Application of advanced fault diagnosis technology in electric locomotives

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Abstract: As the continuous development of intelligent mechatronic systems and robots, the fault diagnosis technology is making full advances in many practical applications. In this paper, an advanced fault diagnosis system, which consists of logical control units, microcontrollers, colour display screens and an industry PC, is developed for SS7E locomotives in China. Based on thoroughly analysing the structures and control principles, a full set of digital checkpoints and fault points of SS7E are presented. The method to obtain diagnosis rules from the fault tree is described and the high-efficiency reasoning mechanism is deduced. The intelligent fault diagnosis knowledge base of SS7E is constructed and the data structure is explained. Finally, an online instance of the SS7E locomotive fault diagnosis system interface is shown.

Keywords: online; fault diagnosis; fault tree; data structure.

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1 Introduction

As the continuous development of computer and artificial intelligence, the fault diagnosis technology is making full applications in many practical applications. For complex system fault diagnosis methods, there are knowledge-based reasoning (Saxena et al., 2006), artificial neural networks (Rajakarunakaran et al., 2008), fuzzy logic (Dev Anand et al., 2008), pattern recognition (Shen and Jensen, 2007), as well as expert systems (Gui et al., 2007) and so on.

The electric locomotive is a complex mechatronic system and the SS7E electric locomotive is the Chinese main passenger transport locomotive which has been manufactured since 2002. It is the trunk line locomotive in China and mostly runs on Long-Hai line and Jing-Guang line. With the recent speeding up of trains in China, the requirement of fault diagnosis and real-time control for the electric locomotive is also rising. The existing SS7E electric locomotive fault diagnosis is still largely confined to the equipment detection, no comprehensive diagnosis for the whole locomotive is available. To improve the reliability and real-time ability of SS7E fault diagnosis, the existing locomotive fault diagnosis system must be reformed.

The equipments by which the SS7E locomotive completes fault diagnosis include the logic control unit (LCU), the computer unit, the train operation monitor device, the axle temperature monitor device and the train operation safety monitor device. The LCU sends out instructions to and collects feedback from the executing equipment. The other equipments above mainly collect the analogue data for the diagnosis system.

The SS7E locomotive online fault diagnosis system obtains the detection information from above equipments and carries out the logic reasoning. The diagnosis result is sent to the computer in driver's cab and displayed through RS-485 (Wang et al., 2006).

The rest of the paper is organised as follows. Section 2 introduces the system configuration and checkpoints of the SS7E locomotive diagnosis system being investigated. The diagnosis theory and applications are discussed in Section 3. Section 4 presents the experimental setup and some preliminary results to show the feasibility and performance of the proposed system. Finally, a brief conclusion and future work are given in Section 5.

