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Finite State Machine Model of Fault Diagnosis for Distribution System under Time Sequence Constraints

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***Abstract*—in order to solve the problem of fast fault diagnosis in power system, this paper introduces a method of finite state machine model of fault reasoning for distribution system under time sequence constraints. Firstly, the concept of time sequence constraint characteristics of SOE data from the SCADA alarm window is introduced, which is crucial to judge whether the alarm sequence are from an individual fault accident. Then, by fully considers the "protection-circuit breaker" action as well as its logic, the Finite State Machine model with various system fault types was constructed. Finally, to prove the effectiveness of the method, a set of alarm data in real accident which happen in 10 kV distribution systems is applied to test the model. The result shows that the model can quickly analyze SOE data within the time interval in system accident, and effectively help the operation dispatcher to handle accident and defect elimination.**

Keywords—intelligent alarm, control integration, finite state machine, timing characteristics

I. Introduction

Supervisory Control and Data Acquisition (SCADA) can be used to monitor and control the substations of power system. Of all the functions of SCADA system, Sequence of Events (SOE) data which shows the alarm sequence triggered by system accident and abnormality is the main basis for the dispatcher to understand status of power grid. SOE displays the alarm information in chronological order. After some optimization, the alarm now are already classified into different types of signals in browsing pages, such as pages of switch displacement, over limit, operation, plant and station conditions, protection events, etc. However, the signal classification is far from enough to meeting the needs of power grid dispatching operation. Whenever there is system fault or an abnormality, a large number of alarm sequence are uploaded, and some important signals are easy to submerge in the alarm signal sea, which makes it difficult for the dispatchers to grasp the accident quickly. Therefore, the study of alarm process in system faults and abnormalities will be helpful for the rapid diagnosis of grid accidents.

At present, a lot of algorithm research work has been carried out on power grid fault diagnosis, mainly including expert system [1,2], artificial neural network [3], Petri network [4], fuzzy logic reasoning calculation [5], analytical method based on optimization technology [6], etc. In reference [7], an expert system of model driven fault logic and fault reasoning is established. In reference [8], a hierarchical weighted fuzzy sequential Petri net fault diagnosis method based on event starting point is proposed. In reference [9], a fault diagnosis method based on maximum entropy hidden Markov model is proposed to mine the hidden abnormal patterns of fault data. All these methods are effective improve the accuracy of fault diagnosis.

In this paper, a finite state machine (FSM) model for substations fault diagnosis is proposed. Firstly, the time sequence characteristics, as well as protection action delay interval of SOE alarm signals are studied. Then, various faults "protection-circuit breaker" action logic of the system are studied. Finally, the finite state machine model of various system faults or an abnormality is constructed, which fully consider the time sequence as constraint, to analyze series of SOE alarms. After testing, it is proved that the model is accurate and fast for fault diagnosis.

II. Time Sequence Characteristics of Alarm Data

When the system is abnormal or malfunctioning, the corresponding electrical quantity and state quantity will change. In case of system failure, the protection device will send out the displacement trip command to the corresponding circuit breaker according to the setting value and time limit characteristics. Considering the error and delay of device action, although the alarm event does not occur at a certain time point, it must be within an effective delay interval. A reasonable delay interval

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can be used as an important criterion for the development of the same accident.

In reference [11], a power system alarm processing model based on time sequence constraints is proposed, which includes time point constraints and time distance constraints. The timing constraint uses the concept of time window, which may take into account the time correlation analysis of both the precursor and the subsequent events. Because this paper is based on SOE alarm information, once the landmark event triggered by an accident is received, only a series of events that are received continuously need to be analyzed, and there is no precursor event analysis problem. Therefore, this paper redefines the time point and time distance of temporal reasoning as follows.

Defines the time variable t as the event occurrence time, t_j and t_i $(t_i \leqslant t_j)$ can be expressed as the time of event *i* and event *j* successively, where t_j is the subsequent event of t_i. In order to describe whether two successive events belong to the same fault alarm event, the time length of two successive alarm events VT is defined as time distance, for example, the time distance of event i and event j is define as Vt_{ij}.

$$Vt_{ij} = t_j - t_i \tag{1}$$

Since the timing characteristic is a specific value in the SOE alarm, Vt_{ij} can be an exact value.

