IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

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To cite this article: V V Kuznetsov *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **985** 012022

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Abstract. The current article is devoted to the topic problem of decision making concerning the choice of the protective means for asynchronous motors operated within industrial shop electric circuits under challenging conditions of improper electric supply. In this paper we show how energy economizing model for the asynchronous motor can be presented in the form of predicate disjunction and be applied with the pattern recognition algorithm for making solutions. The major advantage of a new model is its open character and the possibility of knowledge accumulation with respect to electromechanical equipment. We submit the information on the software and hardware complex applied for the research on the characteristics of the circuit voltage and the asynchronous motors in the real time mode directly within the enterprise industrial shop. The publication also reports on the searching for the best protective solution for asynchronous motors. This work is based on the known recognition algorithm of statistical optimization for non-linear objects given as the aggregates of predicates. The algorithm fruitfully applies the local selection principle. The approach proposed in this publication has been approbated at the protective means selection procedure for the asynchronous motor of 7.5 kW capacity, which performance is 80% of the working cycle under conditions of improper electric energy supply in the experimental shop of Ukrspetsservis.

1. Introduction

As known [1], the electric network mode parameters often do not meet the requirements of GOST 32144-2013 in Russia, of GOST 13109-97 in Ukraine and the guidelines No.39/2015/TT-BCT and No.25/2016/TT-BCT in Vietnam. In real operating conditions, there is very often a non-sinusoidal mode in electrical networks, the consequences of which are voltage and current harmonics. The problem of the presence of low-quality electricity in electrical networks is described in the articles [2-4]. The problem of the negative influence of voltage and current harmonics on electrical equipment, on the efficiency of electric energy use, has recently been increasingly represented in international publications and conferences [5-7]. Even in the countries of Southeast Asia, scientists pay attention to this problem. In paper [8] the authors note that, the parameters of electrical network modes do not meet the requirements of Russian GOST 32144-2013 and the guidelines of Vietnam.

The principal ways of decrease of poor-quality electricity negative impact on electric motor operation in production environment and consequently on the efficiency of production in general are as follows: application of “individual” LC-filters for protection of principal electric drives [9]; application of “sectional” poor-quality supply voltage compensating devices on a workshop level [10]; suppressing of supply voltage distortion in the points of its origin. Rejection of any measures is also considered acceptable despite insignificant motor lifetime reduction. Each of the aforesaid options incurs certain integration cost and expected economic effect.

The known methodology for choosing of protection equipment to secure asynchronous motor (AM) [10] operating under the conditions of poor-quality electric energy is based on its energy-efficient pattern. The above methodology implements computing algorithms involving stochastic model of linear voltage within workshop power supply network, nonlinear electromagnetic and thermal model of AM and economic model as well [11, 12]. However, problems related to practical realization of computing procedures in each particular case prevents its implementation in production.

The goal of this article is justification of the possibility of the above methodology implementation in production environment based on SCADA of Zenon system software installed on PC; and application of predicate models and non-relational data model-oriented recognition algorithms.

2. Research methods and results

Taking a decision on economic viability of the choice (or refusal) of a particular protection equipment depends on the value of several variables (input technical and economic): total harmonic distortion K_U, coefficients of specific harmonic components $K_{U(m)}$ (m=7), negative sequence ratio K_{2U}, zero-sequence index K_{20}, protection equipment cost C_j $(i = \overline{1,r})$, where r – is the number of different types of protection devices. Herewith, indexes $K_U, K_{U(m)}, K_{2U}$ and K_{20} depend on objective laws of linear voltage variation within electric network and asynchronous motor operation pattern [13].

For the purposes of determination of characteristics of linear voltage within workshop electric network and asynchronous motors in real time there was a hardware and software suite developed, see Figure 1.

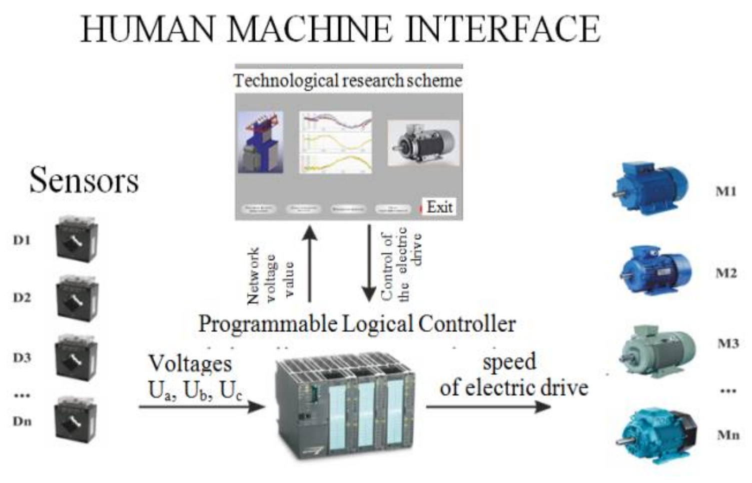

Figure 1. Schematic structure of the system for study of electric network and asynchronous motors.

