Electric Motor Life Estimate Based on Statistic Data

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***Abstract*—Many different methods based on both planned inspection and health inspection for estimate of electrical equipment health are used. The estimation method of residual life of electric motors by their health in pulp and paper industry is considered.**

***Keywords:* distribution function, gamma-percentile probability, lognormal distribution, residual life, technical maintenance, electric motor.**

I. Introduction

Any industrial plant is a complex of sophisticate technical products. Among them, electrical motors play important part. Maintenance expenses of electrical motors are a good proportion of total operating expenses of plants which use thousands of electrical motors. A technology of electric motors maintenance by their health is considered in this paper. Problems related with electric motor health estimate, timely detection of fault and pre-fault situations of electrical motors, residual life estimation are of critical importance. An operability estimation on basis of fault probability by means of finding out the defects and troubles is attained. That allows to exclude faults during the operational period of electrical equipment.

II. Key Features Related with Changeover to Maintenance Technology by Equipment Health

Changeover to maintenance technology by equipment health allows us to control current health of electrical motor and its repair quality, to optimize financial and operation expenses in service, to decrease demands in spare parts, to avoid of unexpected production suspension, to schedule periods and conditions of technical maintenance. Repair start and reconditioning volume by health of electrical motors are determined in service.

Using of various diagnostic methods in industrial operating conditions is limited because access to diagnosable object and mounting of control facilities are not always possible. Thus, methods based on analyzing the electric motors health statistical data have the advantage in practical realization of diagnostic systems. These methods allow to handle data without direct access to diagnosable electric motor and mounting of primary transducer next to it [1]. Consequently, developing the new diagnostics methods based on statistical data of electric motor is actual, scientific and technical problem.

III. Method Description and Problem Formulation

There is a huge class of electric equipment, which does not have complete and sufficient statistical data of reliability. That is highly-reliable and unique equipment without analogs [2]. The method considered is focused on data processing of certain amount of similar production equipment units. The equipment can have limited amount of faults during longtime period. Operation times of non-fault equipment for the same period are addition data about reliability of objects. These operations times are called censored ones.

Initial period of equipment operation is considered when statistical fault data is not accumulated. Even so, there is no possibility to apply more effective and accurate methods but there is a possibility to get initial estimate function shape of fault probability distribution of equipment by initial unit facts of equipment fault. Equipment data for using the method is collected. The data includes starting operation date of equipment, fault equipment date, health of equipment at the time of collecting data, and operation time of equipment in hours or days. Parameters of density probability distribution function by data collecting results are defined. Required reliability indexes of equipment are forecasted on the basis of the function.

An algorithm based on quantiles method is showed on Figure 1. The algorithm allows to gain efficient estimates at the earliest operation stages (under fault of first equipment). Estimates due to faults of each following equipment are detailed. The quantiles method deals with finding values of corresponding parameters, which ensure maximum credibility of curve shape in accordance with points received.

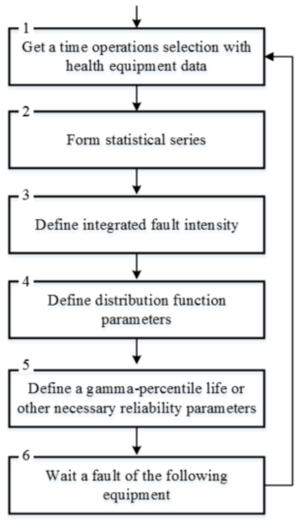

Fig 1. Algorithm of residual life equipment estimation.

Input data for calculation are operation times of each electric motor including fault ones. The operation time of electric motor when fault occurs is time interval from starting operation moment to the moment when electric motor is in fault condition. Operation data of all electric motors at following electric motor fault moment are fixed. The data can be changed inhomogeneously. The example of input data is showed in Table 1.

Actual electric motors health by various methods and ways can be determined. For example, methods based on analyzing the mechanical parameters such as electric motor vibration are used. These methods require proximate mounting the measuring equipment. Diagnostics of increased vibration causes of electric motor should be executed in the case of possible severe load. Furthermore, methods based on analyzing the electric parameters such us current, voltage, power demand and power delivered are used. These methods do not require mounting of special sensors at electric motor, but require special measuring equipment and they are used more often [3][4].

One-dimensional fault time vector (*Noi*) and additional vector of censored operation times (*Nci*) are plotted based on received data of electric motors health. Each next fault time point is fixed at the moment of the following electric motor fault. Operation time of electric motor is descended from censored vector to fault time vector under fault of the following electric motor. Both vectors cannot contain operation time of the same electric motor simultaneously. The example of one-dimensional fault time vector and additional vector of censored operation time are showed in Table 2.

Fault intensity of equipment under investigation is calculated after one-dimensional vector is obtained. Integrated fault intensity is calculated by the following equation:

$$p_i = (m_i^f)/(m_i^f + m_i^{c*}),$$

where

m_i^c – amount of fault objects with the time operation less than q_i, m_i^{c*} – amount of objects with time operation more than q_i.