Due to the difference of fault types and protection time limitations, the delay time of event *j* would be uncertain, but must be in a time interval. We defined the delay time of event as a theoretical delay interval. So the theoretical delay interval of the successive event *i* and event *j* can be expressed as D . As we know, the power system relay protection relay time is configured according to the existing rules and standards, which in reference has made a detailed summary [12] of, that the specific delay interval between two successive events like "protection-circuit breaker" action, which can be find in Table I.

TABLE I. DELAY INTERVAL OF DIFFERENT ACTION OBJECTS (UNIT: MS)

Event *i*	Event *j*	Theoretical Delay Interval (unit: ms)	
		Minimum	***Maximum***
Component failure	Main Protection	10	100
	Near Backup Protection	300	500
	Remote Backup	600	1100
Main Protection	Circuit breaker Switching	40	60
Near Backup Protection		20	40
Remote Backup		40	100

The delay interval of different events which belongs to an alarm need to meet the time constraint of theoretical delay interval, namely:

$$Vt_{ij} \in d_{ij} \tag{2}$$

Otherwise, the event *i* and event *j* are considered to be uncorrelated.

For example, suppose that event *i* and event *j* are two successive alarm sequence.

Event *i* described as "*SOE window of (**substations): time: 15: 49: 42: 445 110kV bus Ⅰ differential protection action, July 12th, 2019*".

Event *j* described as "*SOE window of (**substations): time: 15:49:42:500 110kV the bus joint switch #1112 opening, July 12th, 2019*".

The time distance of event *i* and event *j* can be calculate as $Vt_{ij} = t_i - t_j = 500 - 445 = 55ms$, which is within time constraint of theoretical delay interval that can be check in table I. So according to definition above, it is said that events *i* and *j* belong to a fault alarm.

III. FINITE STATE MACHINE MODEL OF ACCIDENT REASONING

The action alarms of "protection-circuit breaker" actions in accident can be represented by binary number's transposition, taking into account the time sequence characteristics. Finite State Machine can be used to describe the time sequence relationship of binary number's transposition, which can greatly improve the efficiency of fault reasoning.

Finite State Machine (FSM) [13,14] is a mathematical model, which decomposes complex logic into finite stable states and judges events in each state. The finite state machine is described by a five tuple M, $M = (S, \sum, \delta, s_0, F)$. In the five tuple, variable S is a set of system states; $\sum$ represents the set of events that the system can receive; δ is a state transition function, which is usually triggered by the received events; s_0 is the starting state of the system, where $s_0 \in S$; variable F is the set of starting states that are returned again for the ending state of the system, where $F \in S$.

For the 10kV distribution system shown in Fig. 1, equipment protection is configuring as in Table II.

TABLE II. EQUIPMENT PROTECTION OF 10KV DISTRIBUTION SYSTEM IN FIGURE 1

Type of Equipment	Protection Configuration
Distribution Line	Overcurrent Protection(complex voltage)
	Overcurrent Protection(direction locking)
	three-phase Primary Reclosing
Bus	/
Power Transformer	Gas Protection
	Temperature Protection
	Longitudinal Differential Protection
	Over-current Protection
	Current Quick Break Protection

Whenever there is a system fault as points *k1*, *k2* and *k3* that shows in Fig. 1, FSM modeling for faults diagnosis would be show in the following text.

Whenever line *L1* protections action, the circuit breaker *CB1* switches off. Make the line protection status as R_l , then:

$$R_l = r_{prl} \vee r_{srl} \vee r_{trl} \tag{3}$$

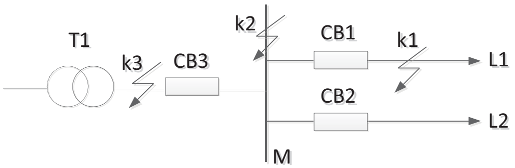

Fig. 1. Typical 10kV distribution system diagram.

When $R_l = 0$, indicates that the line protection reset, while $R_l = 1$, indicates the line protection acted; in the formula, variable r_{prl} is status of Line's main protection, variable r_{srl} is status of the near backup protection, and r_{trl} is status of the far backup protection, $\vee$ indicates logic or.

Bus at voltage of 10~ 35kV do not configure a special bus differential protection, instead of a backup protection action for the power transformer. Therefore, the bus *M* protection status is:

$$R_m = r_{srm} \tag{4}$$

where: $R_m = 0$ refers to protection reset, $R_m = 1$ refers to protection acted, and r_{srm} refers to the backup protection.