2 SS7E locomotive diagnosis system

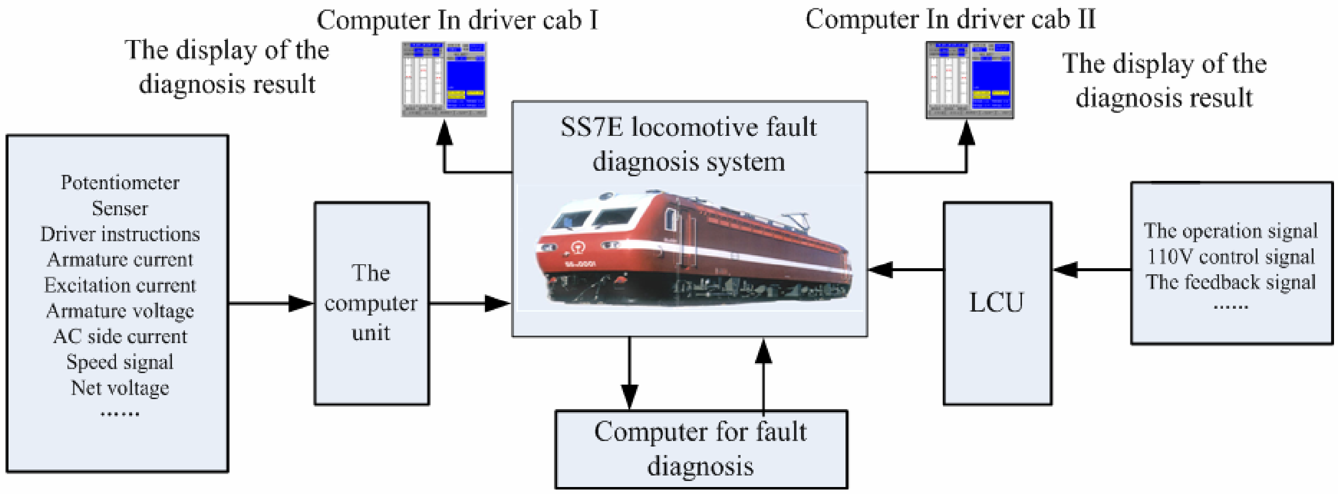
2.1 System configuration

In order to retain the characteristic of modularisation, SS7E electric locomotive fault diagnosis system uses RS-485 to communicate with the other equipments. The system configuration of the diagnosis system is as shown in Figure 1. The LCU is the digital signal acquisition equipment. The computer unit collects the logic signal and changes it to be digital signal by fuzzy recognition. All the check data is sent to the computer unit for fault diagnosis. The computer unit is the kernel of the fault diagnosis, the storage entity of the knowledge base and the perform component of the reasoning mechanism. The system explains and reasons the input data according to the knowledge base.

2.2 Digital checkpoints and fault points

The SS7E locomotive fault diagnosis system mainly diagnoses the fault of control circuit. Since it is a very complicated process to determine the checkpoints of the diagnosis system, we must analyse the control process of SS7E locomotive in detail and must know clearly the run process of each electrical component. The run process can be analysed by the electrical control logic, e.g., the circuit breaker QF.

Figure 1 The structure of SS7E locomotive diagnosis system (see online version for colours)



The SS7E locomotive circuit breaker includes two control processes: the circuit breaker switch on and the circuit breaker switch off. The control logic is as shown in Figures 2 and 3. The control object of this control logic is M2 – the coil to switch on the circuit breaker. M2 is the sign of the middle point in Table 2. This control logic has two routes to switch on the circuit breaker. The first route is D52 = 1; D111 = 1; M86 = 0; D53 = 0; D54 = 0, so M2 = 1. That is, 'the key-switch to switch on the circuit breaker' is push; 'zero position KL10' is on; 'grounding resume KL5' is off; 'inverter 1 key-switch' is off; 'inverter 2 key-switch' is off, so 'the coil to switch on the circuit breaker' is on. Another route is D118 = 1, so M2 = 1. That is, 'automatic switch on the circuit breaker' is on, so 'the coil to switch on the circuit breaker' is on.

Figure 2 The switching on logic of SS7E circuit breaker

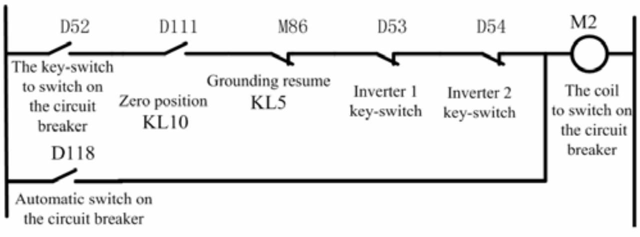
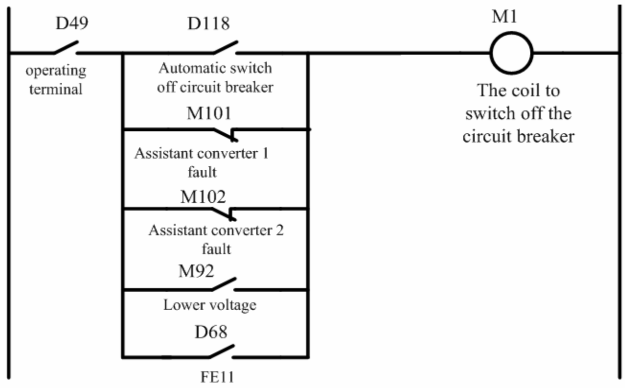


Figure 3 The switching off logic of SS7E circuit breaker



From above analysis, we know that the fault diagnosis of the circuit breaker requires capturing the locomotive state data – the checkpoint. Firstly, we must know D52, D111, D53, D54 and D118 in Table 1 and M86 and M2 in Table 2. Secondly, we must know whether the circuit breaker is switching on, that is, we must know D74 in Table 1.

