Fault Diagnosis of Tractor Start System Based on Structural Analysis Method

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Abstract. In order to achieve accurate positioning of the electrical failure of the tractor starting system, this paper designs a fault diagnosis system based on structural analysis. Firstly, through the analysis of the traction battery and the starting motor, this paper selects four key faults: battery resistance fault, motor armature resistance fault, motor armature fault and motor joint fault, and establishes the electrical fault model of the tractor starting system. Secondly, this paper divides the variables in the fault model into known variables, unknown variables and fault variables. Then the MATLAB dmperm command is used to analyze the observability and isolation of the unknown variables. We find that we can detect and isolate four faults by adding a voltage sensor based on the original engine speed sensor. Then select three equation sets as the test set in all the structural minimum set of over-determined equations (MSO sets), and design the residual value of each test set as the observer of the system. We find that four faults can be detected by different observers. Finally, we design the diagnostic strategy of the system: we select $[-1,1]$ as the feasible domain of the observation. If the value of the observer exceeds the feasible domain, the fault characteristic parameter is 1, otherwise it is 0. The fault feature vector is composed of three fault characteristic parameters and used as system fault judgment. 

In order to verify the correctness of the diagnostic system design, we use MATLAB to build the system simulation platform, which generated 4 faults in 3s-4s, 6s-7s, 9s-10s, 12s-13s respectively. The simulation results show that the results of the three observers are in line with the pre-test. It is determined that the fault feature vector can accurately locate the critical fault. This also shows the advantage of structural analysis for the electrical fault diagnosis of tractor starting systems, which can accurately locate system faults with only a small number of sensors.

Introduction

Agricultural machinery and equipment is one of the “Top Ten” key areas identified by “Made in China 2025”. Intelligent manufacturing is the inevitable direction for the development and upgrading of agricultural machinery and equipment industry. As a typical agricultural equipment product, the proportion of electrical equipment on tractors is getting higher and higher. Therefore, the research on the offline detection technology of tractor electrical faults has been paid more and more attention. This is to improve the quality of products and ensure the safety and reliability of products. Work in the ground is of great significance. The current tractor down-line detection technology has a traditional manual detection method, which relies on the experience of the workers to judge. There are direct observation method, open circuit test method, multimeter detection method, short-circuit test method, and ground test method\cite{1}. These traditional methods are labor intensive, backward in automation, low in detection efficiency, and cumbersome to test data records, making it difficult to accurately and efficiently detect, fault identification and data analysis of tractor electrical faults. There is also a tractor detection system based on virtual instrument
technology. Cai Jianping builds a tractor inspection solution based on the multi-function data acquisition card (DAQ) and the virtual instrument of the graphical programming language LabVIWE [2]. Wang Lida realized the connection of fault data to the database through virtual instrument and network connection[3]. This virtual instrument-based detection method has the advantages of low development and maintenance costs and short update cycle compared to the conventional method. The neural network simulation system is used to diagnose the fault of the tractor electrical system. Gao Hongbo has established a fault diagnosis system for tractor air conditioner electrical appliances based on neural network technology [4]. Tian Erlin et al. based on knowledge mining neural network algorithm and experience database combined with agricultural machinery fault diagnosis theory, comprehensively using neural network communication fault database and neural network DC fault database, formed a practical hierarchical neural network fault dictionary diagnosis model [5]. Although these methods can diagnose faults with high precision, the calculation speed is slow and the real-time performance is poor. The weights and thresholds in the network model are difficult to set, making it unsuitable for the rapid down-line detection of tractors.

There is also a transient signal detection method based on wavelet and sparse representation. Based on this method, Ren Xiaobing built a virtual instrument platform to detect the fault signal of the engine, and then compared the signal characteristics with the empirical features to judge the electrical fault of the engine [6]. However, this method requires spectral analysis, wavelet transform, etc., and the signal processing amount is large, resulting in fault diagnosis accuracy and efficiency.