The transformer protection is configured with body protection, near backup protection and far backup protection. The power transformer protection status is set as R_t , then:

$$R_t = r_{prt} \vee r_{srt} \vee r_{trt} \tag{5}$$

where: $R_l = 0$ indicates protection reset, $R_l = 1$ indicates protection acted; r_{prt} is the main protection of the line, r_{srt} is the near backup protection, r_{trt} is the far backup protection, $\vee$ indicates logic or.

Table II shows the SOE alarms set receive for various fault types of 10kV distribution system. In the table, the value "1" means receiving a variable corresponding alarm, while the value "0" means alarm unreceived. Table IV shows event meaning of variable Binary in Table III.

TABLE III. ALARM SET OF COMMON FAULT TYPES OF 10KV DISTRIBUTION SYSTEM

SOE Alarm Set	Variable Binary													Types of System Fault
	R_{l1}	R_{l2}	R_m	R_t	B_1	B_2	B_3	R_{eB1}	B_1	R_l	R_m	R_t	B_1	
X0	0	0	0	0	0	0	0	0	0	0	0	0	0	Normal
X1	1	0	0	0	1	0	0	0	0	0	0	0	0	*L1* Permanent fault without reclosing
X2	1	0	0	0	1	0	0	1	1	0	0	0	0	*L1* Transient fault, reclosed
X3	1	0	0	0	1	0	0	1	1	1	0	0	1	*L1* Permanent fault, reclosing failure
X4	1	0	0	1	0	0	1	0	0	0	0	0	0	*L1* failure , *B1* fail open, remote backup protection acted, *B3* open
X5	0	1	0	0	0	1	0	0	0	0	0	0	0	*L2* Permanent fault without reclosing
X6	0	1	0	0	0	1	0	1	1	0	0	0	0	*L2* Transient fault, reclosed
X7	0	1	0	0	0	1	0	1	1	1	0	0	1	*L2* Permanent fault, reclosing failure
X8	0	1	0	1	0	0	1	0	0	0	0	0	0	*L2* failure , *B1* fail open, remote backup protection acted, *B3* open
X9	0	0	0	1	0	0	1	0	0	0	0	0	0	*M* failure or near backup protection acted, *B3* open/ *T1* failure or near backup protection acted, *B3* open

TABLE IV. EVENT MEANING OF FINITE STATE MACHINE

Event	Meaning
$R_{l,l1}$	*L1* Line Protection
$R_{l,l2}$	*L2* Line Protection
R_m	Bus Protection
R_t	Transformer Protection
B_1	Circuit breaker on *L1* Line
B_2	Circuit breaker on *L2* Line
B_3	Circuit breaker on 10kV side of *T1*
R_{eB1}	Reclosing

To establish the FSM model for fault diagnosis, in addition meeting the variable binary of the fault alarm set in Table II, the delay time of the successive alarms also need to be checked. Suppose variable *T* is the flag of time delay of the successive alarms, and $T = \{0,1\}$. When there is a SOE alarm receive, suppose the alarm set $X_n = \{x_1, x_2, K, x_m\}$, $m = 1,2,K,m$, for $x_i \neq 0$, $x_i \in X_n$, when $\sum_{j=i+1}^{j<m-i} x_{i+j} - x_i = 0$, if $\forall t_{i,i+j} \in d_{i,i+j}$, then flag *T*=1, else *T*=0.

According to the fault types in Table II, the FSM model for fault diagnosis can be established. Firstly, the event set $\Sigma = \{e_1, e_2, K, e_9\}$, when $X = X1$, $e_1 = 1$, accordingly, when $X = X2$, $e_2 = 1$, so the event set Σ can be obtained.

The state of FSM model is defined as $S: S_0 \sim S_9$, and the 10 state meanings correspond to the fault types defined in Table II, such as S0 means "*normal*", while S1 means"*L1 Permanent fault without reclosing*", and so on. State migration is indicated by arrows "$\rightarrow$", the direction of which represents the direction of state transition, and the arrows indicate the trigger condition event x and state transition rule of state transition δ. In order to make the finite state function return to the initial state after the end of reasoning, a timeout signal t is defined according to experience, normally $t \geq 1.5s$. The effective state machine model of the distribution system is shown in Fig. 2.