Hardware package of the suite has been developed on the basis of VIPA System 200 V programmable logical controller (PLC). PLC is a remote analogue signal input module. Software provides computation process and human-computer interface on HMI/SCADA zenon Supervisor 7.0 based PC [14].

Interaction between programmable logical controller and PC with software suite is implemented by means of Ethernet interface. Current values of linear voltage and motors parameters are reflected on a PC screen and are saved for further processing. The suggested suite helps perform simultaneous study of all engines operating in a workshop.

Technical and economic values have some deviations conditioned by either measuring precision (for technical values) or economic situation (for costs) and are measured within certain range. This makes possible to represent energy-efficient model of AM by a sum-of-predicates form (discrete form) [15]:

$$Z_{\text{em}}\left[\vec{X},\vec{C}\right]=V_{p=1}^{q}\,V_{l}^{\lambda_p}\,Z_{p,l}\left[\vec{X},\vec{C}\right], \quad (1)$$

where:

$$\begin{aligned} Z_{p,l}\left[\vec{X},\vec{C}\right] &= 2^{-n}\prod\nolimits_{j=1}^{n}\left\{1+\operatorname{sgn}\left[(X_j-X_{j\min}^{pl})(X_{j\max}^{pl}-X_j)\right]\right\}+ \\ &+2^{-r}\prod\nolimits_{j=1}^{r}\left\{1+\operatorname{sgn}\left[(C_j-C_{j\min}^{pl})(C_{j\max}^{pl}-C_j)\right]\right\}, \end{aligned} \quad (2)$$

here: V – logic operation of disjunction, q – number of loss experience categories resulting from integration of protection equipment or their clusters, λ_p – number of predicates determining p – range, n and r – number if technical and cost values respectively, $X_{j\min}^{pl}, X_{j\max}^{pl}, C_{j\min}^{pl}, C_{j\max}^{pl}$ – model constants.

Formula (1) defines the relationship between technical $\vec{X}$ and economic $\vec{C}$ variables in discrete form – as the sum of predicates $Z_{p,l}\left[\vec{X},\vec{C}\right]$.

In this case, the element $Z_{p,l}\left[\vec{X},\vec{C}\right]$ defines a "hyperparallelepiped" in a multidimensional feature space and, according to (2), takes the value "1" if the current technical and economic situation falls inside the "hyperparallelepiped", and the value "0" – otherwise.

Generation of predicates parameters and their consolidation in categories may be commenced in the course of teaching the model according to the criterion of minimal economic losses resulting from the availability of AM protection equipment (or their unavailability):

$$E_p \to \min. \quad (3)$$

In this case in the course of input values sampling population recognition learning it's requisite by setting different criteria E_p within the interval $E_{p.\max} \div E_{p.\min}$ to split factor space into two categories: M_1 if $E_S < E_p$ and M_2, if $E_S > E_p$. Provided that the criteria values changes within the range $\Delta E_p = (E_{p.\max} - E_{p.\min})/q$, the q splitting the categories of hypersurfaces will be received, which pursuing the methodology of analytical description by means of methods admitting splitting of the factor space into elementary subfields may be represented by predicate equation (1). Here: ΔE_p – permissible deviation of economic losses from estimated value.

Teaching the model is performed on the basis of computing experiment, structural pattern of which is shown on Figure 2. In the course of experiment, implementation control unit (ICU) generates random sequence of input values within the prescribed limit.

In section "Energy Saving Pattern" calculation of economic losses incurred by application (abandoning) of protection equipment for electric drives in electric networks with poor-quality electrical energy is performed. See design formula for their determination pursuing [16] in Table 1.