Structural Analysis (SA) is a model-based fault diagnosis method. It mainly obtains the fault information by using the redundant relationship between the functions of different parts of the system, obtaining relevant redundant information and generating residuals by means of related technologies [7]. At the same time, the nature of the fault is reflected in the form of a graph, and the appropriate test set is solved by the corresponding graph to calculate the residual, which can realize fault-tolerant control and sensor layout design, thereby optimizing the detectability of the system fault[8]. At present, this method is widely used in automobile fault detection and diagnosis. Alessandro et al. analyzed the mechanical static friction fault and pedal sensor fault of the car pedal, and found that the structural analysis method can diagnose the fault without additional sensors [9]. Chen Qi et al. used this method to establish ABS fault diagnosis and identification system to realize the diagnosis of ABS critical faults [10]. Zhang Zhen et al. conducted a fault diagnosis study on a 6-speed automatic transmission and designed a robust and stable residual to verify the effectiveness of the fault diagnosis theory based on structural analysis [11]. Liu Zhentong studied and analyzed the different faults of the core components of electric vehicle power system - motor drive system and power battery pack, and proposed a practical and robust fault diagnosis method for different characteristics of the system [12]. Nyberg et al. proposed a model-based residual generation method and a data-driven residual statistical evaluation method for fault diagnosis and isolation of automotive engines [13]. Although the structural analysis method has not been widely used in the field of tractor detection, the method does not depend on specific numerical parameters, and only depends on the structural model of the system. It can quickly analyze the fault diagnosability in complex systems, and the design algorithm is simple. Effectively improve the efficiency of fault diagnosis, avoid misdiagnosis and missed diagnosis [14]. Therefore, it has a good application prospect in tractor testing.

This paper relies on the tractor testing technology research and system research project, using the structural analysis method, the process is shown in Figure 1, first based on the typical fault data of the tractor electrical components, the tractor failure model is established. Then analyze the structure and failure of the tractor system, generate the minimum set of overdetermined equations, screen out the appropriate test set, and design the sequence residuals. Finally, the appropriate diagnostic strategy is selected. The MATLAB software is used to establish the tractor electrical fault diagnosis system based on structural analysis method. The validity of the diagnostic method is verified, and the advantage of structural analysis method applied to tractor electrical fault detection is also reflected.
Establishment of Electrical Failure Model for Tractor Starting System

The starting process of the tractor is: the battery supplies power to the starting motor, the motor drives the engine to rotate through the transmission system, and finally transmits the torque to the load. The electrical components are the starter motor and the battery. The key faults are mainly the battery resistive fault during the starting process, the motor armature resistance fault, the motor armature coil fault and the motor joint fault, as shown in Table 1.

Table 1. Key electrical faults in the tractor starting system.

| Fault distribution | Failure mode               | Fault symbol |
|--------------------|----------------------------|--------------|
| Battery            | Resistive fault            | \( f_R \)    |
| Motor              | Armature resistance failure | \( f_{ra} \) |
|                    | Armature coil failure      | \( f_c \)    |
|                    | engagement fault           | \( f_e \)    |

Starter Motor

The function of the motor is to convert the electrical energy of the battery into mechanical energy, and the engine is rotated by the transmission mechanism to start the engine. A series-excited DC motor is usually used on the tractor. During the starting process, there may be faults with insufficient speed or failure to start. This is usually due to motor armature resistance failure or motor coil failure or motor and engine engagement failure, so set its electrical and Mechanical property equation:\[15]:

\[
e_1: \ V = E_a + (R_f + R_a + f_{Ra})I + L \frac{dI}{dt} \\
e_2: \ T_e - T_L = \frac{J}{375} \frac{\partial w_m}{\partial t} \\
e_3: \ \varphi = K \cdot I \\
e_4: \ E_a = (C_e + f_c) \varphi w_m \\
e_5: \ T_e = C_m \varphi I \\
e_6: \ T_L = T_0 + F(w_{eng}) \cdot w_{eng} \\
e_7: \ w_m = (r + f_r) \cdot w_{eng}
\]

In the formula ei(i=1,2,3…)—Equation number
Battery

The battery type is a lead-acid battery, which is used to supply 200~600A to the starter motor for more than 5s to start the tractor. Its main performance parameters are battery voltage, battery capacity and internal resistance. Ignoring the effect of temperature on the internal resistance of the battery and the internal resistance of the polarization, according to the Thevenin battery model, the battery failure model established in this paper is:

\[ E = V + (R_1 + f_{R_1})I + u \]
\[ I = \frac{u}{R_2} + C \frac{du}{dt} \]

In the formula:
- \(E\)—Battery electromotive force
- \(V\)—Operating Voltage
- \(R_1\)—Ohmic internal resistance
- \(R_2\)—Polarized internal resistance
- \(I\)—Working current
- \(u\)—Polarization voltage
- \(C\)—capacitance
- \(f_{R_1}\)—Resistance failure

Sensor

The advantage of structural analysis is that it uses a small number of sensor measurements to quickly and accurately analyze the measurability and isolation of system faults through the established system model. The tractor's own sensor has an engine speed sensor. If the sensor measurement value is ideal, there is no deviation, so set the sensor equation as follows:

\[ y_{w_{eng}} = w_{eng} \]
Start System Troubleshooting Strategy

Starting System Electrical Failure Analysis

The various variables in the tractor fault model can be divided into three categories: known variables, is sensor measurements; unknown variables, is model state variables; fault variables, corresponding to each fault mode of the system.

