The Identification of Selected Imperfections of Electric Traction Motors

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Electric traction motors of rail vehicles operate in very harsh conditions. This is due to their varying load and power fluctuations, as well as their exposure to high humidity, excessive shocks, dust and changing ambient temperature. These conditions can lead to the non-operational state of motors in operation which should be identified as soon as possible. This requires building the mathematical model of a traction drive system, which enables the full simulation of its work in real time. It also requires interference in the construction of the electrical system that allows for measuring the values of the relevant diagnostic features. The measurements of these features and their comparison to the values obtained from the mathematical model with the use of a multi-valued evaluation constitute the basis for the formulation of the operational diagnoses of traction motors.
Keywords: rail-vehicles, electric traction motors, technical diagnostics, fault location, diagnostic features, a three-valued evaluation system.

1. INTRODUCTION

Electric traction motors belong to the sets which condition the fulfilling of rail-vehicle practical functions designed by their constructors. Harsh conditions in which the vehicles operate cause a number of imperfections. Due to the imperfections, traction motors may fully or partially fail to fulfil these functions. Since some of these imperfections, e.g. connected to the resistance of insulation appear in a certain period of operation, it is justified to search for identification methods which enable for detecting the faults in an early stage of their development. To achieve this it is necessary to build a certain diagnostic system which both controls the values of the stated features of motor operation and evaluates these features on the basis of a set of standard data. Thus the features to be checked and the way of evaluating them have to be indicated. As a few forms of imperfections of a given element of a traction motor may appear, which takes place in the case of other motor units [5], the application of a multi-valued evaluation of diagnostic features is required. It allows then for formulating the decision rules which constitute a basis for generating the diagnosis of the technical condition of the traction motor. A similar approach, however with the use of neuro-fuzzy adaptation conclusion techniques with reference to a low-power electric motor (driving the car wipers), was presented in [2].

2. THE MATHEMATICAL MODEL OF A MOTOR

Electric traction motors in rail vehicles operate in significantly more severe conditions than the motors in stationary machines. It results from both the character of loading which changes quickly within the range from 0% to 200% of the rated torque and the unfavourable outdoor conditions (high humidity, powerful shocks and dust). Metal filings which are the result of wearing out cast iron brake inserts are extremely dangerous. The dust of metal filings penetrates into the motor through the ventilation system. It can cause an insulation breakdown and damage of the traction motor. Moreover, the outdoor temperature that changes in Poland from -30^0C to $+40^0$C respectively to the year season considerably influences the motors operation conditions. Significant fluctuations of voltage in the traction contact power line resulting from e.g. the way of powering (a changing distance between the vehicle and the power source) constitute an additional factor that worsens these conditions. Sudden power failures cause overvoltage that is dangerous to the motor windings.

Nowadays, two types of driving motors are used in traction rail vehicles: conventional series excited DC motors and synchronous or asynchronous motors powered by an inverter.

Figure 1 shows a scheme of powering of series excited DC motor. At the moment this type of a motor is commonly used both in traction rail vehicles and in trams. Although this application is slowly being withdrawn, it will be still used in the coming years. The proceeding methodology presented in this paper can also be successfully used in the analysis of the defects of AC motors.

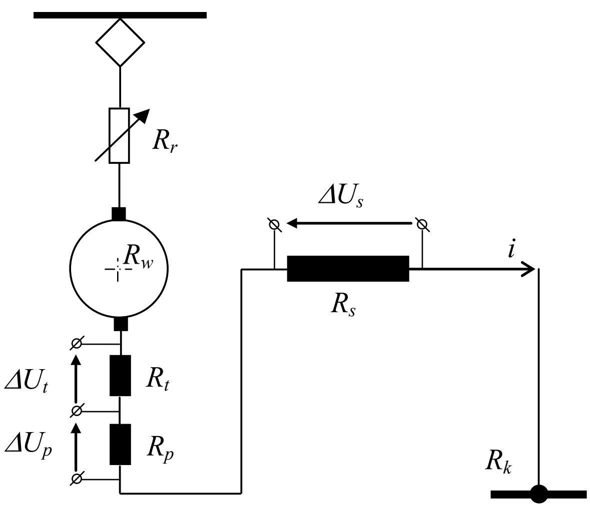

Fig. 1. A scheme of the control system of a series excited DC traction motor: R_r – start-up resistor, R_w – armature winding, R_s – series field winding, R_t – interpole winding, R_p – compensating winding , R_k – rail, ΔU_s, ΔU_t, ΔU_p – voltage drops on relevant windings

