introduction. In the face of the energy crisis, the world is slowly awakening to the problems of global energy conservation, increasing energy demands, and limited resources in nature. These environmental issues have driven efficiency improvement in all aspects of electrical engineering. It is estimated that around 50 % of the electrical energy generated worldwide is consumed by electrical motors, mainly by induction motors [1]. Given the wide range of applications and heavy use, the research towards minimization of the electric power consumption is always relevant, and an introduction of minor improvements brings tangible global economic effects.

Literature review. In industry, the demand for variable speed electrical drives has been continuously increasing during the last decades in a variety of applications from a few watts for small servo-motors up to several hundreds of kilowatts. Rotating field AC machines are known since the very beginning of electrical machines existence, despite the fact that they possess remarkable robustness and low cost, these machines were very seldom used as their rotating speed changes with the frequency of the grid. Whereupon, electrical machines of such a construction were solely used where this feature was essential, for example, for fans where speed adjustment is not required.

Together with the advances of semiconductor technology, the opportunities to construct speed variable AC machines in a simple way enhanced. The task to operate the machine with any rotating speed was solved with the help of an inverter which gave a possibility to generate a three-phase supply voltage with variable frequency. Nevertheless, a dynamic control similar to DC machines, i. e. separate regulation of flux linkage and motor torque was unavailable. This task was solved with the development of the so-called field-oriented control. It was introduced by F. Blaschke in 1971 and has become an extremely popular control strategy. Nowadays it is state-of-the-art for asynchronous machines as well as for synchronous.

Currently, a major part of frequency converters implements vector control or even sensorless vector control. The basic principle of vector control is separate independent regulation of the motor magnetizing current and quadrature current which is proportional to the mechanical torque on the motor shaft. The magnetizing current determines the value of flux linkage of the rotor magnetic flux and keeps it on a certain level. In the case of the rotational speed stabilization, the quadrature current reference is generated by a separate PI-regulator, the input of which is equal to the mismatch between desired and measured rotational speed. Thus, the quadrature current is always set to a minimum level enough to maintain

the desired speed of the motor as well as mechanical torque. Due to that vector control of induction motors have high efficiency at rated speed and torque. However, it has a few drawbacks connected with operation in the part-loaded mode: the efficiency of the induction motor dramatically decreases if the magnetic flux is kept at the nominal level throughout the entire load range. This fact leads to over-excitation and excessive copper losses. Thus, the question of power loss minimization has gained importance in cases when a motor drive is operated in a much wider load range. Due to that, the question of overload potential of the induction machine has also gained importance recently [2].

The reduction of the electrical energy consumed by induction motors is particularly interesting in applications like conveyors and segments of the consumer market like heating, ventilation, and air-conditioning (HVAC). These applications consume a large part of the total energy consumed by induction motors. To reduce the power losses and thus increase the efficiency of the motor in such applications an abundant number of different energy-efficient control strategies have been developed as reviewed in papers [3, 4] and the references cited therein. The focus of these methods is on the minimization of the power losses when the machine is operated in stationary points over considerable time intervals. Hence, energy saving can be achieved by proper selection of the magnetic flux level in the motor [5]. The optimal choice of the magnetizing current makes field-oriented control a truly innovative method in energy saving. The improper magnetization current control can result in even greater power consumption though.

Undoubtedly, this review is not intended to be an exhaustive analysis of the selected problem, because annually an abundance of publications on the analysis and optimization of power consumption of electric drives appear at international conferences and in journals under review. According to IEEE, the total number of papers on the given subject matter is about several thousands, and there is no way to consider all of them. Work [6] can put in a claim for the biggest number of citations, around 2000 other entries. It presents a new quick-response and high-efficiency control of an induction motor, which fairly differs from the field-oriented control. The two most significant differences are as follows. Foremost, the proposed scheme is based on limit cycle control of flux and torque by means of optimum PWM output voltage; a special switching table for selecting the optimum inverter output voltage vectors is used in order to attain fast torque response, as well as a low inverter switching frequency and as low harmonic losses as possible. Secondly, the efficiency optimization in the steady-state operation mode is achieved by controlling the amplitude of the flux according to the torque command. The feasibility of this scheme was verified, and the results proved the excellent characteristics for torque response and efficiency. This scheme was found to be promising and superior in every respect to field-oriented control. The main drawbacks are the necessity of a nonlinear active filter and the effect of the variation of the machine constants.

As most recent works on the energy efficiency of induction motors [7–9] can be distinguished. In [7] the question of power consumption optimization of the positional asynchronous electric drive which works in short-time mode has been considered. It is shown that in such a system the unproductive power loss can be reduced by selecting an appropriate time of specified motion working-off in compliance with heat loss minimization criterion. In work [8] a novel control algorithm is proposed for induction motors in the field-oriented control system for the case of the motionless rotor by means of Euler's optimization equation for the copper losses minimization. The analysis of transient processes and algorithmic expressions showed that motor demagnetization and the pause following its magnetization during the intermittent duty increase the efficiency of the vector control system. However, this approach needs certain minimal pause time during intermittent duty

cycles to operate successfully. Paper [9] establishes generalizing scientific patterns, allowing us to obtain the parameters of the modes of the most energy-efficient operation of technological complexes. However, the technique was tested on pumping stations and conveyors only.