Statistical series under each calculation based on data of all equipment operation times at various moments which correspond to these moments are formed. Both fault operation time and censored operation time can be taken as i point (Table 3).

Reliability parameters based on distribution function selection and its parameters are determined. The following distributions such as normal distribution, lognormal distribution, Weibull distribution are applied more often for technical objects in regulatory and scientific literature [5].

The distribution function shape of each type by parameters values is given in Table 4.

The distribution parameters search in solving the equation system by using of least square method is implemented:

$$\begin{cases} \int_0^{q_1} f(t,\mu,\sigma)dt - p_1 = a_1 \\ \vdots \\ \int_0^{q_n} f(t,\mu,\sigma)dt - p_n = a_n \\ \sum_{i=1}^{n} (a_i)^2 \to \min \end{cases}$$

where

f(t, μ, σ) – distribution function; pi – integrated fault intensity; αi – difference between theoretical and actual integrated fault intensities.

The following shapes of curves depend on distribution function type for one and the same values are showed on Figure 2.

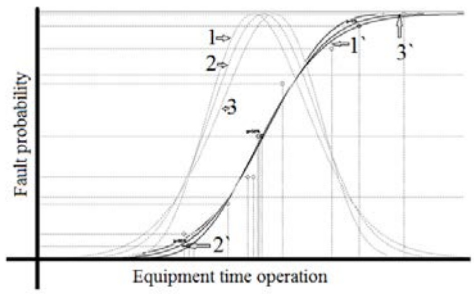

Fig 2. Example of distribution curve: 1 – density of lognormal distribution; 2 – density of normal distribution; 3 – density of Weibull distribution, 1' – integral function of lognormal distribution, 2' – integral function of normal distribution, 3' – integral function of Weibull distribution.

The next to last stage of determining the residual life of equipment is calculation of gamma-percentile indexes of life. The gamma-percentile life is total operation time when object under study does not break down with g probability expressed in percentage. The gamma-percentile fault operation time tg is determined by the equation:

$$\int_0^{t_g} f(t, s_1, s_2)dt = 1 - g$$

The algorithm presented on Figure 1 under fault of the following equipment for residual life determination should be repeated.

TABLE I
EXAMPLE OF EQUIPMENT STATISTICAL DATA

Object name	**Fault cause**	**Object health**	**Starting operation date**	**Fault date**	**Operation time (in days)**
Name 1	Cause 1	Health 1	Starting operation date 1	Fault date 1	Amount 1
Name 2	Cause 2	Health 2	Starting operation date 2	Fault date 2	Amount 2
…	…	…	…	…	…
Name N	Cause N	Health N	Starting operation date N	Fault date N	Amount N

TABLE II
EXAMPLE OF ONE-DIMENSIONAL FAULT VECTOR AND ADDITIONAL VECTOR OF CENSORED OPERATION TIMES

Object name	**Name 1**	**Name 2**	**Name i**	**Name i+1**	**…**	**Name N-1**	**Name N**
Fault operation times	No1	No2	Noi		…		
Censored operation times				Nci+1	…	Ncn-1	Ncn

TABLE III
EXAMPLE OF INTEGRATED FAULT INTENSITY

Objet name	**Name 1**	**Name 2**	**Name i**	**Name i+1**	**…**	**Name N-1**	**Name N**
Fault time operations	No1	No2	Noi		…		
Censored time operations				Nci+1	…	Ncn-1	Ncn
Quintile number (q)	1	2	i	i+1	...	N-1	N
Integrated fault intensity (Pi)	P1	P2	Pi	Pi+1	...	Pn-1	Pn

TABLE IV
DISTRIBUTION FUNCTION SHAPE AND DISTRIBUTION PARAMETERS

Distribution	**Equations for parameter search**	**Distribution parameters**
Normal	$\frac{1}{\sigma\sqrt{2\pi}}\int_0^{q_i} e^{-\left(\frac{(t-\mu)^2}{2\sigma^2}\right)} dt = p_i$	μ, σ
Lognormal	$\frac{1}{\sigma\sqrt{2\pi}}\int_0^{q_i} e^{-\left(\frac{(\ln t-\mu)^2}{2\sigma^2}\right)} dt = p_i$	μ, σ
Weibull	$\int_0^{q_i} \left(\frac{k}{\lambda}\right)\left(\frac{t}{\lambda}\right)^{(k-1)} e^{-\left(\frac{t}{\lambda}\right)} dt = p_i$	k, λ

where μ, σ - expectation value and mean squared departure correspondingly; t – control parameter; k, λ – shape factor and scale factor correspondingly

TABLE V
STATISTICAL DATA OF OBJECTS UNDER INVESTIGATION

Object name	**Fault cause**	**Object health**	**Starting operation date**	**Fault date**	**Operation time (in days)**
VN#1	Stator insulation breakdown	Fault	14.06.2010	16.07.2012	750
VN#2	Bearing runout	Run	12.02.2013	25.12.2013	316
VN#3	Bearing runout	Run	26.03.2013	05.02.2014	316
VN#4	Shaft breakdown	Run	05.05.2013	18.02.2014	289

IV. METHOD IMPLEMENTATION

Four same-type electric motors in pulp and paper production are used as test objects. Collected data for research are showed in Table 5.

