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Fault diagnosis of electric railway traction substation with model-based relation guiding algorithm

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ABSTRACT

Most diagnosis systems used in electric railway traction substation are expert systems based on experience, which cannot diagnose faults beyond experience and are very difficult for transplantation and maintenance. In this paper, the model-based diagnosis (MBD) with integration reasoning is firstly used for fault diagnosis of electric railway traction substation. Aiming at the structural characteristics and actual demands of traction substation, we propose a detailed application plan. Rules for element and system models are established. In addition, we propose a relation guiding algorithm (RGA) for searching candidates of minimal conflict set, in which the hidden messages of analytical redundancy relations can be made full use of and the searching space is reduced further. Taking the autotransformer (AT) traction substation in Hefei–Nanjing Passenger Link of China Railway as an example, we construct models for different device objects, and give the descriptions of system model in traction substation. Based on a sequence of fault observations, the fault diagnosis is tested with the proposed plan. The diagnosis result shows that the application plan with MBD and integration reasoning is feasible and effective for traction substation.
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1. Introduction

The traction power system is one of most important parts in electric railway. The traction substation plays an irreplaceable role as the power supply interface between power system and electric railway system. Unlike general substation of power system, the traction substation has its particular characteristics, such as single-phase supplying power, frequently switching and so on. In order to ensure the safe operation of the traction power system, there are many different monitoring and controlling equipments for the electrical devices in traction substation. In addition, the fault diagnosis systems are adopted as the assistant means for fault diagnosis (Fenton et al., 2001). In general, the assistant systems are expert system based on experience knowledge. The expert system for relay protection and breaker fault diagnosis of traction substations is proposed based on protection integrated automation system (Chen et al., 1996). The expert system based experience knowledge is used to analyze and judge the faults of electrical devices in traction system (Zhuang and Chen, 2003). Obtaining the experience knowledge of diagnosed objects is a long-term process, although the fault diagnosis systems based on expert knowledge have been researched widely (Elsaadawi et al., 2008; Lin et al., 2008; Robinson et al., 2006; Todd et al., 2007). In addition, the actual developing time for expert system is very long, which results into the loss of synchronization between expert system and updating devices. Above all, the expert system based on experience knowledge cannot correctly diagnose the faults beyond experiences. Hence, the system's transplantation and maintenance are very difficult.

To avoid the disadvantages of expert system, some scholars proposed the model-based diagnosis (MBD) method (Ceballos et al., 2005; Console and Torasso, 1991; Reiter, 1987). Reiter firstly described the MBD method with first-order logic and the solution process of diagnosis problem with illustration (Reiter, 1987). The principle knowledge of diagnosed objects is used in MBD method, which can avoid the difficulty of obtaining the expert experience knowledge with traditional expert system. Because of the separation of diagnosis reasoning process and system model, the MBD has good system transplantation characteristic. Console and Torasso proposed a unified framework based on the integration of abductive and consistency-based reasoning where most of such definitions can be described (Console and Torasso, 1991). In general, the evolution of MBD includes two communities separately work in parallel (Ceballos et al., 2005). One is FDI (Fault Detection and Isolation) based on system analytical from automatic control field, the other is DX (Diagnostic) based on artificial intelligence from fault diagnosis field. In Cordier et al. (2004), the relationship of them is analyzed, and formal framework is proposed in order to compare the two approaches and the theoretical proof of their equivalence together with the necessary and sufficient conditions. In addition, a model representation at several levels of details with the goal to increase the efficiency of MBD is proposed in

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Chittaro and Ranon (2004). A novel combination of model-based with the case-based approach to condition diagnosis is presented, which can be implemented on a low-cost computer and offers satisfactory performance (Stanek et al., 2001). A new algorithm for computing all minimal overconstrained subsystems in a model is proposed in Krysander et al. (2008). MBD has been applied in many fields including engineering, economy, spaceflight and circuit diagnosis, such as suspension system (Luo et al., 2008), hybrid systems combined digital supervisory controllers and analog plants (Narasimhan and Biswas, 2007), automotive engine control systems (Luo et al., 2007; Nyberg, 2002), real-time control of electrical power systems (Gonzalez et al., 1996) and gas-turbines condition monitoring (Trave-Massuyes and Milne, 1997). In addition, the MBD is used for fault diagnosis and localization of power grid and relay protection, too. Based on the General Diagnostic Engine (GDE) of MBD, the fault analysis project of power grid is given, and modeling rules of breaker, transmission line, bus-bar, transformer and generator are built up in Beschta et al. (1993). The MBD method is used to analyze the performance of power protection system (McArthur et al., 1996). In Davidson et al. (2003), a software-based toolset of application and development of model-based reasoning systems in power systems applications is presented.

Aiming at the problem of searching Minimal Conflict Set (MCS) in MBD, and considering the characteristics of traction substation, we propose an algorithm of searching MCS with the hidden message of Analytical Redundancy Relation (ARR, where ARR means the restricted equations of observation from the system model) for limiting and reducing the searching space. We call it relation guiding algorithm (RGA). Compared with other algorithms, the performance of RGA is discussed. Based on the system demands of traction substation, the application plan of MBD is given in detail. The plan includes element modeling, system modeling rules, identifying Minimal Conflict Candidate Sets (MinCSCs), and diagnosis process. Finally, an actual fault diagnosis of Autotransformer (AT) traction substation is used for the performance proof of MBD and RGA.