For the most part, it is difficult to call an actual publication of systematic or outline nature which would have been entirely devoted to the energy-efficient vector control. Especially exigency of such a work is felt while trying to analyze domestic publications on the given subject, the material of which is often very closely linked to the foreign works without explicit citation, i.e. authors come to the same or similar ideas in parallel without taking into account previous foreign experience.

A great number of minimum-loss control schemes have been reported previously. If one takes any of the recently published methods for minimizing power losses, it would be quite difficult to classify it to any specific type of existing approaches. However, initially, there were a few trends in this domain around which sustainable development can be traced. These schemes can be divided into three categories: 1) methods based on state control of the motor (simple state control); 2) methods using a model of power losses (model-based control, LMC); 3) methods of straightforward optimization (search control, SC).

Simple state control methods. The given methods were historically the first proposed to minimize power losses in an electric motor and originally were designed for frequency converters operating in scalar V/f mode. Methods of this class are based on the fact that if the machine is in a state of minimum power losses, then its electrical characteristics behave in a special way [10]. The simplest examples are the power factor $\cos\varphi$ and slip speed ω_{slip} , which have a constant value provided that the minimum power consumption is reached.

Power factor control. A strategy where the power factor is maintained at a constant level as energy-efficient control is U.S. patent No. US4249120A, 1981. There have been a lot of studies done in this area and publications written based on the patent. Further development of this method is obtained in papers such as [11] and [5]. Paper [11] shows that for an engine without saturation, the optimum value of the power factor $\cos\varphi^*$ which provides the minimum loss mode is a function of the engine parameters and rotation speed of the rotor shaft ω_2 and does not depend on the load torque on the shaft of the motor $\cos\varphi^* = f(\omega_2)$.

In [5] it is considered how to control the reference for the power factor $\cos\varphi^*$ using fuzzy logic methods, depending on the angular velocity of rotation on the motor shaft ω_2 . This method works satisfactorily with the saturation of the magnetic system of the motor. The value of the power factor $\cos\varphi^*$ remains almost constant at an adequate angular speed ω_2 , which allows for the method to be used in scalar control systems without a speed sensor. In this case the reference for the magnetizing current i_{1d} is obtained as follows

$$I_{1d} = PI[\cos\varphi^* - \cos\varphi],$$

where $PI[\dots]$ is the output of the PI controller, $\cos\varphi$ is the measured value of the power factor. The best dynamic performance is provided if $\cos\varphi$ is measured and calculated for every sample of the control system. Some authors have suggested varying $\cos\varphi$ reference as a function of speed and load. However, additional estimation of speed and torque greatly complicates the system with only marginal improvements.

Slip speed control. Numerically analyzed various indicators in the system of electric drive associated with the power losses are presented in [12]. As a result, it is possible to compare different energy efficiency criteria for the optimization problem. The sufficiently detailed model obtained from the measured experimental data was considered. The effects of saturation were taken into account. For the test, a standard 4-pole 2.2-kW motor (operating speed – 900 rpm, nominal speed – 1500 rpm)

was selected. The analysis of the presented dependences has shown that the slip speed cannot be an indicator of the optimum power losses in the motor with saturation. Indeed, the values of slip speed providing minimum losses are almost two times different for various load torques on the shaft. This indicator will not ensure good performance. On the other hand, the constant power factor quite well agrees with the minimum losses. Nevertheless, the slip speed approach was for the first time presented in [13] and in [14] it was turned into a practical method where the optimal value of slip speed ω_{slip} was calculated as a preliminarily measured tabular function of the angular rotation speed of the rotor shaft ω_2 . Another interesting efficiency optimization technique via constant optimal slip control of scalar controlled induction motor drive is presented in [15]. The key difference from similar optimal slip control approaches is that it requires solving neither losses minimization equations nor search strategies based on minimum losses or minimum power. The technique is based on an intuitive adaptation of Maximum Torque per Ampere algorithm. It is also feasible to integrate the solution in standard adjustable speed drives operated by conventional V/f or slip control. Nevertheless, this type of control of induction motors is a good alternative only for applications where there is no variable load and there are no high dynamic loads.

