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Evaluation Research of Traction Motor Performance for Mine Dump Truck Based on Rough Set Theory

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Abstract

This paper presents the traction motor evaluation method depending on the electric transmission energy transfer characteristics and different source of supply, including motor manufactures, diesel turbine manufacturers, wheel side reducer manufacturers and electric drive system integrated manufacturers. 9 evaluations are proposed in 3 levels from the motor body and control performance, electric drive system coordinate index, driving conditions and specific cycle. Motor performance evaluation system is published by the means of electric transmission tests and computer simulation platform, using rough set theory. Experimental results show that the model can accurate evaluation of state of the traction motor, Evaluation of the accuracy is better than the subjective weighting analysis, verifying the integrity and usefulness of this valuation method. At the same time, the comprehensive evaluations index of permanent magnet synchronous motors is high, it has important research value.

***Keywords**: Vehicle Engineering, Transport, traction motor, rough set theory, evaluation*

1. Introduction

Currently, large dump truck as the main means of transport for large open pit mine bears 40% of the world's coal, 90% of the iron ore mining traffic [1]. Electric Drive is used in mining manufacturers of more than a hundred-ton mining dump truck except the Caterpillar Company. The electric drive system structure is simplified, easy to operate, maintain and energy efficient. Large mining trucks develop to electric drive is an inevitable trend. At the same time, Traction motor characteristics have an important impact on the vehicle dynamic parameter. The matching and evaluation of Motor vehicle driver and vehicle performance is now an issue that needs to be addressed as a matter of urgency.

In the process of choosing traction motor, its evaluation and assessment have been often out of the vehicle electric drive system; just relying on the drive motor bench test or basic parameters matching test. It's difficult to guarantee the accuracy and objectivity of the evaluation, more difficult to achieve efficient use of the system. In the electric drive system of large tonnage dump truck, optional range diesel turbine is limited in scope. Therefore, it is necessary to establish comprehensive evaluation system as the core of a traction motor to provide a theoretical basis for the determination of the overall design of dump truck.

Dump truck electric transmission evaluation at home and abroad is also less，and often for the match and the fuel consumption of the hybrid vehicle power system analysis and evaluation [2]-[9].Domestic Beijing Institute of Technology Wang Wei [10], finish the gray correlation and experimental simulation of the motor performance ;Foreign Livint Gheorghe [11] illustrated evaluation for hybrid electric vehicle control algorithm analysis ,Sung Chul [12] use hardware in the ring needle evaluation and analysis of electric car motors,These studies did not focus on the electric drive system.

According to a variety of vehicle traction motor and electric drive system features, different from the general hybrid vehicles. This paper presents the traction motor evaluation method depending on the electric transmission energy transfer characteristics and different source of supply ,including motor manufactures, diesel turbine manufacturers, wheel side reducer manufacturers and electric drive system integrated manufacturers. 9 evaluations are proposed from 3 levels from the motor body and control performance, electric drive system coordinate index, driving conditions and specific cycle. Motor performance evaluation system is

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published by the means of electric transmission tests and computer simulation platform, using rough set theory.

2. Drive motor evaluation process

Depending on the type of traction motor basic performance and demand characteristics of mining dump truck motor, mining trucks traction motor evaluation system of "Two vertical and three horizontal" is proposed. As Figure 1 shows, three horizontal mainly refers to the traction motor manufacturers, manufacturers of electric drive systems and integrated vehicle manufacturers, two vertical mainly refers to drive motor bench testing and computer simulation platform which is the evaluation testing means of drive motor system. Bench test mainly tests the inherent performance of the motor system, the vehicle driving cycle simulation is to examine the run performance of drive motor in driving conditions.