- Known variables: \( \{y_{\text{weng}}\} \);
- unknown variables: \( \{V, E_a, I, T_e, T_L, w_m, w_{\text{weng}}, \varphi, u\} \);
- fault variables: \( \{f_{R_1}, f_{R_2}, f_{C_e}, f_t\} \).

Based on this, an initial representation of the electrical structure of the tractor starting system can be established \(^{[16]}\). As shown in Fig. 2, * in the figure indicates that the corresponding equation contains corresponding variables. The graph is transformed into a matrix form, and the unknown variable is DM-decomposed by the dmperm instruction in MATLAB software. DM decomposition is a mathematical method of rearranging columns and rows of a sparse matrix resembling an upper triangle. System model can be used. Divided into three different areas \(^{[17]}\), As shown in Figure 3:

1. The structural underdetermined part \( M^- \), is the number of unknown variables is more than the number of equations;
2. The positive definite part of the structure \( M^0 \), is the number of unknown variables is equal to the number of equations;
3. The structure over determined part \( M^+ \), that is, the number of unknown variables is less than the number of equations.

Fault Detection (FD) means that if the fault \( f \) in the equation is located in the overdetermined part of the structure, the fault \( f \) can be measured \(^{[18]}\). In this paper, the TD decomposition results of the tractor fault equation are shown in Figure 4. The red dashed box is the over-determined part of the system model. The results show that all fault equations are located in the over-determined part, indicating that all system faults can be detected.

[Figure 2: Electrical structure representation of the tractor starting system.]

[Figure 3: Schematic diagram of DM decomposition.]
Fault isolation (FI) means that when a system fails, the fault can be isolated and located from other faults, which means that the fault source can be accurately located in a detectable situation [10].

For the faults $f_i$ and $f_j$, if the fault $f_i$ is still in the over-determined part of the system model after the system model removes the equation containing the fault $f_j$, then the faults $f_i$ and $f_j$ have no correlation, and vice versa. The formula is:

$$e_f \in (M/e_f)^+$$

In the formula $e_f, e_f$ -- Equation with faults $f_i, f_j$

$M$ -- Tractor failure model

$(M/e_f)^+$ -- Remove faulty $f_j$ structure overdetermined equation

Obtain the equation containing the fault quantity from the system model separately, and then perform DM decomposition on the remaining part. The resulting fault isolation matrix diagram is shown in Figure 5. * indicates that there is a correlation between the abscissa and the ordinate fault. The result indicates that only the engine speed sensor $(y_{\text{eng}})$ is related to any two faults in the system, i.e., no fault can be isolated. Therefore, in order to make the system faults can be isolated from each other, based on the original sensor, choose to increase the voltage sensor $(y_V)$, then the system’s fault model is:

$$e_1: V = E_a + (R_f + R_a + f_f)I + L \frac{\partial I}{\partial t}$$

$$e_2: T_e - T_L = \frac{I}{375} \frac{\partial w_m}{\partial t}$$

$$e_3: \phi = K \cdot I$$

$$e_4: E_a = (C_e + f_{ce})\phi w_m$$

$$e_5: T_e = C_m\phi I$$

$$e_6: T_L = T_0 + F(w_{\text{eng}}) \cdot w_{\text{eng}}$$

$$e_7: w_m = (r + f_r) \cdot w_{\text{eng}}$$

$$e_8: E = V + (R_1 + f_{R_1})I + u$$

$$e_9: I = \frac{u}{R_2} + C \frac{\partial u}{\partial t}$$

$$e_{10}: y_{\text{eng}} = w_{\text{eng}} + f_{\text{eng}}$$

$$e_{11}: y_V = V$$

In the formula $y_V$ -- Voltage sensor measurements

Assuming that the measured value of the voltage sensor is an ideal value, the isolation of the system fault after the voltage sensor is added can be analyzed. The result is shown in Fig. 6. It can be seen that all system failures can be isolated in pairs.
Structural Minimum Overdetermined Equation Set