Stator current minimization. The input power minimum almost coincides with the stator current minimum according to experimental characteristics given in [12]. It is also well known that minimization of the stator current usually leads to minimization of losses in the motor drive. Such methods are on the verge of state control and model-based control. Although the theoretical optimum obtained is not a strict minimum, but such an approach is certainly simpler than methods that use the loss model, and from an energy point of view the result is almost identical. Such a class of methods is known as maximal torque per ampere (MTPA) strategy [16]. Operation at MTPA is achieved when, at a given torque and speed, the slip frequency is adjusted so that the stator current is minimized. In the simplest case, the minimization of the stator current is provided by constant slip speed control. In addition, the amplitude of the stator current will be minimal when the currents along the q and d axes are equal, which gives a constant slip speed

$$I_1 \rightarrow \min \Leftrightarrow I_{1d} = I_{1q} \Leftrightarrow \omega_{slip} = \text{const.}$$

The proposed global maximum torque per ampere (GMTA) controller in [16] is designed to avoid operation under saturated conditions. The resulting motor efficiency is reasonably close to the optimal value. The approach is insensitive to variations in rotor resistance. However, the dynamic performance is not as good as in field-oriented control and the error in achieving the required torque is up to 25%. In [17] an improved MTPA strategy for induction motor drives is proposed. Compared to [16], it includes the effects of magnetizing and leakage saturation as well as yields superior performance ought to alternate qd induction machine model (AQDM). It is shown that MTPA with AQDM achieves commanded torque with open-loop torque error less than 3% as opposed to the control strategy in [16] and that the MTPA condition is, in fact, achieved.

In [18] MTPA via search-based control for the FOC-based doubly-fed induction motor drives is introduced. The method requires estimation of load torque and rotor speed to calculate the control reference for the minimization of the magnitude of total stator current. It is independent of all motor parameters, which is the inherent feature of online search-based methods. However, from the simulation results, continuous oscillations of the stator current and as a result of the torque, which also affects the speed of rotation, can be observed. This fact may also introduce additional heat and machine positioning errors. Depending on the tasks, drawbacks may not be significant.

Model-based control methods. This is by far the most refined and numerous class of methods for the optimization of

energy consumption. The idea of all these methods, as usual, comes down to the fact that the power losses P_{loss} is expressed as a function of the magnetization current I_{1d} : $P_{loss}(I_{1d})$. Then, the expression for the optimal magnetization current I_{1d}^* as a function of the parameters and the state of the motor is obtained by aligning the partial derivative to zero $\partial P_{loss}(I_{1d})/\partial I_{1d} = 0$. The advantage of LMC strategies is high regulation speed and good accuracy.

Among numerous loss minimization methods, LMC algorithms offer a quick response with not high torque pulsations. Therefore, a technical complexity lies in the plane of deriving simple and accurate loss model as well as knowledge of motor parameters. Another difficulty is developing of the model-based controller with online adaptation. The published methods differ from each other mainly by loss models (account for various sources of losses, use of different equivalent schemes of the motor drive, and others), optimality criteria, the use of loss model parameters adaptation schemes, various methods of model representation and optimum computation (multiple approximation, artificial neural networks, fuzzy logic, particle swarm optimization, genetic algorithms, and so on).

Analytical solution. An elementary analytical solution for the optimal magnetization current I_{1d}^* is obtained by aligning the partial derivative of the expression for power losses to zero $\partial P_{loss}(I_{1d})/\partial I_{1d}$, which is also considered as a model-based optimization. The main drawback is the need to measure or estimate the motor torque M_M . A similar approach is presented in [19], where the setpoint for I_{1d}^* is calculated directly from the analytical expression for power losses. The minimization of the total copper losses was achieved by optimizing the flux level as a function of the motor torque. Changes in motor parameters depending on flux level are taken into account. The paper also discusses the significance of accounting for stator core losses when an induction motor is controlled by the conventional field-oriented control system. The method proposed ensures maximum efficiency in the steady-state mode of operation by means of a deadbeat rotor flux controller without degradation in transient characteristics.

Authors in [20] proposed an online implementable control scheme. The method assumes that the optimal magnetic flux is an exponential function. Moreover, it does not rely on exact knowledge of the torque profile. The Newton-Raphson method was applied by authors to numerically solve the optimal solution online. A PC based test bench was successfully implemented, and, despite heuristic approximation, the solution gives satisfactory results for dynamic transitions. However, the iterative calculation of the Newton-Raphson method would be inefficient, thus it probably will be not applicable for DSP based industrial applications under high sampling rates. A practical solution was put forward in [21] to determine the relationship between stator field-generating current and torque-generating current in the form of a suboptimal solution with acceptable performance based on a look-up table with given data points. However, it is hard work to gain such a look-up table with the desired accuracy for different types of machines especially when saturation effects of the main inductance must be taken into consideration. In the framework of linear induction motors (LIM), authors in [22] presented a very similar and practical method for solving the optimal flux to minimize power losses during dynamic operation mode. The main purpose is to avoid complex computations by means of applying an analytical estimation of the optimal flux defined as

$$\psi_{dr}(t) = \psi_0 + (\psi_1 - \psi_0) \left[1 - e^{-\sqrt{a_1/a_5} t} \right],$$

where ψ_0 is the initial steady-state flux under given load conditions, ψ_1 is the desired final steady-state flux calculated from the LIM scheme, a_1 and a_5 are the loss coefficients. To find proper values of coefficients in exponential function the authors use two approaches: conventional calculations through

the iterative method with a DSP-based controller with a high sampling rate; proposed a simple analytical solution. The difference in trajectories is comparatively small. Nevertheless, this simple method does not bring any tangible improvements in energy efficiency minimization compared to approaches discussed earlier in [21].