Figure 3 is about the control to switch off the circuit breaker. The aim of this control logic is M1 – the coil to switch off the circuit breaker. M1 is the sign of the middle point in Table 2. The fault diagnosis about switching off the circuit breaker requires us to capture the locomotive state data, which are D49, D118 and D68 in Table 1 and M101, M102, M92 and M1 in Table 2. We also must know whether the circuit breaker is switching off, that is, we must know D74 in Table 1.

From the control logic analysis of the circuit breaker, we can diagnose the fault of the circuit breaker and can analyse the reason of the fault. That is F32 and F33 in Table 3, where F32 denotes 'the fault of switching on the circuit breaker' and F33 denotes 'the fault of switching off the circuit breaker'.

Table 1 SS7E locomotive checkpoints

Serial no.	*Function style*	*Name of the checkpoint*	*Value = 1*
D1	Test switch	Main circuit test switch QS14	Test
D2		Main circuit test switch QS13	Test
D3	In- and out-store switch	Auxiliary in-store switch QS22	On
D4		Main in-store switch QS12	On
D5	Oil flow check	Transformer oil relay KA10	On
D6	Zero position relay	Zero position relay KL10	Zero position
…	…	…	…
D142	Load isolation	Load isolation KM19	Isolation
D143	Inverter switch	Inverter switch SA31	On
D144	Breaker	Traction fanner breaker QA1	On
D145	Key-switch	Key-switch SB109	On
D146		Main compressor SB107	On
D147		Auxiliary compressor key-switch	On

Table 2 SS7E locomotive fault diagnosis middle points

Serial no.	*Function style*	*Name of the middle point*	*Value = 1*
M1	The circuit breaker	Switch off QF1	Switch off
M2		Switch on QF1	Switch on
M3	Exchange action	The forward exchanger YV5, YV6	Forward
M4		The backward exchanger YV7, YV8	Backward
M5		Traction YV9, YV10	Traction
M6		Braking YV11, YV12	Braking
M7	Contactor or relay	Line contactor KM1, KM2, KM3	On
M8		Line contactor KM4, KM5, KM6	On
…	…	…	…
M104	Inverter relay	Inverter relay 2KL54	On
M105		Inverter relay 3KL55	On
M106		Inverter relay 4KL56	On

By system analysis of SS7E electric locomotive control logic, the full set of checkpoint is summarised in Table 1. There are some data that the fault diagnosis can identified, but they are neither checkpoints, nor fault points, so we call them 'middle points'. They include the anticipative output state; the delay relay state, and the middle relay state. These middle points have important value for fault diagnosis. For example, the M35 in Figure 4 is a middle point.

By analysis and statistics of SS7E locomotive electrical fault, the full set of fault points is summarised in Table 3.

Table 3 SS7E locomotive electrical fault points

Serial no.	*Fault style*	*Auxiliary style*	*Specific details of the fault*
F1	Overcurrent fault	Original overcurrent	Transformer original overcurrent
F2		AC overcurrent	First power supple overcurrent
F3			Second power supple overcurrent
…	…	…	…
F32	Circuit breaker fault	Circuit breaker fault	Fault of switching on the circuit breaker
F33			Fault of switching off the circuit breaker
F34	Exchange fault	Forward/backward exchange	Forward exchange fault
F35			Backward exchange fault
F36		Traction/braking exchange	Traction exchange fault
F37			Brake exchange fault
F38	Relay fault	Middle relay fault	Zero position relay KL10 fault
F39			Middle relay KL459 fault
…	…	…	…
F86	Contactor fault	Circuitry contactor	Circuitry contactor KM1 fault
F87			Circuitry contactor KM2 fault
F88	Other fault	Transformer	Transformer oil fault
F89		LCU	LCU logic or power supply fault

3 The diagnosis theory and applications

If a computer system can use the store knowledge to explain the input data, and has the right to generate an appropriate hypothesis and verify it, the system is known as the knowledge base system. The knowledge base always includes the fact base and the rule base.