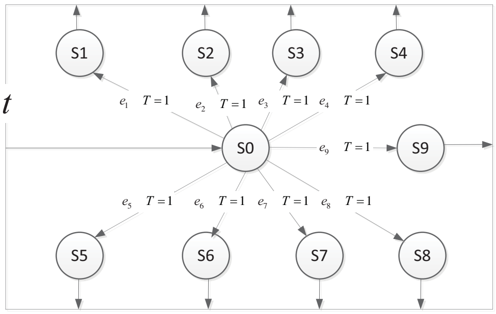

Fig. 2. Fault state transition diagram of distribution system.

The size of FSM model is related to the scale of the system. For each additional outgoing line, at least four transfer states need to be added; when multiple buses and transformers operate in parallel, the state variables will be further increased. However, it is very simple and efficient for the fault reasoning of standard substation, especially for the common fault types using the finite state machine model.

IV. Example Analysis

Here takes 220kV substation for example, a substation call Dayan which's wiring is shown in Fig. 3. It is a typical 220kv substation with 10kV distribution bus in the system. The automatic power input device (marks BZT in Fig. 2) for bus coupling circuit breaker #1006 of 10kV bus adopts the dark standby mode, i.e. The circuit breakers #1005 and #1011 at the transformer are closed, while the bus coupling circuit breaker #1006 is open. Transformer #1 runs bus *I*, and transformer #2 runs bus *II* and *III*.

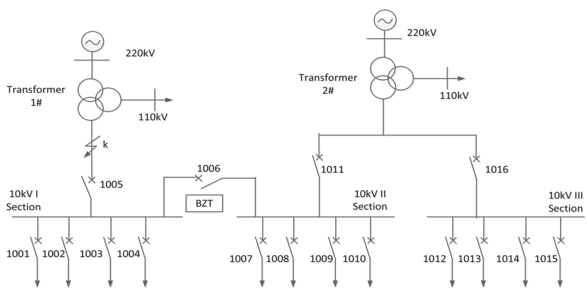

Fig. 3. 10kV Side System Wiring Diagram of Dayan Substation with Voltage of 220kV.

On July 12, 2018, point K in the system grounding, and the protection, switch and standby automatic switch of the station all acted correctly. During the accident, the SOE alarm window receives 478 alarm signals in total, of which, about 30 are for "protection-circuit breaker" acts and reset, 100 ear accident associated, 200 are related to bus voltage loss abnormal, and about 150 generated by equipment abnormal after the standby automatic switch on. The dispatcher centrally handles the accident for 5 minutes.

In this case, the FSM model for fault diagnosis under time constrain method is adopted, which can judge 57 types of system failure, including 48 types of feeders failure, 3 types of bus couple switches failure and 6 types of power transformers failure. The FSM modeling course can be referred to Section II of this paper. Here, Fig. 4 gives the fault diagnosis branch of the FSM modeling of the example, which ignored the other 56 faults types.

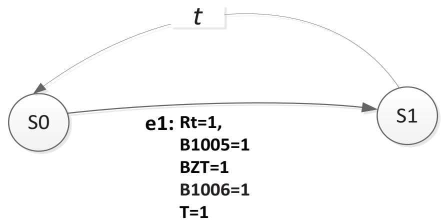

Fig. 4. The path graph of FSM corresponding to accident reasoning of the example.

By adopting the FSM model, the time for fault diagnosis is reduced to 3.2s, and the SOE alarms are compressed into five items, as shown in Table V. The fifth alarm in the table indicates that all the accident associated signals are normal reset. Combined with the analysis results, the accident was developing as follow. Firstly, the 10kV-voltage side of the power transformer #1 where a grounding occurred, the protection that the low-voltage compound closing overcurrent section *II* is tripped by the action, circuit breaker #1005 switch off. Then bus *I* lost its voltage, the bus coupling standby automatic switching #1006 action, circuit breaker #1005 switch on, and the bus *I* is restored to power. By FSM model, it can be inferred that point *K* is in fault.