Paper [23] presents an interesting approach of optimizing the efficiency of induction motor drives through so-called natural variables and reference frame independent quantities as state variables. The state variables such as electromagnetic torque, reactive torque, rotor speed and square of the rotor flux linkage magnitude are changed to natural variables that are invariant under the transition between coordinate systems. The expression for the power losses P_{loss} is a function of the reactive torque T_r and the square of the rotor flux linkage magnitude λ_{rr} . The total loss minimization in such an equivalent model is achieved through an appropriate command of the qd -axis voltages. The total electrical loss is minimized in the case when the following partial derivatives are constrained to be zero

$$\frac{\partial P_{loss}}{\partial T_r} = 0; \quad \frac{\partial P_{loss}}{\partial \lambda_{rr}} = 0.$$

In [24] it was noticed that q and d axes are equal under the condition of the minimum of energy consumption

$$P_{loss,q} = P_{loss,d}.$$

Thus, the implementation of the method consists in calculation of these components based on the loss model, where total losses in windings and core for the Γ -inverse equivalent circuit

$$P_{loss} = \left(R_1 + \frac{1}{R_{fe}} \omega_1^2 L_m^2 + \frac{R_1}{R_{fe}^2} \omega_1^2 L_m^2 \right) I_{1d}^2 + (R_1 + R_2) I_{1q}^2 - 2 \frac{R_1}{R_{fe}} \omega_1 L_m I_{1d} I_{1q},$$

and PI -regulator for obtaining the setpoint of field-generating current $I_{1d} = a \cdot PI[P_{loss,q} - P_{loss,d}] + b$ (a, b – shift constants).

Paper [25] analyses the possibility of improving the dynamical characteristics of a three-phase asynchronous motor. The study is based on a loss model and three control schemes are proposed: with a low-pass filter; injection of quadrature current that generates a torque; speed controller of variable structure. All proposed methods have shown satisfactory results. There is another recent approach in which the PID controller and the internal model controller as an alternative to the classic feedback structure are used to maintain a given speed and desired setpoints during disturbances in the load. The results of implementing the internal model controller have shown better system stability and performance in the system when compared with the PID controller for the speed control of the induction motor.

Numerical solution. If the loss model $P_{loss}(I_{1d})$ is rather complicated than the analytical one, solution for I_{1d}^* is not possible to obtain. This situation usually takes place when modeling saturation effects or power losses in the frequency converter. Thus, the equation $\partial P_{loss}(I_{1d})/\partial I_{1d} = 0$ is solved numerically with respect to I_{1d} for the given parameters and state of the motor drive.

Such an approach is proposed in the often-cited paper [26], in which the loss function including the saturation phenomenon is presented in the following form

$$P_{loss}(\psi_2, T_M, \omega_2) = a I_{1d}^2(\psi_2) + (b + c R_2^2) \frac{T_M^2}{d^2 \psi_2^2} + c \omega_2^2 \psi_2^2 + 2 \frac{c}{d} \omega_2 R_2 T_M,$$

where $I_{1d}(\psi_2)$ is the magnetization characteristic, a, b, c, d are parameters identified in real-time according to measurements of input power $P_{in} = a I_{1d}^2 + b I_{1q}^2 + c L_m^2 I_{1d}^2 \omega_1^2 + d L_M I_{1d} I_{1q} \omega_2$. The setpoint for ψ_2 is sought by numerical minimization of the loss function $P_{loss}(\psi_2, T_M, \omega_2)$. The algorithm is coded into a low-cost 16-bit DSP and verified on a 2.2-kW induction motor drive prototype. Despite the advantages of the proposed method, which is an original combination of SC and LMC, there are a few possible issues: flux and torque pulsations, and sensitivity to parameter variations.

Another example of a paper which also uses the numerical search is [27]. It presents a dynamic space-vector model for energy-efficient control of induction motors by means of determining the loss-minimizing flux linkage reference based on the corresponding steady-state power losses function both for static and dynamic modes of operation. It is based on stator currents and magnetization flux estimate ψ_2 . Loss minimization law is expressed as

$$\psi_{2,ref}^* = \arg \min \{ \hat{P}_{loss}(\psi_2) \}; \\ \psi_2 \in [\psi_{2,min}, \psi_{2,max}].$$

The minimum point of the loss function is found by means of a 1-D golden section method at each sampling. However, in such an approach the flux linkage reference must be filtered in order to avoid high magnetization current levels during flux transients. Although the following filter was used

$$\frac{d}{dt} \psi_{2,ref} = \alpha_{1,pf} [\psi_{2,ref}^* - \psi_{2,ref}],$$

the appropriate choice of the filter time constant has not been discussed. This point was further numerically investigated in [28] with respect to an appropriate choice of the filter coefficients. The analysis was conducted for three induction motors with rated powers of 370-W, 4-kW and 11-kW. Simulation results and numerical study has shown that an appropriate choice of the filter time constant as a fraction of rotor time constant leads to a reduction of power losses during a torque step change in load.