Fact base = (fact_1, fact_2,…, fact_m);
Rule base = (rule_1, rule_2,…, rule_n);
Fact = (<object attribute>); (note: the conclusion is a kind of fact)
Rule = (<rule name>(IF<fact>)(THEN<conclusion>)).

For SS7E locomotive fault diagnosis system, there are two forms of fact and one form of rule.

- The first form is fault point fact. For example: fact_1 = (<F1 1>), it denotes the fact_1's object name is F1, the corresponding name is 'transformer original overcurrent' and it has only one kind of attribute, fault or not. If the attribute is 1, it denotes that the transformer original overcurrent happened.
- The second form is checkpoint fact. For example: fact_2 = (<D1 1>), it denotes the fact_2's object name is D1 and the corresponding name is 'main circuit experiment switch QS14'. The attribute denotes the state of the switch. If the attribute is 1, it denotes the switch is on.
- The form of the rule is, for example, rule_1 = (<F81_1> (IF<D92 0>AND<D145 1> AND<D27 0>) (THEN <F81 1>). It denotes the name of rule_1 is F81_1, and the conclusion fact <F81 1> comes from the three facts <D92 0>, <D145 1> and <D27 0>.

3.1 The minimal cut sets and the fault tree

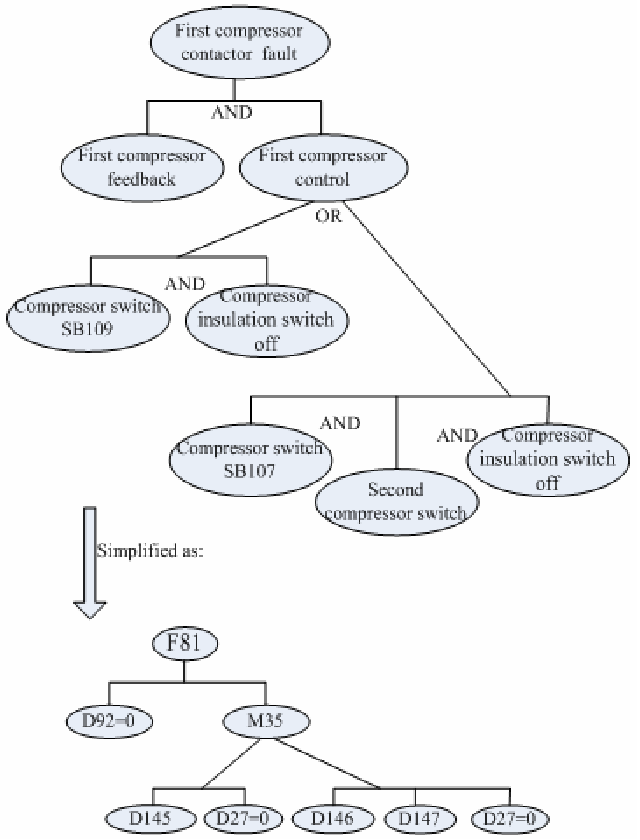
The fault tree analytical method is a model of the logic diagnostic method. The basic result of fault tree method is to capture the minimal cut sets (Assaf and Dugan, 2003). All SS7E fault trees are abstracted by the statistical analysis of the SS7E locomotive fault. An example of getting rule from the SS7E fault tree is described as follows. It is about compressor contractor fault, and the fault tree is as shown in Figure 4.

3.2 Capture the rule base on the fault tree

The analysis is beginning with the simplified fault tree that is as shown in figure 4. According to the method of getting rule from fault tree, we get all the minimal cut sets from the fault tree. The process is as follows:

1. Top event F81 is replaced by (D92=0; M35).
2. In (D92=0; M35), the M35 has two ways to replace, and then we get two minimal cut sets: (D92=0; D145; D27=0) and (D92=0; D146; D147; D27=0).

Figure 4 SS7E locomotive compressor contactor fault tree (see online version for colours)



According to the method of getting rule from minimal cut sets, the top event is the conclusion of the rule and every minimal cut sets is the condition (or precondition) of the rule (Shi et al., 2005). The relationship of the elements in one minimal cut set is AND. So, two rules are gained from the two above minimal cut sets.