In order to streamline the test set and improve the efficiency of fault diagnosis, it is necessary to determine the minimum set of system over-determined sets (MSO sets, Minimal Structural Overdetermined Sets). The process of obtaining is to determine whether the set of model equations is a complete structure over-determined set. Then the redundancy $\varphi(N)$ of the complete structure over-determined set $M$ is obtained, and $\varphi(N)$ is the number of equations in the set minus the number of unknown variables. Finally, if and only if the redundancy $\varphi(N)=1$ of the complete structure overdetermined set $M$, the set $M$ is the set of structural minimum overdetermined equations. You can use the MATLAB toolbox to obtain all the minimum over-determined equations, and then select the minimum over-determined equations as the test set according to the number of equations in the system of the smallest type of over-determined equations and the relationship between the fault variables. The selected test set can contain all fault parameters.

In this paper, according to the method in [19], all the minimum overdetermined equations are generated, as shown in Table 2. Then select the test set from the smallest type of overdetermined equations. The final test set selected must first be able to contain all the fault parameters, and secondly contain as few fault equations as possible, and the fault parameters can be isolated by the test set. According to this principle, three test sets are selected as shown in Table 3. The faults corresponding to each test set are shown in Table 3. The drawing $\sqrt{\cdot}$ indicates the fault that the corresponding equation set can detect, and the blank indicates the fault that cannot be detected. For example, MSO1 can detect faults $(f_{R1}, f_{r})$, and cannot detect other faults.

| Number | Equations | Corresponding fault |
|--------|-----------|---------------------|
| 1      | $e_2$ $e_3$ $e_5$ $e_6$ $e_7$ $e_8$ $e_9$ $e_{10}$ $e_{11}$ | $f_{r}$ $f_{R1}$ |
| 2      | $e_1$ $e_3$ $e_4$ $e_7$ $e_8$ $e_9$ $e_{10}$ $e_{11}$ | $f_{Ra}$ $f_{ce}$ $f_{r}$ $f_{R1}$ |
| 3      | $e_1$ $e_2$ $e_4$ $e_5$ $e_6$ $e_7$ $e_8$ $e_9$ $e_{10}$ $e_{11}$ | $f_{Ra}$ $f_{ce}$ $f_{r}$ $f_{R1}$ |
| 4      | $e_2$ $e_3$ $e_4$ $e_5$ $e_6$ $e_8$ $e_9$ $e_{10}$ $e_{11}$ | $f_{ce}$ $f_{R1}$ |
| 5      | $e_1$ $e_2$ $e_3$ $e_4$ $e_5$ $e_6$ $e_7$ $e_{10}$ $e_{11}$ | $f_{Ra}$ $f_{ce}$ $f_{r}$ |
| 6      | $e_1$ $e_2$ $e_3$ $e_4$ $e_5$ $e_6$ $e_7$ $e_8$ $e_9$ $e_{11}$ | $f_{Ra}$ $f_{ce}$ $f_{r}$ $f_{R1}$ |
| 7      | $e_1$ $e_2$ $e_3$ $e_4$ $e_5$ $e_6$ $e_7$ $e_8$ $e_9$ $e_{10}$ | $f_{Ra}$ $f_{ce}$ $f_{r}$ $f_{R1}$ |
Table 3. Equations and corresponding faults included in the test set.

| MSO  | Test set contains equations | Corresponding fault          |
|------|-----------------------------|-----------------------------|
| MSO1 | {e2, e3, e5, e6, e7, e8, e9, e10, e11} | \(f_r, f_{R1}\)          |
| MSO2 | {e2, e3, e4, e5, e6, e8, e9, e10, e11} | \(f_{ce}, f_{R1}\)       |
| MSO3 | {e1, e2, e3, e4, e5, e6, e7, e10, e11} | \(f_{Ra}, f_{ce}, f_e\) |

Residual Design

**Residual r1.** As can be seen from Table 3, the equations included in the test set MSO1 are: \{e2,e3,e5,e6,e7,e8,e9,e10,e11\} These equations are related to the battery model and the motor model. It can be seen that the main function of the MSO1 is to detect the fault with the internal resistance of the battery and the fault of the motor joint. Therefore, the e8 with the internal resistance \(R_1\) can be selected as the analytical redundancy relationship of the test set MSO1:

\[
E = V + (R_1 + f_{R1})I + u \tag{13}
\]