One more class of solutions in this domain consists of the fact that the dependence of the optimal field-generating current I_{1d} on the state of the engine is approximated polynomially or tabularly in advance (off-line). This makes it possible to simplify the algorithm as much as possible, but, obviously, binds the implementation of the method to a specific motor. Hence, the simplest option is to choose the optimal setpoint of the magnetization flux $\psi_{2,ref}$ (and, consequently, $I_{1d,ref}$) from a polynomial approximation of the dependence $\psi_2 = f(I_1)$. In [29], a more detailed loss model is considered (taking into account core losses, main flux saturation, and rotor deep bar effect) and a preliminary calculation of the optimum as a function of the motor torque and angular speed $\psi_2 = f(T_M, \omega_2)$.

In an effort to overcome the drawbacks of LMC, the so-called adaptive backtracking based nonlinear control schemes (BSC) incorporating the effect of leakage inductance are used. For the case of its work in association with indirect field-oriented control, there have been many versions developed, but only a few verified experimentally. The feedback control laws of backstepping control schemes are based on the Lyapunov stability theory. Moreover, they can successfully reach global stabilization in the situation of parameter uncertainty. The comparative study between the rotor field-oriented control and non-linear backstepping control was conducted in [30]. For an experimental test, a five-phase induction motor drive and DS1104 card were used. The experiment confirmed the higher performance of backstepping control compared to indirect field-oriented control in terms of faster transient response and rise time both for static and dynamic operation. The drawback of BSC is the excessive complexity of implementation and parameter tuning.

Artificial intelligence techniques. A noticeable part of the recent publications has been devoted to the application of artificial neural networks (ANN) and fuzzy logic (FL) to solve the problems of electric power consumption minimization in electric motors. One of the most effective fuzzy system applications is fuzzy logic control (FLC), in control systems that are normally impossible to describe analytically. The basic idea of such methods is an approximation of some nonlinear function. The approximated function may be a dependence of the field-generating current or magnetic flux linkage of the rotor on the state of the engine. In addition, ANN and FC have a high versatility to implement the functional dependencies of the electric machine. Moreover, they can also be used to evaluate the motor state, power losses, update the reference value of the field-generating current, as well as ensure the boundary conditions of the regulated quantities, and so on. In light of the fact that it is onerous to systematize all of the works presented in this domain in a particular classification, the discussion will be limited to a review of some recent papers.

A very simple FL-based efficiency optimization scheme uses feedback on speed and torque to generate an appropriate level of voltage on stator windings of the three-phase induction motor. In [31] the method for obtaining a simplified fuzzy model in the case of induction motor is presented. The idea of the paper is based in general on the fuzzy linearization of a nonlinear dynamic system using an inverse fuzzy model. However, due to simplifications done the given linearization technique does not fully consider the peculiarities of the nonlinear components in the investigated system. An approach that utilizes the unstable behavior of the subsystem, as well as smooth switching between controllers of the linear subsystems, was further investigated by the authors in [32]. It has been proved that the application of the controller synthesized for one of the subsystems with unstable behavior improves the characteristics of the dynamic system keeping its stability. The controller was further used in [33] in the framework of a general approach to the dynamical system's fuzzy controller synthesis. This is particularly useful during the initialization process to form the system with roots on the right side of the s -plane when the mismatch between the desired value and the output of the system is huge.

In recent years many solutions have also been devoted to direct torque control (DTC) methods improvement using ANN. The main drawbacks behind the high current and torque ripples in the conventional DTC schemes are by far the presence of hysteresis comparators as well as the limited number of voltage vectors and their combinations. In addition, the DTC switching frequency of the inverter is not invariable and is affected by the rotor speed, load torque, and hysteresis comparators bandwidth. These drawbacks can be overthrown by using ANN in DTC. The proposed solution in [34] uses the Levenberg-Marquardt backpropagation algorithm for weights adjustment.

In general, the fuzzy logic approach optimizes the system more systematically, but the need for good knowledge of the drive dynamics is still required.

Search control methods. Another noticeably advanced class of methods is based on the approach to minimization as a numerical optimization problem. It consists in the fact that the objective function is the measured value of power consumption. The search for the minimum is performed directly in real-time over the control object without using its mathematical model (so-called model-less multivariable control). The optimization criteria can be measured values of the active power or power in the DC link, the motor stator current, DC current, and others. Parameters calculated based on the measured information, such as power losses, can also serve as an objective function. When the goal is to minimize, the functions are often called cost function. In a matter of scalar optimization, the power losses minimization SC algorithm can be described as follows:

- 1) increase the magnetization current by some value;
- 2) measure or calculate the cost function, if it is less than the previous one, then continue to increase the magnetization current, and if more, begin to decrease it;
- 3) an algorithm terminates if the change becomes insignificant starting from some step in the algorithm.

Improvements to this class of methods are focused on reducing the minimum search time and measurement noises. The typical optimization time for modern methods is from several to ten seconds. A systematic approach in terms of optimal control is presented in [35].