Using Figure 1 and assumptions referring to the operational conditions of a motor one can determine its analytical model in a form of a system of electromechanical equations which describe the electrical and mechanical phenomena for the motor's work:

$$U = \left(r_r + r_w + r_t + r_p + r_s\right) i + L\frac{di}{dt} + E \qquad (1)$$

$$J\frac{d\omega}{dt} = M_e - M_z \qquad (2)$$

where: U – supply voltage,

i – armature current,

ω – angular velocity of the rotor,

r_r – resistance of the start-up resistor,

r_w – resistance of the armature winding,

r_t – resistance of the interpole winding,

r_p – resistance of the compensating winding,

r_s – resistance of the series field winding,

L – total inductance of the armature circuit,

J – moment of inertia of the rotating parts,

M_z – mechanical load torque,

$\varphi = f(i)$ – magnetic flux generated by the series field winding,

c_m, c_e – the constants of DC machine,

E – electromotive force $E = c_e \varphi \omega$,

M_e – the electromagnetic torque of DC motor $M_e = c_m \varphi i$.

The quantities present in the equations such as U, r_r, r_t, r_p, J, L can be measured in a real system, and the M_z can be determined using the way of complex calculations as the function of many variables or using the method of direct measurements. The remaining ones, i.e.: $\varphi = f(i)$, r_w, r_s, c_m, c_e are the values supplied by the manufacturer of the motor.

An additional value which is taken into account is the power of the electric motor N_s which can be derived from the formula:

$$N_s = M_e \omega \qquad (3)$$

The above-shown systems of equations which create a mathematical model of an electric traction motor enable for a full simulation of its work. This simulation can be conducted in real time so there is the possibility of currently comparing the characteristic values of an operating motor to its equivalents obtained from the mathematical model. This idea is shown in Figure 2.

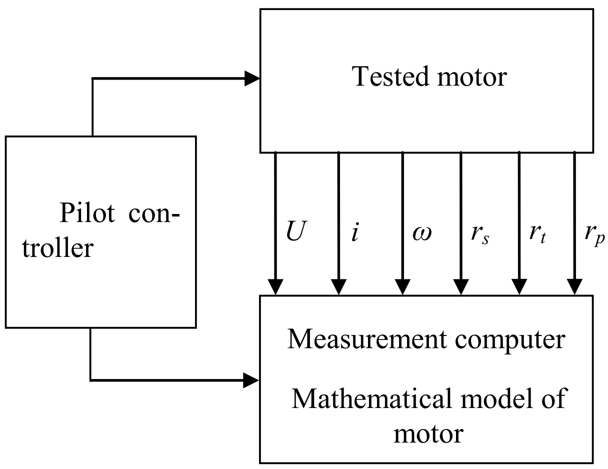

Fig. 2. A scheme of operation of the identification system of the traction motor damage

Since the whole system is controlled by the pilot controller, the condition of the motor work is identical to the mapping model. The ability of a continuous comparison of the mentioned values is an additional advantage to the system because it enables a continuous evaluation of the motor technical condition and the identification of the motor's possible faults. In order to achieve this it is necessary to formulate for the given type of a motor the boundary conditions of all the values whose exceeding leads to the occurrence of the imperfections in the examined motor. It is done by placing a computer in a traction vehicle. The computer should be equipped with the proper software which enables a current signalling of possible faults. The proper instrumentation (measuring devices) of the motor is also required. There also should be conducted an analysis of the possibilities of identifying imperfections which appear in the system.

3. THE FORMAL MODEL OF EVALUATION OF THE DIAGNOSTIC FEATURES

The configuration from Figure 1 can be shown as a functional model [3, 4] that consists of five distinguished elements creating a set which, in this case, may be determined on the basis [6] in the following way:

$$E = \{ e : e_j \wedge j \in N \wedge 1 \le j \le 5 \} \tag{4}$$

where: E – object,
e_j – object component elements,
j – identifier from the set N (natural numbers).