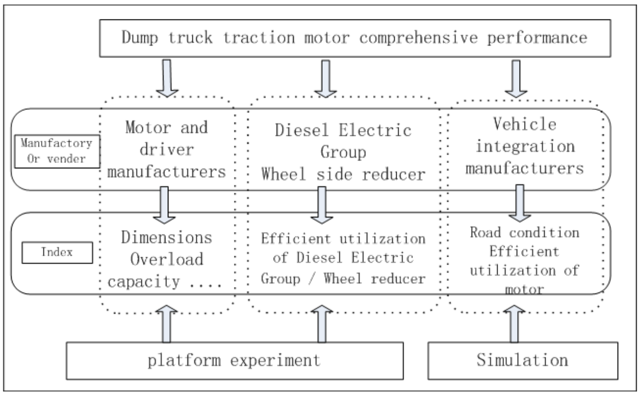

Figure 1. Traction motor evaluation system diagram

3. Dump truck evaluation index

The main types of dump truck driving motor include[13]:AC induction motor (IM), permanent magnet synchronous motor (PMSM), brushless DC motor (BLDC), DC the brush motor (BDC)and switched reluctance motor (SRM). Each type of drive motor has a unique structure design and control algorithms, while the selected drive motor type the hybrid vehicle of different structural forms is not the same. Therefore, combined with the basic characteristics of different types of vehicles and the vehicle condition, nine types of evaluation is presented comprehensively. Among these motors, AC asynchronous motor is the mostly widely used. In order to evaluate more intuitive and full use of existing data, multiple sets of ACIM is used for comparison.

3.1. Motor body and Control indicators

Electric dump truck wheel motor is placed directly in the wheel hub, and combined with the drive system, brakes and wheel side reducer as a whole; this installation and transmission form has a high demand for the volume of the motor. Consider the mine dump truck tonnage load characteristics, to stress overload and constant power range, and to meet the basic requirements of the rated condition, the following six indicators is comprehensively proposed: Efficient area overload capacity, constant power range, response time, cost and volume manipulation. Among them, overload capacity and control response time refers to the data of the rated conditions.

3.2. Electric drive system combining index

The so-called electric drive system is that: fuel energy pass through the engine, generator rectifier inverter, and finally export energy after the mechanical part of the wheel side reducer tire. To make the system fully efficient operation, the entire system should run on efficient district. On the base of definition of motor itself efficient district, motor development degree index is presented in the paper, they are diesel generator group efficient development degree index and wheel side reducer efficient development degree index. The motor itself efficient interval is defined as following:

$$\eta_{mo\_eff} = \frac{N_{mo\_i}}{N_{mo}} \tag{1}$$

Where, $N_{mo\text{-}i}$ is amount of motor operating points drop in the efficiency zone, N_{mo} is all amount of motor operating points

According to the corresponding speed relationship between the motor and diesel motor group, efficient utilizing index of diesel electric group can be obtained as following:

$$\eta_{de\_eff\_i} = \frac{i_{de\_mo} N_{mo\_de\_i}}{N_{de\_i}} \tag{2}$$

Where, $N_{mo\text{-}de\text{-}i}$ is amount of motor and diesel electric group operating points drop in the efficiency zone at the same time, $N_{de\text{-}i}$ is all amount of diesel electric group efficient operating points

The efficient utilizing formula is similar for wheel side reducer and diesel electric group, the range which motor accounts for should be concluded in the wheel side reducer efficient range.

3.3. Driving cycle combining index

Mining dump truck driving conditions are complex and changeable. With regard to such working condition, we must also consider the basic speed of the vehicle and motor to match the design of the entire system. In this propose, the vehicle index in the efficient use of interval is presented as following :

$$\eta_{\mathrm{R}\_eff\_i} = \frac{N_{\mathrm{R}\_mo\_i}}{N_{mo\_i}} \tag{3}$$

Where, $N_{mc\text{-}i}$ is amount of motor common operating points drop in the efficiency zone. Nmc is all amount of motor efficient operating points.

4. Rough set evaluation method

Main idea of rough set theory is to approximate portrayed imprecise or uncertain knowledge by using the knowledge in the knowledge which we have known. That is, when the object information is uncertain, inexact approximate, classifying the data and inferring the relationship between the reasoning data in order to identify implicit knowledge to reveal potential law, and then complete the judgmental forecasting and decision-making of things [14].