Based on collected data on the VN#1 operation it should be noted that this electric motor is operated at different time interval. The VN#1 at the moment of other electric motors operation was not ued. For this reason, VN#1 will be used in calculation circumstantially. Consequently, the operation time of VN#1 is 750 days and it will not change in following calculations. VN#2 and VN#3 and VN#4 electric motors were used under similar conditions. Therefore, all calculations for the last three electric motors will be described in the paper.

Operation times of electric motors are calculated by collected data and one-dimensional fault time vectors when electric motor breaks down and censored vectors are generated. The following vectors under second, third and fourth faults are showed in Table 6.

TABLE VI
ONE-DIMENSIONAL FAULT VECTOR UNDER VN#2, VN#3, VN#4 FAULTS

	Second object fault				**Third object fault**				**Fourth object fault**			
Object name	VN#1	VN#2	VN#3	VN#4	VN#1	VN#2	VN#3	VN#4	VN#1	VN#2	VN#3	VN#4
Fault operation times	750	316			750	316	316		750	316	316	289
Censored operation times			269	230				271				

The fault operation time vector includes operation times of fault electric motors. The censored operation time vector includes operation times of running electric motors. The operation time of VN#2 is 316 days at the moment of its fault. Operation times of VN#3 and VN#4 are 269 and 230 days consequently at the censored vector because they work at the moment of VN#2 fault. Under the following fault vectors are generated in the same manner.

The integrated fault intensities are calculated based on fault time vectors and censored vectors given. The following fault intensities of VN#2, VN#3, VN#4 per quintiles are obtained correspondly (Table 7).

TABLE VII
INTEGRATED FAULT INTENSITY UNDER VN#2, VN#3, VN#4 FAULTS

	Second object fault				**Third object fault**				**Fourth object fault**			
Object name	VN#1	VN#2	VN#3	VN#4	VN#1	VN#2	VN#3	VN#4	VN#1	VN#2	VN#3	VN#4
Fault operation times			316	750		316	316	750	289	316	316	750
Censored operation times	230	269			271							
Quintile number (q)	1	2	3	4	1	2	3	4	1	2	3	4
Integrated fault intensity (Pi)	0	0	0,33	1	0	0,25	0,5	1	0,2	0,4	0,6	1

It should be noted that an same-type electric motor with 20% probability after 289 days and with 60% probability after 316 days based on calculation of integrated fault intensity breaks down.

In this case parameters search for data under investigation is realized simultaneously by few quintiles corresponding to current operation times of certain electric motors. A fault is fixed only for one electric motor. For this example, the highest informativeness is reached by lognormal distribution.

The curve shape of lognormal distribution under VN#4 fault as a result of calculation is given on Figure 2.

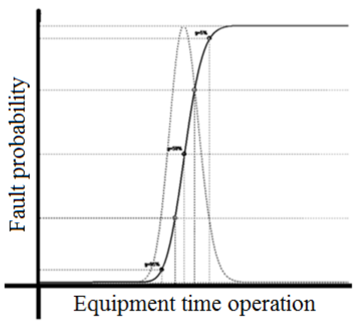

Fig 3. Lognormal distribution curve. Solid line – distribution density f(t); doted line – integral function of probability distribution F(t).

Unprecise parameter values of distribution function under the first electric motor fault are determined. These parameters under the following faults are clarified. The following parameter values after VN#4 fault as the result of equation system solution by least square method are obtained:

$$\mu=8,89$$
$$\sigma=0,07$$

These values under calculation of gamma-percentile operation time at the moment of current equipment fault are used. For determination of operation time g is 95% because this values is more often used for determination of objects reliability. In this way, when step, maximum value, accuracy are known and the following equation is calculated by numerical method:

$$\int_{0}^{t_g} f(t,\mu,\sigma)dt = 1 - 0{,}95$$

then the gamma-percentile operation time tg4 after the fourth fault is 271 days. It should be noted that each following electric motor must be checked not later than 271 days after gamma-percentile indexes calculation. The gamma-percentile operation time after each new spontaneous equipment fault will be corrected. That will increase probability calculation accuracy of the same electric motor fault.

V. CONCLUSION

The algorithm of equipment residual life determination has been developed. This algorithm allows to calculate fault probability of each equipment unit before its fault. Statistical data of electric motors operations in pulp and paper production are considered. Dates of new electric motors Fault have been computed based on statistical data.

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