TABLE V. "Protection-Circuit Breaker" Action Alarms Sequence

Num	Substation	Event
1	Dayan substation	Time: 2018-07-12 15:36:14:910 2 (Dayan substation) SOE alarm: Power Transformer #1 10kV-side Remote backup protection outlet-action
2	Dayan substation	Time: 2018-07-12 15:36:15:080 1 (Dayan substation) SOE alarm: Power Transformer #1 10kV-side Circuit Breaker # 1005-Switch off
3	Dayan substation	Time: 2018-07-12 15:39:16:080 1(Dayan substation) SOE alarm: bus coupling circuit breaker #1006 Automatic Power Input Device 10kV RCS-9651 -action
4	Dayan substation	Time: 2018-07-12 15:39:16:210 1(Dayan substation) SOE alarm: bus coupling circuit breaker #1006-switch on
5	Dayan substation	Time: 2018-07-12 15:39:16:690 1 (Dayan substation) SOE alarm: Bus *I* power off-reset

It is proved that the method proposed in the paper can quickly sort out the key signals of accident development, accurately analyze and summarize the types of accidents, and can greatly compress the information associated with operation and frequently sent misinformation in the SOE alarm window.

V. CONCLUSION

The paper proposed a method to solve the problem of alarm analysis and fault diagnosis in the operation system of power grid dispatching and monitoring, and assist the dispatching and monitoring personnel to make decision-making response in case of fault. Failure occur with the highest probability in 10kV distribution system, establishes the common FAM model for fault diagnosis in the distribution system by studying the SOE alarms data, and finally uses it to help the dispatcher to handle accident. The test results show that the time sequence causality and FSM model established in this paper can achieve fast and accurate alarm processing.

Now, this model does not include researches of other voltage levels in power system, the completeness of fault types still needs to be improved. Meanwhile, since some types of the fault occur very similar SOE alarms, so how to reduce the decoupling of the FSM model is also the focus of the next research.

REFERENCES

[1] Lin Zhenjia, Chen Haoyong, Wu Qiuwei, Li Weiwei, Li Mengshi, Ji Tianyao. Mean-tracking model based stochastic economic dispatch for power systems with high penetration of wind power[J]. Energy, 2020, 193 (C).

[2] Jiajun Zhang, Long Zhou, Yang Zhao et al. Synchronous bidirectional inference for neural sequence generation [J]. Artificial Intelligence, 2020, 281.

[3] Partha hakroborty, Shinya Kikuchi Calibrating the membership functions of the fuzzy inference system: instantiated by car-following data [J]. Transportation Research Part C, 2003, 11(2).

[4] Hamed Sohrabpoor, Sushant Negi, Hamed Shaiesteh et al. Selecting optimal parameters on selective laser sintering process: A combined simulation and optimization approach [J]. Optik, 2018.

[5] Ralf Wieland. Fuzzy Models [M]. Elsevier B.V. : 2019-12-19.

[6] Jeevan Kumar Pant. Optimization Techniques in BME [M]. Elsevier Inc.: 2019-12-19.

[7] Baihao Qiao, Jing Liu. Multi-objective dynamic economic emission dispatch based on electric vehicles and wind power integrated system using differential evolution algorithm [J]. Renewable Energy, 2020, 154.

[8] Erofeev Evgeny, Barylska Kamila, Mikulski Å• ukasz,PiÄ tkowski Marcin. Generating all minimal petri net unsolvable binary words[J]. Discrete Applied Mathematics, 2020, 274 (C).

[9] Lilia Tightiz, Morteza Azimi Nasab, Hyosik Yang,Abdoljalil Addeh. An intelligent system based on optimized ANFIS and association rules for power transformer fault diagnosis [J]. ISA Transactions, 2020.

[10] Yongxin Xiong, Wei Yao, Weibiao Chen, Jiakun Fang, Xiaomeng Ai, Jinyu Wen. A data-driven approach for fault time determination and fault area location using random matrix theory [J]. International Journal of Electrical Power and Energy Systems, 2020, 116.

[11] Tianpeng Li, Wenjun Wang, Xunxun Wu, Huaming Wu, Pengfei Jiao, Yandong Yu. Exploring the transition behavior of nodes in temporal networks based on dynamic community detection [J]. Future Generation Computer Systems, 2020, 107.

[12] M Whiteley, S Dunnett, L Jackson. Simulation of polymer electrolyte membrane fuel cell degradation using an integrated Petri Net and 0D model[J]. Reliability Engineering and System Safety, 2020, 196.

[13] King Jacob M,Bergeron Clint A,Taylor Charles E. Finite state machine implementation for left ventricle modeling and control.[J]. Biomedical engineering online, 2019, 18 (1).

[14] Cui Jianjiang, Liu Zixuan, Xu Long. Modelling and simulation for table tennis referee regulation based on finite state machine [J]. Journal of sports sciences, 2017, 35 (19).