1 IF (D92 = 0) AND (D145) AND (D27 = 0) THEN F81

2 IF (D92 = 0) AND (D145) AND (D147) AND (D27 = 0) THEN F81.

In SS7E fault diagnosis system, (D145) denotes (D145 = 1) or D145 happened; F81 denotes F81 = 1 or F81 happened.

The two above rules can described as follows, according to the normal form of the rule (the rule name is described by the fault number + sequence number).

(<F81_1> (IF<D92 0>AND<D145 1>AND<D27 0>)
(THEN <F81 1>))

(<F81_2> (IF<D92 0>AND<D145 1>AND<D147 1>AND<D27 0>) (THEN <F81 1>))

It can make out from the above process that the relationship between events of every rule is AND, and the relationship OR, is kept in more rules coming from one fault tree. According to the SS7E locomotive electrical fault tree and above method, the SS7E locomotive fault diagnosis rule base is built.

3.3 *SS7E locomotive fault diagnosis reasoning mechanism*

The fault diagnosis based on knowledge is the process of the rule matching. The most simply method to do the rule matching is matched one by one (Anil and Roddy, 1999). In order to improve the speed of the matching, the priority weight is used. There are two aspects about the algorithm: one aspect is designing a subset of currently state fact set and the frequent fact is put in it according to the priority weight in order to improve the hit rate of the algorithm. The other aspect is arraying the rule in the rule base according to the priority weight of the rule in order to improve the reaction speed of the diagnosis. The priority weight is modified after every matching. It includes the priority weight of the fact and the priority weight of the rule.

The design and realisation of the high-matching algorithm is as follows:

1 Get the checkpoints state of the locomotive and build the fact base according to the usage frequency, which is defined as a set D = {dj} (where j = 1,2, … 147). Give a priority weight initial value 0 for every fact and choose 40 facts randomly from them as priority subset Dy, while the other fact is to be the residual subset Dx.

2 Give every rule in the rule set G a priority weight initial value 0.

3 Get the current state sets D = {dj}, store them in Dy and Dx respectively.

4 Get a rule from set G according the sequence and pick-up the condition fact as di and make them a set Sk = {di}, the k denotes this rule is the k first rule, the i denotes the fact is the i first fact. Put the fact in the rule Sk to match the fact in Dy. If it cannot match, match it with the fact in Dx.

5 If all facts in Sk are matched, we put Fk, the conclusion fact of this rule, in the conclusion fact base F, and give an alarm. The priority weight of this rule in rule base G is increased (+1).

6 The priority weight of the fact in Dy or Dx is increased (+1), if they are in Sk.

7 Are all rules matched? If not, jump to Step 4.

8 Sort the fact in Dy and Dx according to the priority weight and deal with the highest priority weight. If the value is larger than 100, all the priority weight in Dy and Dx is decreased (–1), if the result is less than 0, assign 0.

9 If the most high priority weight of the fact in Dx is larger than the least priority weight of fact in Dy, move the fact from Dx to Dy.

10 Sort the rule in G according to the priority weight and deal with the highest priority weight. If the value is larger than 200, all the priority weight in G is decreased (–1), if the result is less than 0, assign 0.

11 The current matching is finished, jump to Step 3.

The above process is easy to change to computer program. In the process of practical debugging, when the program has been running for a period of time, the time for once matching program is reduced obviously. The other measure for improving the speed is: when getting the current state data D = {dj}, compare them with the last state data, if they are not changed, the whole matching program must not execute. For the locomotive state is relatively steady, this measure can improve the speed of the program.

4 Experimental setting and results

4.1 The communication protocol

The communication standard between the diagnosis system and the computer in driver's cab is RS-485. The communication mode is principal and subordinate control mode. The computer in driver's cab is principal computer and the communication address is 3CH. The diagnosis system is as subordinate computer and the communication address is 6AH. Serial data format for each frame has 11 bits. They are start bit (0), 8 bits data, the judge bit ('1'for address and '0' for data) and stop bit (1). The format is as shown in Table 4:

1 The communication method

In the fault diagnosis system initialisation process, the serial port of the diagnosis system is set to receive state and the computer in driver's cab is set to be host computer. When the computer in driver's cab sends the address of the diagnosis system, the system is ready to receive the command. When the command data have been received, and the checksum is right, the fault diagnosis system changes itself to send state. It sends the address of computer in driver's cab and then sends the corresponding data according to the received command. The last byte is the checksum. After the checksum is sent, the system delays a few milliseconds and changes itself to receive state for the next cycle.