Thus obtaining the residual r1

\[
r1 = E - V + (R_1 + f_{R1})I + u \tag{14}
\]

**Residual r2.** Test set MSO2 Its main function is to motor armature coil fault, battery resistive fault, you can choose equation e2 containing \(w_m\) as the analytical redundancy relationship of test set MSO2:

\[
T_e - T_L = J \frac{\partial w_m}{\partial t} \tag{15}
\]

Thus obtaining the residual r2

\[
r2 = T_e - T_L - J \frac{\partial w_m}{\partial t} \tag{16}
\]

Residual r2 can be used to diagnose motor armature coil faults and battery resistive faults.

**Residual r3.** The test set MSO3 contains equation e1 containing the differential term, its main function is to calculate the induced electromotive force of the motor, so equation e1 is chosen as the analytical redundancy relationship of the test set MSO3.

The above formula contains a derivative term. Since the e2 used in obtaining the \(T_L\) value also contains a derivative term, in order to ensure the stability of the system, e2 is brought into the above equation, and the transformed redundancy relationship is obtained:

\[
\frac{375C_e\phi}{J} w_m + \frac{375C_e\phi}{J} w_m - \frac{C_m\phi}{J} T_e + \frac{1}{J} T_e = (p + \beta)r_3 \tag{17}
\]

\(p\) is a differential operator. According to the literature, the stability of the system can be guaranteed when \(\beta>0\).[20]

Set the state space \(X\);

\[
X = r3 - \frac{375C_e\phi}{J} w_m \tag{18}
\]

Thus the state space representation of r3 is:

\[
\begin{align*}
\dot{X} &= -\beta X + \left[\frac{375C_e\phi}{J} - \beta \frac{375C_e\phi}{J}, -\frac{C_m\phi}{J}\right] \begin{bmatrix} w_m \\ T_e \end{bmatrix} \\
\dot{r_3} &= X + \left[\frac{375C_e\phi}{J}, 0\right] \begin{bmatrix} w_m \\ T_e \end{bmatrix} \tag{19}
\end{align*}
\]

Residual r3 can be used to diagnose motor armature resistance faults, motor armature coil faults and motor engagement faults.
Table 4. Residual table.

| Residual | equation | Fault that can be checked |
|----------|----------|---------------------------|
| R1       | $r_1 = E - V + (R_1 + f_{R_1})I + u$ | Motor engagement failure, battery resistance failure |
| R2       | $r_2 = T_e - T_L - \frac{375}{J} \frac{\partial w_m}{\partial t}$ | Motor armature coil failure, battery resistance failure |
| R3       | $r_3 = X + \left[ \frac{375C_0 \phi}{J}, 0 \right] \left[ \frac{\partial w_m}{\partial t} \right]$ | Motor armature resistance failure, motor armature coil failure, motor engagement failure |

**Diagnostic Strategy Design**

Here, the fixed feasible domain [-1, 1] is used as the evaluation standard of the observation value. When the observed value exceeds the feasible domain, the system has a fault. If it is not exceeded, the system has no fault. And treat the residual value as the corresponding observation:

$$R_i = ri, i = \{1,2,3\}$$  \hspace{1cm} (20)

Get the fault characteristic parameters:

$$f_{R(i)} = \begin{cases} \{0,R^{(i)}\} & \text{Within the feasible domain} \\ \{1,R^{(i)}\} & \text{Outside the feasible area} \end{cases} \quad i \in \{1,2,3\}$$  \hspace{1cm} (21)

In the formula $R_i$—Observations

$f_{R(i)}$—Fault characteristic parameter

Finally, the fault feature vector: \(F=(f_{R(1)}, f_{R(2)}, f_{R(3)})\) is used as the basis for system fault judgment.

**Simulation Analysis**

**Diagnostic System Design**

In order to verify the correctness of the structural analysis method in the fault detection of the tractor electrical system and the actual detection of the above four residuals, the structural schematic diagram of the fault detection isolation system (FDI) system was designed with MATLAB software, as shown in Fig. 7. First build the tractor electrical system model in MATLAB, then connect the measurement signal of the relevant sensor into the FDI system, and set the deviation value as the fault quantity. The deviation should be beyond the feasible value. The specific deviation setting is shown in Table 5. Then observe the observations of the FDI system, and finally locate the fault type according to the feature vector.