Generation of predicate pattern components is commenced in section "Education and Adaptation" pursuing [17-19]. Herewith the number of predicates of completely defined predicate pattern depends upon parameters of input variables and defined with the help of the following formula [15]:

$$K_q = \prod_{i=1}^{n} \frac{d_i}{\Delta x_i}, \tag{4}$$

here $d_i; \Delta x_i$ – turndown and sample spacing of input value. The ratio $\frac{d_i}{\Delta x_i}$ in formula (4) determines the number of intervals in which the current value of the input variable i^{th} (technical or economic) can fall. Then, the total number of intervals, and hence the total number of predicates in formula (1) will be equal to the product of the number of intervals for all n – input variables.

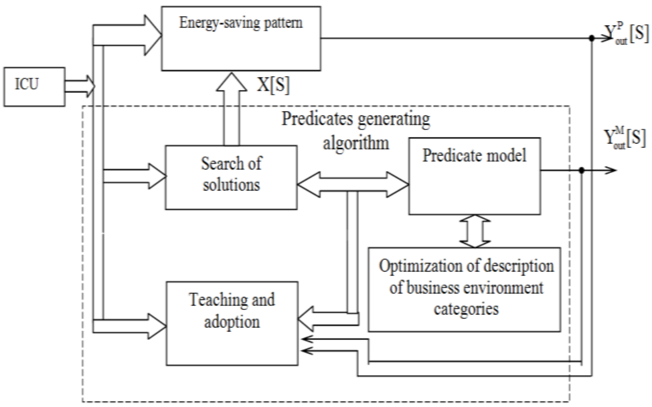

Figure 2. Schematic structure of predicates generation model.

Table 1. Phase of economic losses computation.

Phase no.	**Computing subsection**	**Output parameter**		
		Symbol	**Design formula**	**Name**
1	2	3	4	5
1	**Voltage pattern in workshop networks**	K_U	$K_U = \sqrt{\sum_{n=2}^{40} U_n^2} \cdot \frac{100}{U_{nom}}$	Harmonic distortion ratio
		$K_{U(n)}$	$K_{U(n)} = \frac{U_n}{U_{nom}} \cdot 100$	Specific harmonical component ratio
		K_{2U}	$K_{2U} = A_2 / A_1$	Reverse sequence ratio
		K_{20}	$K_{20} = A_2 / A_1$	Zero-sequence ratio
2	**Electric magnetic pattern of AM**	I_{Aeq}	$I_{Aeq} = \sqrt{\frac{1}{N} \sum_{n=0}^{N} (i_{An})^2}$	Equivalent stator current value (calculated for each phase)
		I_{Req}	The same for rotor current	The same for rotor
		$\underline{I}_{M_n}$	$\underline{I}_{M_n} = \underline{I}_{stator\,n} + \underline{I}_{rot\,n}$	Excitation current
		ΔP_{m1}	$\Delta P_{m1} = \left(I_{Aeq}^2 + I_{Beq}^2 + I_{Ceq}^2\right) R_{stator}$	Losses in stator copper
		ΔP_{m2}	The same for rotor	The same for rotor

Continuation of Table 1

1	2	3	4	5
2	**Electric magnetic pattern of AM**	ΔP_s	$\Delta P_s = 3 \cdot I_M^2 \cdot R_S$	Losses in steel
		ΔP_Σ	$\Delta P_\Sigma = \Delta P_{m1} + \Delta P_{m2} + \Delta P_s$	Losses in steel
		P_1	$P_1 = U_A I_A + U_B I_B + U_C I_C$	Consumed actual power
		Q_1	$Q_1 = \sqrt{S_1^2 - P_1^2}$	Consumed reactive power
		S_1	$S_1 = U_{Aeq} I_{Aeq} + U_{Beq} I_{Beq} + \ldots + U_{Ceq} I_{Ceq}$	Consumed total power
		P_2	$P_2 = \omega_{av} \cdot M_{av}$	Shaft power
		η	$\eta = P_2 / P_1$	Efficiency factor
		$\cos\varphi$	$\cos\varphi = P_1 / S_1$	Coefficient of performance (with the regard of distortions)
		THD_I	$THD_I = \frac{1}{I_1}\sqrt{\sum_{n=2}^{N}(I_{avn})^2}$	Harmonic current distortions ratio
		THD_T	The same for the torque	The same for the torque
3	**AM thermal model**	$\tau(t)$	$\tau_k = \tau_{(k-1)} + 1/C\left(\Delta P - A\tau_{(k-1)}\right)$	Excessive temperature-time relationship
		τ_{av}	$\tau_{av} = \frac{1}{M}\sum_k \tau_k$	Average temperature of isolation
		α'	$\alpha' = \frac{1}{T_{\text{cycle}}}\sum_n\left(\Delta\tau_n \cdot t_n\right)$	Equivalent duration of AM operation involving overheating
		T	$T = T_H \cdot e^{-\beta\cdot\alpha'}$	Isolation life time
4	**Economic damage pattern**	$E_{\text{generalized}}$	$E_{\text{generalized}} = \Delta P_{\Sigma\text{allowable}} \cdot C \cdot T_{\text{work}}$	Collateral damage
		E_{year}	$E_{\text{year}} = E_{summ1} - E_{summ2} - e \cdot K$	Annual economic damage
5	**Determination of selected protection equipment parameters**	C_1	assigned 1 μF	Choke filter capacity
		L_1	$L_1 = \frac{1}{\omega_r^2 C}$	Choke filter coefficient of induction
		C_2	Evaluated iteratively	Capacity in the part of a “star” of a compound filter
		E_{TC}	Evaluated separately	Protection equipment cost