Bonds between the model elements (presented in Figure 3) symbolize a possibility of reverse propagation of the error. It means that the imperfections of the given elements influence the values of the diagnostic features of the preceding elements in this configuration.

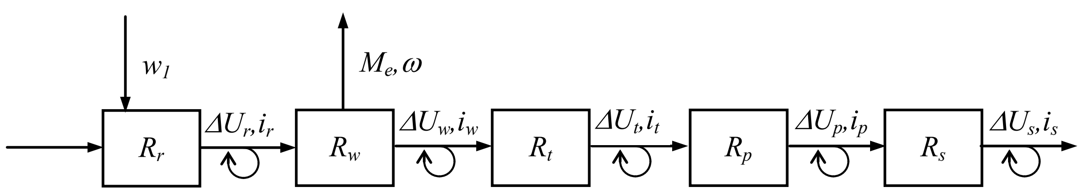

Fig. 3. A functional model of the power supply system of an electric traction motor: w_I – the position of the pilot controller (the position of a start-up resistor) , $\Delta U_r \div \Delta U_s$ – the values of voltages, $i_r \div i_s$ – the values of current intensity

In the case of electric system elements, the appearance of such basic faults like a break in the circuit or the insulation punch-through can significantly influence the values of the object's diagnostic features, i.e. generate separate technical conditions. That is why, for each i element of the examined object, a set of technical conditions S_j can be determined. This set contains:

– the ability condition - S_j^o ,
– the imperfection condition caused by the insulation punch-through - S_j^n ,
– the imperfection condition of the element which results from a break in the circuit - S_j^d ,

which is:

$$S_j = \left\{ S_j^o, S_j^n, S_j^d \right\} \tag{5}$$

A graph of walks between the element conditions is shown in Figure 4. In operation it is possible to go from the ability condition to one of the two imperfection conditions. A return to the ability condition takes place after the appropriate operational activities (repairs) have been completed.

Walks from the ability condition to each of the imperfection conditions of the power supply system distinguished in (5) are connected with the influencing the values of the diagnostic features, i.e.

- voltage drop - ΔU_j,
- current intensity - i_j.

Theoretically, if we take into consideration the number of the compound elements in the model of an object, as in Figure 3, (in the situation when in the system in which there are m forms of the imperfection of these elements and additionally it is impossible to guarantee that the imperfection of one element causes the immediate imperfection of the whole object) then the complete set of the technical conditions SU_m [7] will have the following form:

$$SU_m = \left\{ S_0, S_1, \ldots, S_k, \ldots, S_{k \times r}, \ldots, S_{l_m - 1} \right\} \tag{6}$$

where: $l_m = (m+1)^5$ – the number of technical conditions equal to the number of the k-term variations with repetitions from the set of the $m+1$ elements ($l_m = 3^5 = 243$).

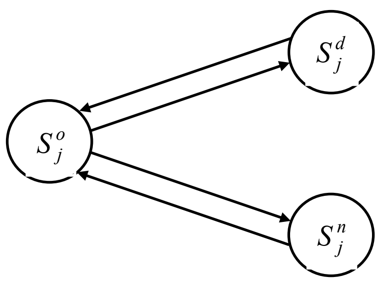

Fig. 4. A graph of walks for the set of the conditions of the power supply element of an electric traction motor

With a binary evaluation of the object diagnostic features shown in Figure 3 there is no way to distinguish such a numerous set of technical conditions determined from the Formula (6). To increase the potential ability of the identification of the conditions in objects in which more than one imperfection form of compound elements is present, besides choosing more than one diagnostic feature for each element one has to accept a three-valued mode of the evaluation of these features. In the latter case, the measured values of each feature must be subjected to a three-valued evaluation with the use of the characteristic function $\phi_3(y_j)$ in the following form [5]:

$$z_j^3 = \phi_3(y_j) = \begin{cases} 0, \ if \ y_j < (y_j)_{min} \\ 1, \ if \ (y_j)_{min} \le y_j \le (y_j)_{max} \\ 2, \ if \ y_j > (y_j)_{max} \end{cases} \tag{7}$$

where: z_j^3 – the result of the evaluation of the measured value of the diagnostic feature y_j.