![FDI system structure schematic](image)
### Table 5. Deviation setting.

| Fault variable | Deviation | Time of occurrence /s |
|----------------|-----------|-----------------------|
| $f_{Ra}$       | +5        | 3-4                   |
| $f_{ce}$       | +5        | 6-7                   |
| $f_r$          | -5        | 9-10                  |
| $f_{R1}$       | +4        | 12-13                 |

### Table 6. Fault Feature Vector Comparison Table.

| Characteristic Parameters | $f_{Ra}$ | $f_{ce}$ | $f_r$ | $f_{R1}$ |
|---------------------------|----------|---------|-------|---------|
| $f_{R(1)}$                | 1        | 1       |
| $f_{R(2)}$                | 1        | 1       |
| $f_{R(3)}$                | 1        | 1       | 1     |

**Simulation Results and Analysis**

The simulation results are shown in Figure 6. In order to quickly evaluate the system, the residual threshold is set to a fixed value of -1 and 1. As can be seen from FIG. 5, it can be seen that the residual r1 can detect the fault at 9s and 12s, that is, the faults $f_r$, $f_{R1}$ are detected, and other faults cannot be detected. The residual r2 can detect the fault at 6s and 12s, that is, the fault $f_{ce}$, $f_{R1}$ is detected, and other faults cannot be detected. The residual r3 can detect the fault at 3s, 6s, and 9s, that is, the faults $f_{Ra}$, $f_{ce}$, $f_r$ are detected, and other faults cannot be detected.

The test results of the three kinds of residuals are summarized. As shown in Table 6, 1 indicates that the corresponding residual can detect the fault, and null indicates that the fault cannot be detected. The feature vectors for each fault in the table are different, so a fault state can be uniquely located through the fault feature vector. For example, at 12 seconds, according to the actual observation value, the corresponding fault feature vector $F=(1, 1, 0)$ can be obtained, and it can be judged that the battery resistance is faulty at this time. In addition, comparing the contents of Table 6 and Table 3, the fault system is consistent with the theoretical analysis conclusion, and all faults can be isolated. This also proves the correctness and feasibility of the electrical fault diagnosis design of tractor based on structural analysis.

**Conclusion**

1. Through the analysis of the tractor battery and starter motor, the electric fault model of the tractor starting system is established, and four key faults are selected: motor armature resistance fault $f_{Ra}$, motor armature coil fault $f_{ce}$, Motor engagement fault $f_r$, battery resistive fault $f_{R1}$.

2. The design process of electrical fault diagnosis system for tractor starting system based on structural analysis method is introduced in detail. Firstly, the observability and isolation analysis of the unknown variables in the fault model are carried out by MATLAB’s dmperm command. It is found that if only the tractor's own engine speed sensor is used, the four faults can only be detected, but not isolated. If you add another voltage sensor, you can achieve four faults that are detectable and isolated. Then use the three sets of equations in the MSO sets of all structures generated by MATLAB as the test set, and design the residual value of each test set as the observer of the system.
Different observers detect different faults, but the four faults must be detected by three observers. Finally, the diagnostic strategy of the system is designed: [-1,1] is selected as the feasible domain of the observation. If the value of the observer exceeds the feasible domain, the fault characteristic parameter is 1, otherwise it is 0, and then it is composed of 3 fault characteristic parameters. The fault feature vector is used as the basis for system fault judgment.

(3) Use MATLAB to build the FDI system simulation platform, and generate 4 key faults in 3s-4s, 6s-7s, 9s-10s, 12s-13s, respectively, and simulate the results and presets. Comparing the faults, it is found that the detection results of the three observers are in accordance with the preset, and the four faults can be detected and can be isolated from each other. The fault feature vector can accurately locate the critical faults, indicating the correctness and effectiveness of the diagnostic system. This also shows the advantage of structural analysis for the electrical fault diagnosis of tractor starting systems, which can accurately locate system faults with only a small number of sensors. Compared with other tractor fault detection methods based on neural network and signal processing, the diagnostic system established in this paper does not need to set too many parameters, and will not fall into the dilemma of a large number of signals to be processed. Only a small number of sensors can be used to realize the tractor. The diagnosis of critical electrical faults in the starting system simplifies the method and reduces development costs.

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