See Table 2 for data on input values parameters during the study of 7.5 kW AM operation under the conditions of poor-quality electrical energy. As it appears from Table 2 and (4) $K_q = 1.664 \cdot 10^{13}$. Computation of such number of predicates within reasonable timeframes is rather difficult.

Table 2. AM input values parameters.

No.	Input value	Turndown	Variation range	Note
1	Total harmonic distortion	2–15%	0.5%	
2	Specific harmonic components ratio	0 – 10%	0.5%	First 7 harmonic components
3	Reverse sequence ratio	0 – 5%	0.1%	
4	Zero sequence ratio	0 – 5%	0.1%	
5	Protection equipment cost	UAH 0…200000	UAH 2000	10 options of technical solution

To overcome the above problem called "curse of dimensionality" in the course of teaching the predicate model, the algorithm of accelerated education has been applied [15]. This algorithm allows to include untaught fields of factor space into predicative pattern once simple criteria for two predicates of a certain class are met:

$$\begin{cases} X^1_{u\min} \le X^2_{u\min} \\ X^1_{u\max} \ge X^2_{u\max}, \quad when \quad u = \overline{1,n}; u \ne 1 \end{cases} \tag{5}$$

where $X^1_{u\min}, X^1_{u\max}, X^2_{u\min}, X^2_{u\max}$ – parameters of the merged fields projections, u – number of factor space feature axis towards which subfields are combined.

The system of inequalities (5) defines an area in the n-dimensional feature space, which is not defined in (1). To describe the specified area, it is necessary to have the corresponding technical and economic situations in the training sequence. However, taking into account (4), the expectation of their appearance can go beyond reasonable time intervals.

This problem can be overcome by the invariance of the mathematical structure of the predicate equation (2) to the size of the domain specified by it. Therefore, a strict fulfillment of one of the inequalities (5) is sufficient to form the parameters of the corresponding predicate and include it in (1).

"Predicate Model" module generates economic environment in the form of a predicate and assigns it to p-class based on defined values of technical and economic parameters and economic damages from application of protection equipment computed with energy saving pattern involved. The number of the class is defined using the following formula:

$$p = entier\left|E_p \times \Delta E_p^{-1}\right| + 1. \tag{6}$$

In (6), E_p is the range of values of economic losses when choosing various methods of protecting an asynchronous motor, and ΔE_p is the possible deviations of economic losses from the calculated ones caused by the forecast of fluctuations in exchange rates, inflation and other economic macroindicators in the considered time interval.

It is also worth noting that an adaptation algorithm has been developed for predicate model which makes possible its updating to reflect expansion of hardware park and its cost changes:

$$Z_p\left[\vec{X},\vec{C}\right] = \\ = \left[\mathrm{V}_{l=1}^{L_1+\lambda_p} \mathrm{Z}_{p,l}\left[\vec{X},\vec{C}\right]\right] \Lambda \left[V_{v=1}^{L_2} \mathrm{Z}_{t,v}\left[\vec{X},\vec{C}\right]\right], \tag{7}$$

where L_1 and L_2 − is the value obtained as a result of recognition of the first and second order controversies (respectively), Λ − logical operation of the conjunction.

The first order controversy should be thought of as affiliation of a predicate with P class though the given predicate should be referred to T class pursuing economic losses value (as a result of technical and economic conditions) and the second order controversy should be thought of as affiliation of a predicate with T class though the given predicate should be referred to P class.