4.1 Determination of the functional properties

Relational data modeling: evaluation index is used as the condition attribute, and then the condition attribute collection C= $\{c_1,c_2,\ldots,c_n\}$; Regarding expert evaluation of the results as the decision attribute, then the decision attribute set D= $\{y\}$. Regarding the index value of the k-objects to be evaluated and the final composite score as a system of knowledge, then we can define uk=$(c_{1k}, c_{2k}, \ldots c_{nk}, y_k)$, thus U= $\{u_1,u_2,\ldots,u_m\}$, Two-dimensional information table constituted by uk is relational data model about the evaluation object.

4.2. The function attribute data processing

First, some attribute indicators can be quantified in the evaluation system, some attribute index can not be quantified.The indicators which can not be quantified may take the form of scoring by experts to determine the possibility of good or bad, Quantifiable indicators data can be rated according to the measure values. Because different indicators is different on the magnitude and the dimensionless, even the impact direction on evaluation objectives is also inconsistent.Therefore, the the rating rules should be in unified magnitude and eliminate dimensionless, the scoring method is as follows [15]:

When indicators are bigger the better

$$y_{ij} = \frac{x_{i\max} - x_{ij}}{x_{i\max} - x_{i\min}} \times 100\% \tag{4}$$

When indicators are smaller the better

$$y_{ij} = \frac{x_{ij} - x_{i\min}}{x_{i\max} - x_{i\min}} \times 100\% \tag{5}$$

Continuous data must be discretized, there are many discretization methods.According to the actual situation someone can be selected.In this paper, the the equidistant attributes discretization is choosen.

a.calculatin of the attribute interval length

$$\overline{z_i} = (z_{i\max} - z_{i\min}) / ni \tag{6}$$

where, zimax is the maximum of the i-th attribute; zimin is the the minium of the i-th attribute; ni the number of intervals.

b.Determine the properties of the interval range. The range of each interval of the i th attribute is

$$\left[z_{i\min},\ z_{i\min} + \overline{z_i}\right],\ \left[z_{i\min} + \overline{z_i},\ z_{i\min} + 2\overline{z_i},\right],\ \ldots,\ \left[z_{i\min} + (n_i - 1)\overline{z_i},\ z_{i\max}\right] \tag{7}$$

c.Calculate the quantized value of the property.

4.3. Determination of functional attribute weights

In the multi-index evaluation, different functional attributes may have different importance.By rough set theory, when some properties added to the classification,the system will directly be affected. In order to find out the importance of certain functional properties,the method is to remove some functional properties, and then examine the classification changes after the attribute. If the attribute is removed, the corresponding changes in the classification is great, the strength of the properties is high, that is of high importance. Conversely, the strength of the properties.That is of low importance . Weight multi-index evaluation can be determined by importance principle in rough set attribute

Dependence of the knowledge D (decision attribute index) to the knowledge of C (evaluation set):

$$\gamma_{c-\{ci\}}(D) = card\,(pos_{C-\{ci\}}(D) / card\,(U) \tag{8}$$

Calculation of the evaluation importance $\sigma(ci)$:

$$\sigma(ci) = \gamma_c(D) - \gamma_{c-\{ci\}}(D) \tag{9}$$

Weight coefficient of evaluation:

$$\lambda_i = \sigma(ci) / \sum_{j=1}^{n} \sigma(c_j) \tag{10}$$

5. Application examples

5.1. Determination of attributes and evaluation system

16 sets of traction motor data mining trucks in different tonnage are applied for the reference sample,rough set thory is used for data mining and allocation weighting coefficient to evaluate comprehensive quality. Condition attribute set C={ c_1 Efficient range, c_2 Overload multiple, c_3 Constant power range, c_4 Torque response time, c_5Cost, c_6Volume, c_7 Diesel Electric Group Efficient range, c_8 Wheel side reducer efficient range, c_9 Traffic efficient range} ; Decision attribute set D={ y The motor evaluation index average score} , C is shown as table 1:

Table 1. motor evaluation parameters of various types

Performance Indicators	c_1/%	c_2	c_3	c_4/ms	C_5\$/kw	C_6/kw	C_7 /%	C_8/%	C_9/%
IM1	81	1.3	3.5	40	9	460	80	90	81
IM2	80	1.2	3	45	10	452	81	91	82
IM3	82	1.35	3	44	8.9	450	90	92	82
IM4	83	1.4	2.5	46	10.2	442	82	89	83
IM 5	84	1.5	3	44	9.5	443	83	92	82
IM6	86	1.2	3	43	9.6	449	81	92	87
PMSM1	93	1.8	3	30	13	410	90	91	89
PMSM 2	88	1.7	3	28	13.5	420	92	92	90
PMSM 3	80	1.3	3.5	42	9.6	455	81	89	82
PMSM 4	88	1.7	2.7	32	13.4	409	93	93	89
BLDC1	77	1.5	3.2	43	11	456	82	92	81
BLDC2	76	1.65	2.5	46	10.2	457	82	91	82
BLDC3	75	1.6	2.4	47	10.1	460	83	92	84
SRM1	76	1.6	2.9	36	11.5	420	92	85	91
SRM2	76	1.62	2.8	38	12	421	91	80	92
SRM3	79	1.6	3.1	43	9.6	452	83	92	85

5.2. Data processing

Motor evaluation shows that they are all quantifiable indicators, except C_4, C_5 is the smaller the better,the rest are the bigger the better indicators.According to the national institute standards and the actual use requirements,evaluation of the upper and lower limits are presented as equation (11).

$$\begin{Bmatrix} x_{1\min} & x_{1\max} \\ x_{2\min} & x_{2\max} \\ x_{3\min} & x_{3\max} \\ x_{4\min} & x_{4\max} \\ x_{5\min} & x_{5\max} \\ x_{6\min} & x_{6\max} \\ x_{7\min} & x_{7\max} \\ x_{8\min} & x_{8\max} \\ x_{9\min} & x_{9\max} \end{Bmatrix} \Rightarrow \begin{Bmatrix} 70 & 95 \\ 1 & 2 \\ 2 & 4 \\ 25 & 55 \\ 8 & 15 \\ 400 & 500 \\ 70 & 95 \\ 70 & 95 \\ 70 & 95 \end{Bmatrix} \tag{11}$$

Table 2. Score

U	C1	C2	C3	C4	C5	C6	C7	C8	C9	D
1	44	30	75	50	86	40	40	80	44	54
2	40	20	50	33	71	48	44	84	48	49
3	48	35	50	37	87	50	80	88	48	58
4	52	40	25	30	69	58	48	76	52	50
5	56	50	50	37	79	57	52	88	48	57
6	64	20	50	40	77	51	44	88	68	56
7	92	80	50	83	29	90	80	84	76	74
8	72	70	50	90	21	80	88	88	80	71
9	40	30	75	43	77	45	44	76	48	53
10	72	70	35	77	23	91	92	92	76	70
11	28	50	60	40	57	44	48	88	44	51
12	24	65	25	30	69	43	48	84	48	48
13	20	60	20	27	70	40	52	88	56	48
14	24	60	45	63	50	80	88	60	84	62
15	24	62	40	57	43	79	84	40	88	57
16	36	60	55	40	77	48	52	88	60	57

5.3. Weight determination

Using Eq.11 to calculate the score of each index, such as shown in Table 2; Using Equations (6) and (7) to determine discrete each attribute interval, according to the size of each attribute range. Discrete data should be finished. The results are shown in Table 3.

Table 3. System simplifies

U	C1	C2	C3	C4	C5	C6	C7	C8	C9	D
1	2	1	3	1	3	1	2	3	1	2
2	2	1	3	1	3	1	1	3	1	1
3	2	1	3	1	3	1	3	3	1	2
4	2	1	1	1	3	1	2	3	1	2
5	2	1	3	1	3	1	2	3	1	2
6	2	1	3	1	3	1	2	3	2	2
7	3	3	3	3	1	3	3	3	3	3
8	3	3	3	3	1	3	3	3	3	3
9	2	1	3	1	3	1	2	3	2	2
10	3	3	2	3	1	3	3	3	3	3
11	2	1	3	1	2	1	2	3	1	2
12	2	2	1	1	3	1	2	3	1	1
13	1	2	1	1	3	1	2	3	1	1
14	2	2	2	2	2	2	3	2	3	2
15	2	2	2	2	2	2	3	1	3	2
16	2	2	3	1	3	1	2	3	2	2