2. Model-based diagnosis theory

As a fault diagnosis method of being different from expert system with "shallow knowledge", the MBD uses "deep knowledge". Through the difference between actual observation and expectant action for diagnosed system, the non-normal elements can be found and judged with computation and reasoning methods based on the interior structure and behaviors of diagnosed system model. The basic idea of MBD is illustrated in Fig. 1.

Reiter gave the solution process including the production of diagnosis problem, searching of conflict sets, and production of candidate diagnosis and checking of diagnosis solution (Reiter, 1987). Subsequently, De Kleer et al. developed and improved some theories in De Kleer et al. (1992). Some concepts used in the paper are introduced as follow.

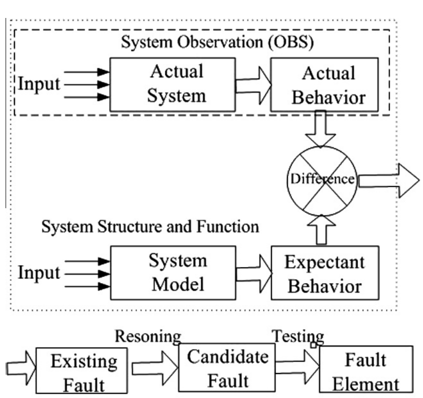

Fig. 1. Basic idea of model-based diagnosis.

Definition 1. A system is a triple (*SD*, *OBS*, *COMP*). Where *SD* is the system description. *OBS* is a set of observations. Both are a set of first-order sentences. *COMP*, the system component, is a finite set of constant.

Definition 2. Giving two sets of component C_p and C_n, define $D(C_p, C_n)$ to be the conjunction:

$$\left[\bigwedge_{c\in C_p} \mathrm{AB}(c)\right] \wedge \left[\bigwedge_{c\in C_n} \neg\mathrm{AB}(c)\right]$$

A diagnosis is a sentence that describes one possible status of the system, where this status is an assignment of normal or non-normal status to each system.

Definition 3. A conflict set (*SD*, *OBS*, *COMP*) is set of $\{c_1, c_2, \ldots c_k\} \in$ *COMP* components, which makes $\mathrm{SD} \cup \mathrm{OBS} \cup \{\neg AB(c_1), \ldots, \neg AB(c_k)\}$ not being satisfied.

Definition 4. A diagnosis for (*SD*, *OBS*, *COMP*) is a minimal set $\Delta \subseteq COMP$ such that $\mathrm{SD} \cup \mathrm{OBS} \cup \{AB(c)|c \in \Delta\} \cup \{\neg AB(c)|c \in COMP - \Delta\}$ is consistent.

Definition 5. Suppose *C* is a collection of sets. A hitting set for *C* is a set $\mathrm{H} \subseteq \cup_{S\in C}\mathrm{S}$ such that $\mathrm{H} \cap \mathrm{S} \neq \emptyset$ for each $\mathrm{S} \in \mathrm{C}$. A minimal hitting set for *C* means iff its any subset is not a hitting set for *C*.

Theorem 1. *$\Delta \subseteq COMP$ is a diagnosis for (SD, OBS, COMP) iff Δ is a minimal hitting set for the collection of conflict sets for (SD, OBS, COMP).*

Definition 6. Suppose $E \subseteq COMP$ be set, and $\forall e \in E$. If $\neg AB(e)$, *E* is an environment, namely EVN.

Definition 7. Let *f* be a supposition sentence, $E = \{e_1, \ldots e_k\}$ is an EVN. If $SD \cup \{\neg AB(e_1), \ldots, \neg AB(e_k)\} \mapsto f$, *E* is a supporting EVN when *f* is true, namely $[f, E]$.

Definition 8. If *E* is the Minimal Supporting Environment (MSE) of some ARR,*E* is a MinCSC.

Theorem 2. *Suppose the MSE of f_e be$E = \{e_1, \ldots e_n\}$, give a set of observation OBS, which satisfies*

(1) $SD \cup OBS \cup f_e \vDash \bot$
(2) $\forall E' \subset E$, *if* $\left[f'_e, E'\right], SD \cup OBS \cup \{f'_e\} \nvDash \bot$

Then $C = \{e_{i1}, \ldots e_{in}\}$ is minimal conflict set (MCS).

An EVN is a set of assumptions all of which are assumed to be true (e.g., the environment {M1; M2} indicates that M1 and M2 are assumed to be working correctly), a candidate is a set of assumptions all of which are assumed to be false (e.g., the candidate [M1; M2] indicates that M1 and M2 are not functioning correctly).

A conflict is a set of assumptions, at least one of which is false (e.g., the conflict {M1; M2} indicates that M1 or M2 is faulted). Intuitively an environment is the set of assumptions that define "context" in a deductive inference engine, in this case the engine

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