4. THE DISTINGUISHING OF THE CHOSEN TECHNICAL CONDITIONS OF AN ELECTRIC TRACTION MOTOR

Due to their importance to the life cycle of an electric traction motor the following typical faults of the motor have been chosen for the further analysis:

- a winding short-circuit in the series field winding, i.e. technical condition S_s^z,
- a winding short-circuit in the interpole winding, S_t^z,
- a winding short-circuit in the compensation winding, S_p^z,
- a winding short-circuit in the start-up resistor, S_r^z,
- a break in the section of the start-up resistor, S_r^d.

These measurements may be additionally complemented with the monitoring of the resistance of the motor insulation and the controlling of the condition of the start-up resistor.

The symptom quantities [1] for the system as in Figure 3 evaluated by the characteristic function (7) with $i = i_r = i_w = i_t = i_p = i_s$ are:

- the resistance of the start-up resistor

$$r_r = \frac{\Delta U_r}{i} \tag{8}$$

- the resistance of the commutation winding

$$r_t = \frac{\Delta U_t}{i} \quad (9)$$

– the resistance of the compensation winding

$$r_p = \frac{\Delta U_p}{i} \quad (10)$$

– the resistance of the excitation winding

$$r_s = \frac{\Delta U_s}{i} \quad (11)$$

An accurate determination of the imperfection criteria of the elements of the examined motor, i.e. stating the permissible degree of changing a certain value in comparison to the standard value, is very important to the process of technical condition distinguishing. The accurate determination of these boundary values may be carried out only during examinations in a real system. It can be preliminary assumed that, e.g. the change of the evaluated value by ±5% already indicates the imperfection of an object element. However, the value of such a criterion may be different for each evaluated value.

Individual differences between motors in rail vehicles may also constitute a certain problem. It can be, however, solved in a simple way by introducing the corrective coefficients remembered by a system in the data base and then used in need.

A diagnostic matrix (Table 1) may be built for the analyzed and specified technical conditions. The values of the evaluations of the symptom quantities are presented in the columns.

The evaluation values from Table 1 allow for a formal determination of the individual technical conditions. They are:

– for the ability condition S_0

$$S_0 \Leftrightarrow \begin{Bmatrix} w_1 = 1 \wedge U = 1 \wedge R_r = 1 \wedge R_w = 1 \wedge \\ R_t = 1 \wedge R_p = 1 \wedge R_s = 1 \wedge i = 1 \wedge M_e = 1 \wedge \omega = 1 \end{Bmatrix} \quad (12)$$

– for the imperfection condition S_s^z

$$S_s^z \Leftrightarrow \begin{Bmatrix} w_1 = 1 \wedge U = 1 \wedge R_r = 1 \wedge R_w = 1 \wedge \\ R_t = 1 \wedge R_p = 1 \wedge R_s = 0 \wedge i = 1 \wedge M_e = 1 \wedge \omega = 1 \end{Bmatrix} \quad (13)$$

– for the imperfection condition S_t^z

$$S_t^z \Leftrightarrow \begin{Bmatrix} w_1 = 1 \wedge U = 1 \wedge R_r = 1 \wedge R_w = 1 \wedge R_t = 0 \wedge \\ R_p = 1 \wedge R_s = 1 \wedge i = 1 \wedge M_e = 1 \wedge \omega = 1 \end{Bmatrix} \quad (14)$$

– for the imperfection condition S_p^z

$$S_p^z \Leftrightarrow \begin{Bmatrix} w_1 = 1 \wedge U = 1 \wedge R_r = 1 \wedge R_w = 1 \wedge R_t = 1 \wedge \\ R_p = 0 \wedge R_s = 1 \wedge i = 1 \wedge M_e = 1 \wedge \omega = 1 \end{Bmatrix} \quad (15)$$

– for the imperfection condition S_r^z

$$S_r^z \Leftrightarrow \begin{Bmatrix} w_1 = 1 \wedge U = 1 \wedge R_r = 0 \wedge R_w = 1 \wedge R_t = 1 \wedge R_p = 1 \wedge R_s = 1 \wedge \\ (i = 1 \vee i = 2) \wedge (M_e = 1 \vee M_e = 2) \wedge \omega = 1 \end{Bmatrix} \quad (16)$$

