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Fault Diagnosis Based on Fuzzy Relations Using Protective Relays and Circuit Breakers

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***Abstract**: In order to deal with the incomplete information and uncertainties imposed on fault section diagnosis, this paper proposed a fault section diagnosis method based on fuzzy relations for power generation stations, substations and transmission lines. The proposed method utilizes information of protective relays and circuit breakers to build sagittal diagrams which represent the fuzzy relations for power stations, substations and transmission lines. It diagnoses the faulted sections correctly for complicated multiple faults as well as simple faults. The proposed scheme also examines the mal -operation of circuit breakers based on the relays information and determines the faulted section (item). The section's possibility of being faulty is given by degree of the membership of the fault section candidates. Computer simulation of a real system such High Dam power station (Hydro Plants Generation Company HPGC) in Egypt shows that employing this type of diagnosis is useful in diagnosing faults that have uncertainty. Hence, it helps the control center operation engineers to make a reasonable decision and strong practicability of fault diagnosis methods to the real power station.*

I. Introduction

The objective of the faulted section diagnosis method is to identify faulted components in the power station e.g. generation units, power transformers, autotransformers, service transformers, buses and lines that based on the status of protective relays and circuit breakers. To reduce the outage time and ensure stable and reliable supply for electric power for customers, it is essential for control centers to quickly identify the faulted section in power system prior to start restoring actions. Therefore, the operators must have the capability to estimate and restore the faulted section in an optimal procedure. An effective diagnosis system is required to suggest the possible way to remove faults and assist the operator to protect the systems. Recently, the possibility of implementing the heuristic rules using expert systems has motivated extensive works on the application of expert systems in fault diagnosis.

Considerable efforts have been made toward developing fault diagnosis system. Most of these efforts are based on Expert Systems (ES) [1 – 3]. Although ES based approach offers powerful solutions to the fault diagnosis, but it has shortcomings, e.g. the procedure of knowledge acquisition and knowledge base revision or maintenance is quite burdensome. In addition, dealing with the large amount of data is difficult due to the conventional knowledge representation and inference mechanisms.

During the last two decades, much research work has been done for estimating the fault section diagnosis in a power system by using several artificial intelligence approaches. Such as, artificial neural networks [4,5], genetic algorithm (GA) [6], fuzzy Petri nets [7,8], family eugenics based evolution theory [9] and immune algorithm [10]. However, the only work addressing the power plant control and fault diagnosis [11] that aimed to control and supervision the plant system control of the station but not related to the protection system of all station through generation units, transformers, buses and lines. Since there are some wrong and missed signals in a power system, which may be caused by data transmission error or loss, in addition to maloperation and nonoperation of circuit breakers or relays, uncertainty reasoning is highly recommended to diagnose the system's faulted section. Among the existing uncertainty reasoning approaches, the fuzzy relations approach is accurate, which applied on the power system that include the transmission lines and bus bars [12]. In this paper, the fuzzy relations based set theory for fault diagnosis of power stations including, generation units, power transformers, autotransformers, service transformers, reactors, bus bars and lines is proposed to deal with uncertainties. It is represented by sagittal diagrams through the complete protection scheme of them. This method provides the most likely faulted section or sections as the form of degree of membership as well as the faulted sections candidates.

The proposed method is tested for High Dam Power Station 11/15.75/220/500KV. Test results show that the proposed method is useful in the final decision process of fault diagnosis by reducing the faulted section candidates.

II. Protection Systems

A. Protection System of a Generation Unit

Protection relays are hardware devices responsible for sensing different actuating quantities that indicating

case of fault (the over-currents) and tripping the circuit breakers to isolate generation unit fault from the system as soon as possible. The generation unit protection system of High Dam power station is more complex since it has two cascaded generators to produce the output voltage. Moreover, each
generator has protection devices to protect itself, so more complex protection relations are extracted. In general, the protection systems of electrical power system are composed of main protection relays (MR), some back-up protection relays (BR) and (CB) breaker's failure protection. A typical generation unit for the High Dam power station shown in Fig. 1 [13] is used to illustrate the procedure of electrical protection and also illustrate how it is connected to the other elements (main power transformers and service transformer).

The procedure of protection system when a fault occurs as follows. If a fault occurs on the main generator of unit 7, which causes the action of protection relay, U7 M87M (the protection definition shown in Appendix A) that is dependent on a fault kind U7CB. If there are some problems due to the circuit breaker can not trip and the faulted section is not isolated, the breaker failure protection of breaker operates and give retrip order to the circuit breaker. If the circuit breaker does not trip again, the breaker failure gives a trip order to U7CB, U8CB, U9CB, B3CB1, B3CB2 and TS3CB for unit 7CB, unit 8CB, unit 9CB, the first CB of Block 3, the second CB of Block 3 and service transformer no.3 CB respectively. In the most cases, the breaker failure protection is associated with the differential protection.