2 Transfer rate and data format

The transfer baud rate is 28.8 kb/s. The computer in driver's cab sends 8 bytes data to the diagnosis system, and the format of the data is as shown in Table 5. The diagnosis system sends back 32 bytes data to the computer in driver's cab and the format of the data is as shown in Table 6.

Table 4 The serial data format of a frame

Start bit	D0	D1	D2	D3	D4	D5	D6	D7	Judge bit	Stop bit

Table 5 The format of the data from the computer in driver's cab

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
6AH	Year	Month	Day	Hour	Minute	Second	Checksum

4.2 Data structure

1 The data structure of checkpoint

```
typedef struct _INPUT_DATA
{
int iSerialNumber;          //The serial number of input data.
int iDigitValue;            //The value of input data.
cstring sMeaningOfInput;    //The meaning of input data, use
                            to explain the solution.
int iWeightOfInput;         //The Weight of input point
}INPUT_DATA;
```

Table 6 The format of the data from the diagnosis system

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
3CH	6AH	Data1	Data2	Data3	Data4	Data5	Data6
9	*10*	*11*	*12*	*13*	*14*	*15*	*16*
Data7	Data8	Data9	Data10	Data11	Data12	Data13	Data14
17	*18*	*19*	*20*	*21*	*22*	*23*	*24*
Data15	Data16	Data17	Data18	Data19	Data20	Data21	Data22
25	*26*	*27*	*28*	*29*	*30*	*31*	*32*
Data23	Data24	Data25	Data26	Data27	Data28	Data29	Checksum

2 The data structure of fault point

```
typedef struct _OUTPUT_DATA
{
int iSerialNumber;            //The serial number of output
                              data.
int iDigitValue;              //The value of output data.
cstring sMeaningOfFault;      //The meaning of output data, use
                              to explain fault.
int iWeightOfFault;           //The Weight of fault
}OUTPUT_DATA;
```

3 The data structure of rule base

```
typedef struct _RULE
{
int iSerialNumber;       //The serial number of the rule.
struct _OUTPUT_DATA iResultOfRule;      //The fault come
                                        from this rule.
struct _INPUT_DATA *InputList      //The list of input point to
                                   bring the fault
int iWeightOfRule;       //The Weight of rule;
}RULE;
```

From the data structure mentioned above, we can clearly see the relationship between the structure of the knowledge base and disposal modules. The knowledge base is brought closer together by citing the data structure of the checkpoint and the fault point.

4.3 *System interface*

In the application of SS7E locomotive fault diagnosis system, when the compressor contactor has no feedback signal (D92 = 0), the compressor switch is kept on (D145 = 1) and the insulation switch of the compressor is on normal position (D27 = 0), the system points out the compressor contactor fault (F81 = 1). The SS7E locomotive fault diagnosis system interface is shown in Figure 5.