In all probability, the earliest experimentally implemented solution in this domain is the system that adaptively adjusts the flux setpoint stepwise in the motor based upon direct measurement of the power input to the drive until the reduction of power consumed by the frequency converter has stopped. Some discrete gradient descent algorithms were proposed in this domain as well. The change in field-generating current is set to be proportional to the change in power in the DC link. Thus, a reduction in search time is achieved compared to a simple stepwise search. In [36], the idea of a hybrid method, where the initial approximation of the optimum is calculated analytically from the loss model approach and the subsequent adjustment of the flux is through the search technique activation, which finds the final optimal value of the field-generating current.

In [37] a controller is developed to optimize the efficiency of an induction motor, based on the search of a stator voltage that would maximize the specified parameter, namely efficiency. To reduce the slip parameter at low load on the motor shaft and at low operating frequencies, a slip compensator is introduced.

Numerous heuristic optimization techniques have been published in response to tuning controller gains including Particle Swarm Optimization (PSO), Genetic algorithms (GA) and Backtracking search optimization (BSO). However, optimization techniques usually have limitations on global minimum, trial-and-error procedure, local minimum value, and optimum trapping, high computational time to achieve the best results, etc. To solve the above-mentioned problems, a quantum lightning search algorithm (QLSA) is applied to improve the FLC the IM drive applications in terms of damping capability and transient response, which was further developed as a combination of a hybrid FLC and GA method in [38].

Unsolved issues. The aforementioned techniques play an important role in enhancing the performance of electric drive control systems. However, they encounter the following challenges and issues in implementing:

- polynomial or tabular approximation of the optimal control trajectories in offline mode, which leads to tight binding to the specific control object and operating conditions;
- high computational time to achieve best optimization performances;
- embedding low-pass and nonlinear filters;
- a step-change in the field-generating current reference leads to disturbances in the electromagnetic torque of the motor resulting in undesirable pulsations in the shaft speed and additional power losses during transients;
- the question of the dynamic mode of operation is still of high priority as only a comparatively small number of publications address the question of power losses minimization in dynamics;
- degradation of the stability of vector control to a disturbance in the load torque with the magnetization flux decreased below the minimum;
- pre-calculation of control behavior only for the next sampling cycle;
- restricted dynamics which can be achieved with a cascade structure for highly dynamic drive applications.

Purpose. To solve and improve these issues, an optimization technique is recommended as an alternative which has the following advantages:

- calculation of the optimal control trajectories online in comparison to conventional control, in which as a rule a pre-calculated control law is applied;
- quicker convergence to a minimum with the same parameters of the digital system;
- a continuous pattern of control variable regulation which results in a smoother and faster drive system performance and more accurate maximum efficiency, which is not possible by the conventional stepwise change in the control variable (filtering is no longer required);
- power losses minimization in both static and dynamic modes of operation;
- facility to handle constraints on inputs and state variables of the multivariable system in an optimal way as well as taking into account the cost function to be minimized;
- pre-calculation of the future dynamic behavior of the system over a finite horizon in contrast to conventional controllers possessing no knowledge about the control object itself.

Results. An interesting approach that could bring listed advantages for power losses minimization of closed-cycle operation IM drive is based on dynamic programming (predictive control optimal magnetic flux). In order to calculate the optimal flux trajectory, it is necessary to elaborate on the cost function, system dynamics equations and constraints for state and control variables.

The cost functional of the optimal control problem is as follows

$$J = \int_{t_0}^{t_0+Th} L(\tau, \dot{x}(\tau), u(\tau)) d\tau,$$

where $T > 0$ is the prediction horizon; the $L: \mathbb{R}_0^+ \times \mathbb{R}^{N_x} \times \mathbb{R}^{N_u} \rightarrow \mathbb{R}_+^0$ function is the integral cost of $x(t) \in \mathbb{R}^{N_x}$ state variables and $u(t) \in \mathbb{R}^{N_u}$ control variables in vector form.

The system equations are

$$\dot{x}(\tau) = f(t_k + \tau, x(\tau), u(\tau)),$$

and $f: \mathbb{R}_0^+ \times \mathbb{R}^{N_x} \times \mathbb{R}^{N_u} \rightarrow \mathbb{R}^{N_x}$ is a nonlinear function describing the dynamics.

The system is subjected to box constraints of the form

$$u(t) \in [u_{\min}, u_{\max}];$$

$$x(t) \in [x_{\min}, x_{\max}].$$

Following these steps, it is possible to define the cost function, system dynamics equations, constraints and boundary conditions for a vector controlled IM drive where the rotor flux linkage ψ_2 is oriented along the d -axis of the synchronously rotating coordinate frame $\psi_{2d} = \psi_2, \psi_{2q} = 0$:

1. The cost function of power losses is

$$J = \int_0^T \left(\frac{3}{2} (R_1 + R_2) I_{1d}^2 + \frac{2}{3} (R_1 + R_2) \frac{T_D^2}{z_p^2 \psi_2^2} + \frac{3}{2} \frac{R_2}{L_m^2} \psi_2^2 - 3 \frac{R_2}{L_m} \psi_2 J_{1d} \right) dt,$$

the equation parameters are from [39].