– for the imperfection condition S_r^d

$$S_r^d \Leftrightarrow \begin{Bmatrix} w_1 = 1 \wedge U = 1 \wedge R_r = 0 \wedge R_w = 1 \wedge R_t = 1 \wedge R_p = 1 \wedge R_s = 1 \wedge \\ i = 0 \wedge (M_e = 1 \vee M_e = 0) \wedge \omega = 1 \end{Bmatrix} \quad (17)$$

For each formula (12 -17), one can write the proper variants of procedures of computer evaluation with taking into account each possible situation. Regardless of the taken program language, adequate simple or complex conditional instructions of the type: *if ... then ...else* can be

Table 1. A diagnostic matrix for the distinguished imperfections of an electric traction motor: S_0 - the system ability condition

Item number	Technical condition	The evaluation of entries									
		w_1	U	R_r	R_w	R_t	R_p	R_s	i	M_e	ω
1.	S_0	1	1	1	1	1	1	1	1	1	1
2.	S_s^z	1	1	1	1	1	1	0	1	1	1
3.	S_t^z	1	1	1	1	0	1	1	1	1	1
4.	S_p^z	1	1	1	1	1	0	1	1	1	1
5.	S_r^z	1	1	0	1	1	1	1	$1 \vee 2$	$1 \vee 2$	1
6.	S_r^d	1	1	2	1	1	1	1	0	$1 \vee 0$	1

easily constructed. It must be added that there can be a few variants of concrete solutions in each case. For example, for Formula (12) which identifies the ability condition S_0 it can be:

```
if (w1=1) and (U=1) and (Rr=1)
and (Rw=1) and (Rt=1) and
(Rp=1)
  and (Rs=1)and (i=1) and (Me=1)
and (omega=1) then xk:=S0;
```

For Formula (13), i.e. the imperfection condition S_s^z, the form of the conditional instruction is as follows:

```
if (w1=1) and (U=1) and (Rr=1)
and (Rw=1) and (Rt=1) and
(Rp=1)
  and (Rs=0)and (i=1) and (Me=1)
and (omega=1) then xk:=Ss_z;
```

Another example, for Formula (16) – the condition S_r^z – it can be as follows:

```
if (w1=1) and (U=1) and (Rr=1)
and (Rw=1) and (Rt=1) and (Rp=1)
  and (Rs=1)and ((i=1)or(i=2))
and ((Me=1)or(Me=0)) and
(omega=1)
  then xk:=Sr_z;
```

Each value of the variable `xk` present in the conclusion part of the instruction can have an adequate message assigned to. This message can be displayed or printed as a result of checking which goes on in real time. The value of this variable can also be used by the control system to perform the adequate reaction to a rising situation.

5. SUMMARY

The realization of the idea of the identification system of faults in an electric traction motor requires undertaking certain technical and programming enterprises. The technical enterprise is the adaptation of motors for diagnostic tests, i.e. the installation of the control-measurement devices and the establishing of connections with a tested object and the on-board computer. The constructing of a proper software must refer to the two co-operating modules, i.e.:

- the motor load simulation module,
- the technical condition evaluation module.

Both of these modules have to use the properly designed database where it is necessary to save the data of the measured values, the determinants of the taken decisions, and the auxiliary data.

The values of the measured quantities, if they all are within the permissible range, can be recorded in temporary registers. In the opposite case, they should be saved in the database as a significant event which has to be analyzed.

The data which shows the conditioning of the taken decisions must be introduced earlier at the stage of the system testing. This data includes:

- the boundary values of the measured quantities,
- the trends of changes of the values of these quantities,
- the relation operators of their evaluation,
- the set of operational decisions.

Among the auxiliary data, the information about the following items should be recorded:

- the way of the identifying of electric traction motors and their location in vehicles,
- the values of the individual corrective coefficients of the boundary values of the measured quantities which are assigned to the individual motors,
- the parameters of the test distances for testing the motor load,
- the persons who drive the vehicles.

The possibility of supplementing the set of the recognized technical conditions of electric traction motors is an additional advantage of such a designed system. It is done with the use of the analysis of the data gathered in the system during the operation of vehicles.

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