From the Table.3 the deduction is as following:

U/indD={(1,2,3,4,5,6,9,12,14,15,16),(7,8,10),(12,13)}
U/indC={(1,5),(2),(3),(4),(5),(6),(7),(8),(9),(10),(11),(12),(13),(14),(15),(16)};
U/ind(c2,c3,c4,c5,c6,c7,c8,c9,c10,c11,c12)={(1,5),(2),(3),(4),(6),(7),(8),(9),(10),(11),(12,13),(14),(15),(16)};
U/ind(c1,c3,c4,c5,c6,c7,c8,c9,c10,c11,c12)={(1,5,16),(2),(3),(4),(6),(7),(8),(9),(10),(11),(12),(13),(14),(15)};
U/ind(c1,c2,c4,c5,c6,c7,c8,c9,c10,c11,c12)={(1,4,5),(2),(3),(6),(7),(8,10),(11),(12),(13),(14),(15),(16)};
U/ind(c1,c2,c3,c5,c6,c7,c8,c9,c10,c11,c12)={(1,5,9),(2),(3),(4),(6),(7),(8),(10),(11),(12),(13),(14),(15),(16)};
U/ind(c1,c2,c3,c4,c6,c7,c8,c9,c10,c11,c12)={(1,5,11),(2),(3),(4),(6),(7),(8),(9),(10),(12),(13),(14),(15),(16)};
U/ind(c1,c2,c3,c4,c5,c7,c8,c9,c10,c11,c12)={(1,5),(2),(3),(4),(5),(6,9,16),(7),(8),(10),(11),(12),(13),(14),(15)};
U/ind(c1,c2,c3,c4,c5,c6,c8,c9,c10,c11,c12)={(1,5),(2,3),(4),(5),(6),(7),(8),(9),(10),(11),(12),(13),(14),(15),(16)};
U/ind(c1,c2,c3,c4,c5,c6,c7,c9,c10,c11,c12)={(1,5),(2),(3),(4),(5),(6),(7),(8),(9),(10),(11),(12),(13),(14,15),(16)};
U/ind(c1,c2,c3,c4,c5,c6,c7,c8,c10,c11,c12)={(1,5,6),(2),(3),(4),(5),(6),(7),(8),(9),(10),(11),(12),(13),(14),(15),(16)};

And then,
posc(D)= 14; posc-c1(D)= 12; posc-c2(D)= 13; posc-c3(D)= 11; posc-c4(D)= 13;
posc-c5(D)= 13; posc-c6(D)= 11; posc-c7(D)= 12; posc-c8(D)= 12; posc-c9(D)= 13

From the Eq.8 and 9, we can get:
γc(D)=14/16; γc-{c1}(D)=12/16; γc-{c2}(D)=13/16; γc-{c3}(D)=11/16; γc-{c4}(D)=13/16;
γc-{c5}(D)=13/16; γc-{c6}(D)=11/16; γc-{c7}(D)=12/16; γc-{c8}(D)=12/16; γc-{c9}D)=13/16。

From Eq.10 we get each weight indicators:
λ1=0.125; λ2=0.0625; λ3=0.1875; λ4=0.0625; λ5=0.0625; λ6=0.1875; λ7=0.125; λ8=0.125; λ9=0.0625;

Analysis of the final weight indicator shows that: the constant power range and volume of a larger size will affect the motor's comprehensive evaluation index, but overload multiples, response time, cost and traffic utilization factor is little difference in a variety of motor evaluation should be relatively weakened.

For example, take the original average the 7th highest permanent magnet synchronous motor analysis, we can see than E7 = 74.99%, further highlighting the advantages in the original basis. Overall evaluation of permanent magnet synchronous motor in the cost and control index is not very good, but the good comprehensive utilization rate makes the comprehensive evaluation index is high; on the other hand, induction motor although cost is low, but the comprehensive utilization rate is low, unable to play a maximum efficiency of the system. Switched reluctance motor and brushless DC motor control system based on the mature insufficiently, the comprehensive evaluation index in this field is not high, but has broad popularization prospect. This analysis shows that this system can be convenient for comprehensive evaluation of multi-motor.