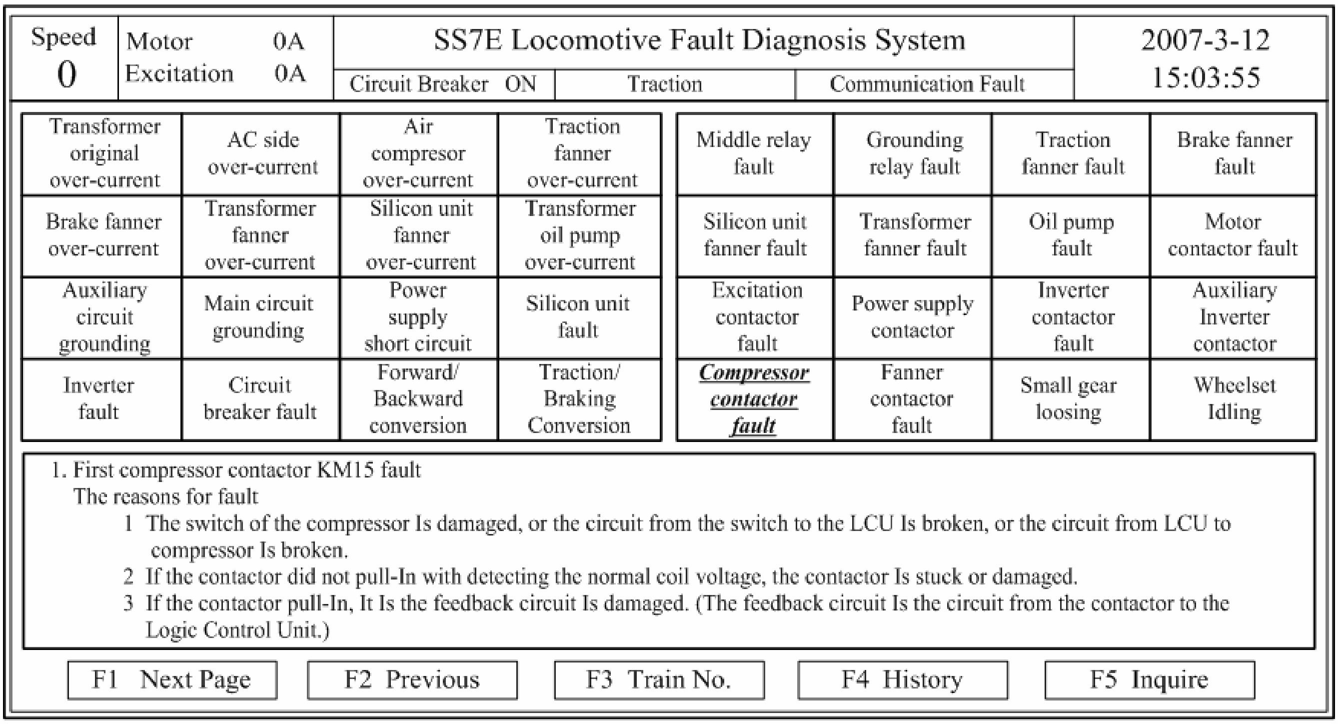
4.4 *Experimental results*

Figure 5 is also one of the fault diagnosis results. It describes the SS7E locomotive have occurred the compressor contactor fault, so 'compressor contactor fault' in the above part of Figure 5 is in italics. The underside of Figure 5 is the description of the current status, the reason of the current fault and the measure to deal with the fault.

The SS7E locomotive electrical faults are all described in Figure 5. It includes the all faults in Table 3. One page cannot display the all faults, so there is the 'Next page' button in the interface.

From the fault data of the railway department, it makes out the function of the SS7E locomotive fault diagnosis system. Figure 6 is the statistical analysis graphics from the fault data of 23 units SS7E locomotive in one year before the installation of the fault diagnosis system in one railway bureau.

Figure 5 The instance of the compressor contactor fault diagnosis



Speed 0	Motor 0A Excitation 0A	SS7E Locomotive Fault Diagnosis System			2007-3-12 15:03:55
		Circuit Breaker ON	Traction	Communication Fault	

Transformer original over-current	AC side over-current	Air compresor over-current	Traction fanner over-current	Middle relay fault	Grounding relay fault	Traction fanner fault	Brake fanner fault
Brake fanner over-current	Transformer fanner over-current	Silicon unit fanner over-current	Transformer oil pump over-current	Silicon unit fanner fault	Transformer fanner fault	Oil pump fault	Motor contactor fault
Auxiliary circuit grounding	Main circuit grounding	Power supply short circuit	Silicon unit fault	Excitation contactor fault	Power supply contactor	Inverter contactor fault	Auxiliary Inverter contactor
Inverter fault	Circuit breaker fault	Forward/ Backward conversion	Traction/ Braking Conversion	***Compressor contactor fault***	Fanner contactor fault	Small gear loosing	Wheelset Idling

1. First compressor contactor KM15 fault
The reasons for fault
1 The switch of the compressor Is damaged, or the circuit from the switch to the LCU Is broken, or the circuit from LCU to compressor Is broken.
2 If the contactor did not pull-In with detecting the normal coil voltage, the contactor Is stuck or damaged.
3 If the contactor pull-In, It Is the feedback circuit Is damaged. (The feedback circuit Is the circuit from the contactor to the Logic Control Unit.)