2. The dynamics of the rotor flux is represented as

$$\frac{d}{dt} \psi_2 = -\frac{R_2}{L_m} \psi_2 + R_2 i_{1d}.$$

3. The only constraint to be applied is based on the nominal value of the field-generating current. Regarding the boundary-value problem, basically, it is calculated between two steady-state points for the flux that constantly change online $\psi_2(0) = \psi_{2, \text{stat}}(T_D)$ and $\psi_2(T) = \psi_{2, \text{stat}}(T_D + \Delta T_D)$.

The imposition of constraints on the control variables and especially state variables complicates the optimal control problem in general. From another point of view, they simplify the data array size.

A few assumptions are taken into account:

- 1) the speed and current regulators of field-oriented control have high enough performance to ensure the control characteristic close to perfectly rigid;
- 2) for the sake of simplification, no saturation effect is accounted;
- 3) core losses are not considered.

At this point the definition of the Hamiltonian function from the dynamic programming theory

$$H(\tau, \dot{x}(\tau), \lambda(\tau), u(\tau)) = L(\tau, \dot{x}(\tau), u(\tau)) + \lambda^T(\tau) f(t_k + \tau, \dot{x}(\tau), u(\tau)),$$

where $\lambda \in \mathbb{R}^{N_x}$ is the adjoint state or costate. The system of the first-order optimality conditions follows from Pontryagin's

Maximum Principle, where $\frac{\partial H}{\partial I_{1d}} = 0; \frac{\partial H}{\partial \psi_2} = -\dot{\lambda}; \frac{\partial H}{\partial \lambda} = \dot{\psi}$ partial derivatives.

Simulation results. Simulations have been performed in order to verify the proposed strategy. The algorithm is implemented with Matlab/Simulink software, C language. Parameters of 370 W induction motor were used. The comparison between nominal and predictive approaches for flux control is made through the test. A load step change is analyzed from 25 to 100 % of nominal motor torque in the time interval $t \in [0-200]$ ms and from 100 to 25 % of the nominal motor torque in the time interval $t \in [200-400]$ ms. Speed and load torque references for one operating cycle are shown in Figs. 1 and 2. A plot of summary energy losses for this period is presented in Fig. 3. The simulations illustrate the improvement in regard to energy consumption due to the predictive approach with respect to the nominal case.

Conclusions. Algorithms for energy-efficient control in induction motor drives are briefly discussed in the sequel. The described optimization strategies can be successfully applied particularly in vector and direct torque controlled electrical drive control systems. Significant power loss reduction is ob-

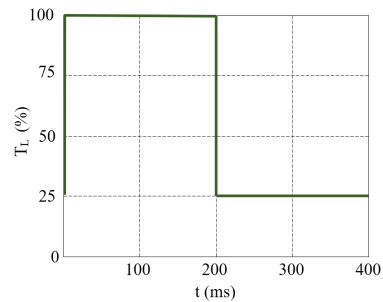


Fig. 1. Plot of load torque reference

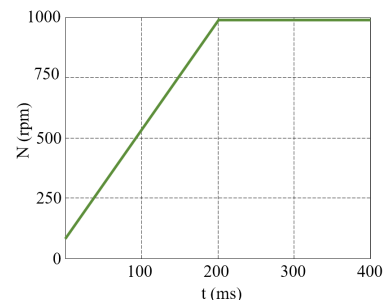


Fig. 2. Plot of speed reference

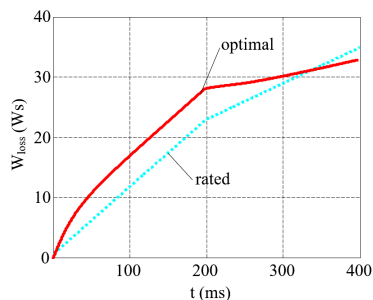


Fig. 3. Comparison of loss energies

tained when the machine is operated in part-loaded mode. The choice of the energy-saving method directly depends on the drive itself and its field of application. In addition, the choice of energy-efficient strategy and specific methods is also dependent on many conditions. IM drive with vector control is by far the most advanced now, but its algorithms in most cases do not take into account the saturation of the magnetic circuit, as well as other losses in the motor. It should be noted that some manufacturers supply frequency converters only with their motors (SEW-Eurodrive for example). This is particularly due to the use of non-linear motor models, which allows us to significantly improve the characteristics of regulation compared to linear motor models. Even though the methods of simple state control have historically been the very first, they are practically not used. Instead, the choice is between LMC and SC strategies. LMC is the fastest but more sensitive to parameters variation of the plant. SC methods technically can be applied for any motor as they are insensitive to parameters of the plant but have much slower convergence time of the search.

An alternative LMC-based predictive algorithm for efficiency optimization of induction motor drive has been proposed. The simulation results show significant loss reduction in the long run, good dynamic features and stable mode of operation of the drive system. Also, some new techniques for parameter identification of the loss model have made LMC extremely actual. The substitution of a vector control system with a single predictive controller can be a very attractive topic for further research in this field.