The actual road conditions efficient use and the efficient using of diesel electric group must be combined with the real vehicle and platform experiment and analysis, In the platform experiment,diesel electric group and generators are as shown in Figure 2, Motor and dynamometer section is shown in Figure 3, the data in Table 3 is for manufacturers to provide a basic design data. The system we built ensures that energy transport from the diesel-electric group to motor after the rectifier inverter, by way of rectifier and inverter. Then the dynamometer turbine consumes the power. We selected the Cummins Engine (Cummins QSL9-C325) as shown in Figure 2. As shown in Figure 4, it's the engine speed-torque curve we measured in the laboratory. The engine common interval is from 1200 to 1800 rpm. This is enough to meet the demand for generators. Table 4 for the actual vehicle measurement data:

Figure 2. Diesel electric group and generators

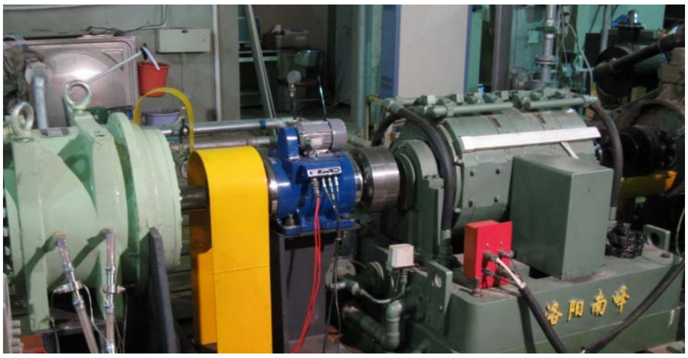

Figure 3 in-wheel motor and danamometer.

For efficient use of high efficient utilization of the actual road conditions and diesel generator, the wheel reducer must be combined with the real vehicle and platform experiment were measured and analyzed, the original data in Table 3 provide basic design data for the factory. Table 4 shows the real measurement data.

Table 4 measurement data

U	IM	PMSM	BLDC
Diesel Electric Group Efficient range /%	85	90	81
Wheel side reducer efficient range /%	82	92	85
Traffic efficient range /%	82	85	80

Comparison of the measured data, we found that the difference is not big for road use efficiency, the weight should be appropriately reduced, relative to the differences in the efficiency of the use of firewood in the electric drive is big different from hybrid cars drive turbine wheel side reducer, should be given full attention, adjust the weights, the advantage of permanent magnet synchronous motor is more apparent, which also bears out our rough sets to the accuracy of the theoretical system evaluation.

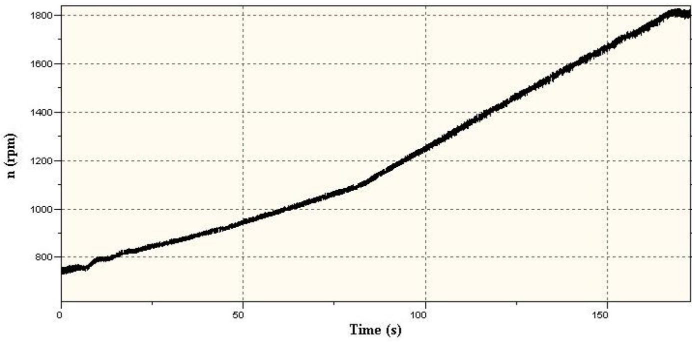

Figure 4.Measured commonly used engine curve

6. Conclusion

In accordance with the main source of supply of the dump truck electric drive system and electric drive energy transfer characteristics evaluation index system, a series of evaluation indicators proposed to make the motor evaluation more objective. The method of comprehensive evaluation based on rough sets mining dump truck traction motor, the evaluation index to make effective use of the rough set evaluation system. According to the importance of performance indicators index, based on rough sets empowering way, provides a theoretical basis for the selection of parameters of transmission system and electric motor matching, shorten the development cycle. The combination of platform experiment data, simulation results and real car long-term measurement data verify the accuracy and usefulness of the overall performance evaluation method based on the rough set method motor.

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