Figure 6 The SS7E locomotive fault distribution ratio (before the installation of the fault diagnosis system)

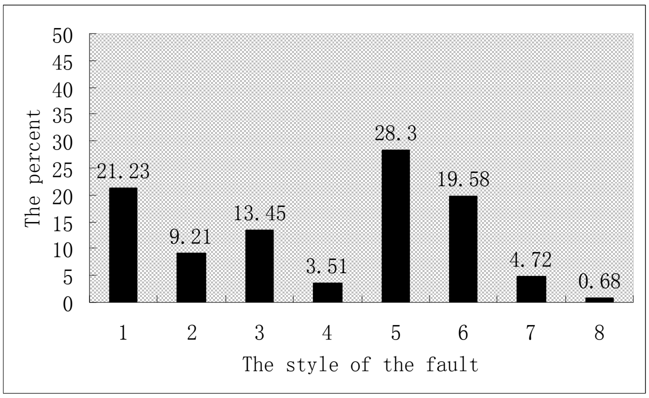
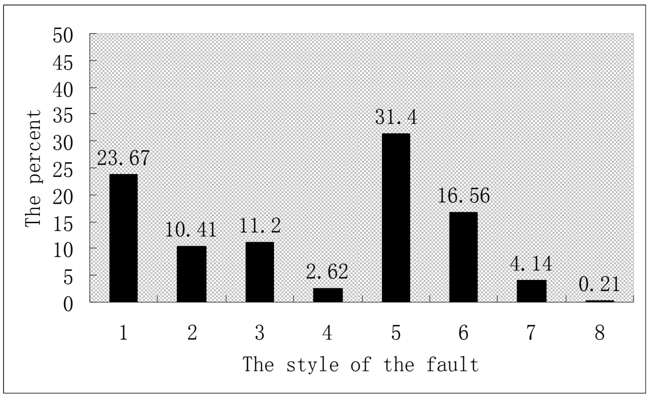


Figure 7 The SS7E locomotive fault distribution ratio (after the installation of the fault diagnosis system)



In the figure, the abscissa describes the style of the fault, and the ordinate is the percentage of this fault style. The abscissa from 1 to 8 separately represents overcurrent fault (21.23%), circuit short fault (9.21%), converter fault (13.45%), exchange fault (3.5%), relay fault (28.3%), contactor fault (19.6%), the other fault (4.7%) and stop running (0.68%). The stop running fault is a serious fault; it is statistic data from all style of faults.

After the installation of the fault diagnosis system, from the fault data of the same 23 units SS7E locomotive in a year, we get the analysis graphics as Figure 7.

From Figures 6 and 7, it is easy to see that the percentage of non-serious faults is increased on the contrary after the installation of the fault diagnosis system. For example, the percentage of the relay fault increases from 28.3% to 31.4%. But the serious fault, such as the stop running fault, is significant reduced from 0.68% to 0.21%, it is only one-third. This shows that when the locomotive in the event of non-seriousness fault, the fault diagnosis system prompts the driver to do the corresponding emergency treatment, and it makes the locomotive continue to work well, it effectively prevents the locomotive to stop running fault.

5 Conclusions and future work

According to the actual feature of a SS7E electric locomotive, the paper proposes a novel approach method to its real-time fault diagnosis. It is the first time to give the full set of the digital checkpoints and fault points of the SS7E locomotive. This paper describes the method to obtain rules from a fault tree and deduces the effective reasoning mechanism, as well as the data structure and communication protocol of the SS7E locomotive fault diagnosis system. A great part of the diagnosis theory and method, which are mentioned in this paper, have been used on SS7E locomotive. The digital signals fault diagnosis system, which is based on the logical control units, microcomputer and colour display screen, provides the main evidence for the driver to deal with the fault.

Now, there are hundreds of SS7E locomotives in service on the Chinese railway, all of them have used the fault diagnosis system discussed in this paper. It has realised the real-time online fault diagnosis in SS7E electric locomotive, and the diagnosis result is the importance information for the drivers and engineers to deal with the fault, and it effectively avoided the locomotive to stop on railway track abnormally.

The part of the proposed theory and method will be put in practice on the locomotive for further verification in our next stage of research.

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