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Огляд методів підвищення енергоефективності асинхронних машин

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Мета. Представити комплексний огляд на основі вітчизняного й зарубіжного досвіду існуючих методів оптимізації в задачах мінімізації втрат в електромеханічних системах з асинхронною машиною для зменшення загальної кількості споживаної електроенергії з мережі.

Методика. Проведено детальне вивчення розробок у галузі оптимізації енергоефективності трифазних машин змінного струму, що спираються на використання оптимальних методів управління та проектування. Особлива увага приділена системам, що використовують векторний тип керування як основу для подальших досліджень. У цій галузі було простежено стійкий розвиток кількох тенденцій. Опорне значення струму, що генерує поле, є додатковою мірою свободи в математичній моделі досліджуваної системи. Крім того, даний струм впливає на динаміку магнітного потокозчеплення й величину механічного крутного моменту. Реалізована модель дозволяє проводити порівняльний аналіз різних підходів для забезпечення мінімального споживання енергії при адекватній інтенсивності перехідних процесів.

Результати. Серед численних методів управління було виділено просте управління станом двигуна, алгоритми оптимізації ефективності на базі моделей втрат і пошукові алгоритми. Приклад моделювання оптимізації енергоефективності асинхронної машини був виконаний у рамках системи векторного керування, орієнтованій по полю ротора з урахуванням ступінчастої траєкторії крутного моменту навантаження. Ступінчаста траєкторія можлива як результат механічного збурення або коли двигун виконує складні профілі швидкості, або протидіє ударному навантаженню.

Наукова новизна. Ретельний аналіз показав, що існуючі алгоритми оптимізації у звичайних системах все ще можуть бути використані для прикладних застосувань. Однак деякі існуючі проблеми в досягненні найкращого контролю не були узагальнені. Відповідно, цей огляд уперше дає деякі пропозиції щодо майбутніх досліджень і розробки енергоефективного управління асинхронними двигунами в динамічних режимах.

Практична значимість. Трифазні асинхронні електроприводи – це нелінійна система, яку важко точно теоретично описати через їх раптові зміни умов режиму роботи та зміни параметрів. Таким чином, необхідні розширені алгоритми для підвищення їх енергетичної ефективності на додаток до ефективних апаратних рішень. Запропонований приклад альтернативного рішення призведе до розробки вдосконалених систем управління електромеханічними системами.

Ключові слова: асинхронна машина, енергоефективність, алгоритми оптимізації, динамічна робота, прогнозне керування

Обзор методов повышения энергоэффективности асинхронных машин

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Цель. Представить комплексный обзор на основе отечественного и зарубежного опыта существующих методов оптимизации в задачах минимизации потерь в электромеханических системах с асинхронной машиной для уменьшения общего количества потребляемой электроэнергии из сети.

Методика. Проведено детальное изучение разработок в области оптимизации энергоэффективности трехфазных машин переменного тока, опирающихся на использование оптимальных методов управления и проектирования. Особое внимание уделено системам, которые используют векторный тип управления в качестве основы для дальнейших исследований. В этой области было прослежено устойчивое развитие нескольких тенденций. Было замечено, что опорное значение тока, который генерирует поле, является дополнительной степенью свободы в математической модели исследуемой системы. Кроме того, этот ток влияет на динамику магнитного потока сцепления и значение механического крутящего мо-

мента. Реализованная модель позволяет проводить сравнительный анализ различных подходов для обеспечения минимального потребления энергии при адекватной интенсивности переходных процессов.

Результаты. Среди многочисленных методов управления были выделены простые алгоритмы контроля состояния, алгоритмы оптимизации на основе модели потерь, а также поисковые алгоритмы. Пример моделирования оптимизации эффективности асинхронной машины был выполнен в рамках системы векторного управления, ориентированной по полю ротора с учетом ступенчатой траектории момента нагрузки. Такая траектория возможна как результат механического возмущения или когда двигатель обрабатывает сложные профили скорости или противодействует ударным нагрузкам.

Научная новизна. Тщательный анализ показал, что существующие алгоритмы оптимизации в обычных системах все еще могут быть использованы для прикладных приложений. Однако некоторые существующие проблемы в достижении лучшего контроля не были обобщены. Соответственно, этот обзор впервые дает некоторые предложения относительно будущих исследований и разработки энергоэффективного управления асинхронными двигателями в динамических режимах.

Практическая значимость. Трехфазные асинхронные электроприводы – это нелинейная система, которую трудно точно теоретически описать ввиду их внезапных изменений условий режима работы и изменения параметров. Таким образом, необходимы расширенные алгоритмы для повышения их энергетической эффективности в дополнение к эффективным аппаратным решениям. Предложенный пример альтернативного решения приведет к работе усовершенствованных систем управления электромеханическими системами.

Ключевые слова: асинхронная машина, энергоэффективность, алгоритмы оптимизации, динамический режим, прогнозное управление

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