Realization of adaptation algorithm pursuing (7) leads to gradual structural complication of predicate model and difficulties in its real-world application. To overcome structural complication of the model is possible by means of application of algorithms used in "Reduction of Economic Conditions Categories Description". Reduction of categories description provides enlargement of subareas by way of their merging with the following encoding of the parameters of predicate equation which determines enlarged area [20, 21].

Merging of subareas is commenced upon the fulfillment of equality conditions in the right and left parts of the formulas in (6). Hence, the resultant subarea has the minimal and maximum value of $u-$ attribute determined as $X_{u\min}^{12}=\min\left\{X_{u\min}^{1},X_{u\min}^{1}\right\};X_{u\max}^{12}=\max\left\{X_{u\max}^{1},X_{u\max}^{2}\right\}$.

It's obvious that in the context of enlargement of subareas the transition of predicates from one category to another and consequently resolution of the first and second order controversies is possible.

Encoding of predicate equations parameters involves determination of their numbers on feature axis in the form of some vector $\vec{B}$ and its collapse to some scalar by formula [15]:

$$K=\sum\nolimits_{u=1}^{2(n+r)}b_j q^{(2(n+r)-j)}, \tag{8}$$

where b_j – collapsing vector $\vec{B}$ component, matching with j – feature axis; q – system base.

Moving from encoding figures K_γ to vector $\overrightarrow{B_\gamma}$ is done by the formula:

$$b_{j\gamma}=\operatorname{mod}(\left[K_\gamma / q^{(2(n+r)-j)}\right],q),\ j=1,\overline{(n+r)}. \tag{9}$$

Transformations (8) and (9) make it possible to reduce the recording of the mathematical model given by formulas (1), (2), and, hence, to reduce the requirements for computing and information resources of the software and hardware that implement them.

Determination of the best technical option of AM protection according to predicate model is based on algorithm of recognition static optimization in "Solutions Search" unit as follows. For current technical values $Z_{em}\left[\vec{X},\vec{C}\right]$ is computed starting from the first category of economic $p=1$, which is an equivalent of minimal value of economic losses. If $Z_{1l}\left[\vec{X},\vec{C}\right]=0$ for all $l=\overline{1,\lambda_1},$, then the second category of economic conditions should be analyzed, etc. This procedure is performed unless some $p=c$ and $l=Z_{cg}\left[\vec{X},\vec{C}\right]=1$. Then according to the values of the chosen predicate constants financial expenditures and consequently the chosen technical option of protection are determined.

In [15] mentions that predicate equations (1) may be represented by relational data model. It helps describe the processes of teaching, adaptation, minimization and search of the optimum solutions based on single mathematical apparatus $-\alpha-$ algebra.

Taking into consideration that relational model is supported by Data base control system this approach towards determination of optimum protection equipment for AM with regard to its operation under poor-quality electricity conditions is easy to implement in production environment [22, 23] and railway transportation systems [24-26].

The proposed approach has been tested while choosing asynchronous motor protection equipment with 7.5 kW capacity operating during 80% of operation cycle under the conditions of poor-quality electrical energy in research-and-development shop of "Ukespetsservice" Ltd. The results of the research are listed in the Table 3:

It follows from Table 3 that for the purposes of protection of this induction motor it's enough to use passive LC-filter at the cost of UAH 2.000.00. With regard to the above mentioned annual economic losses will be E_p= UAH 3.700 per year.

Table 3. Results of the research.

No.	Input variable	Technical parameter	Cost	Note
1	Total harmonic distortion coefficient	2.5%	-	
2	Specific harmonic components coefficients	1.5%	-	
		0.5%		
		0.5%		
		2.5%		
		0.5%		
		2.0%		
		2.0%		
3	Reverse sequence coefficient	2.3%	-	
4	Zero-sequence coefficient	1.5%	-	
5	The cost of protection equipment	-	UAH 2.000.00	Passive filter

3. Conclusions

The analyzed approach towards determination of optimum option of protection of electrical equipment operating under conditions of poor-quality electricity networks is possible to implement in production environment. The proposed algorithms make it possible to derive mathematical models of electrical units under research in the form of logical sum of predicates standing for specific economic losses. Based on predicate models it's easy to find a range of optimal solutions for different conditions of electric devices operation. Obtained solutions may be saved on data store electronic component.

For practical application of the obtained results it's enough to estimate the quality of electric energy on specific enterprise and engine`s health and afterwards, by means of data base control system, to choose the most economically reasonable protection equipment.

Acknowledgments: This paper is elaborated in the framework of the project co-financed by the Polish National Agency for Academic Exchange.

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