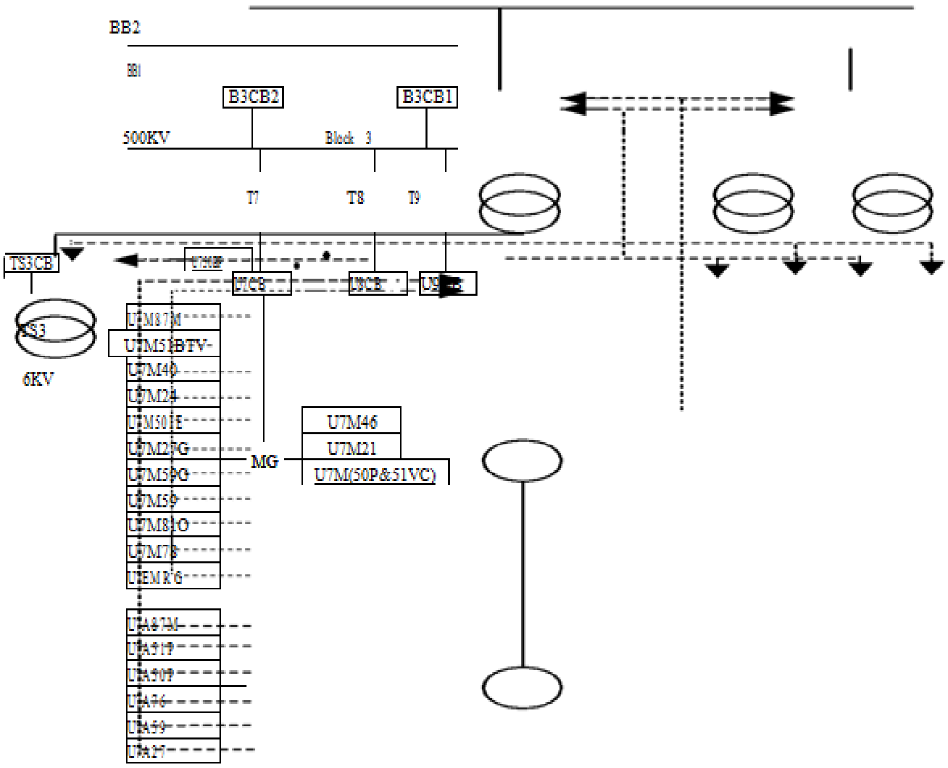

Fig. 1. A typical model for High Dam generation unit

B. Protection System of the Main Power (Step Up) Transformer

A real step up transformer for High Dam power station, shown in Fig. 2**,** is used to illustrate the procedure of electrical and mechanical protections of the transformer, also illustrate how the connected to the other elements (units, bus bars, autotransformers, lines). If a fault occurs on the main transformer 7, which causes the action of protection relays T787H that is dependent on a fault kind trip U7CB, U8CB, U9CB, TS3CB, B3CB1 and B3CB2. If B3CB1 can not trip due to any problem, the breaker failure for that circuit breaker gives a retrip order for that breaker. If the breaker does not trip again, the breaker failure protection gives a trip order to trip all the breakers feeding that breaker, i.e., trip L1CB1, L2CB1 and T13CB for line 1 CB1, line 2 CB1 and autotransformer CB respectively.

Similarly, the protection system models for block 3, high voltage bus bars 1 and 2, autotransformers 13 and 14 can be done. It is difficult to diagnose the fault with the binary logic due to the uncertainties; this is the reason that fuzzy relations have been selected in this work.

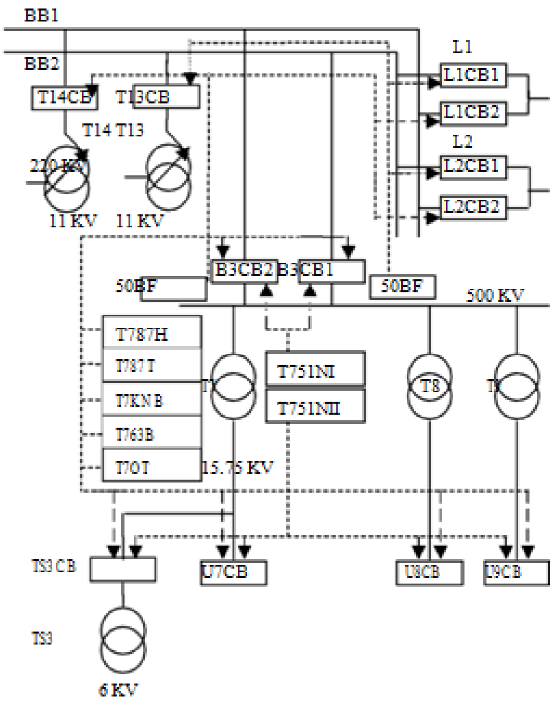

Fig. 2. A typical main power transformer scheme for High Dam Power Station

III. Fuzzy Relations For Power Generation Stations

A crisp relation represents the presence or absence of association, interaction, or interconnectedness between elements of two or more sets. This concept can be generalized to allow various degrees or strengths of relation or interaction between elements. Degrees of association can be represented by membership grades of a fuzzy relation in the same way as degrees of set membership are represented in a fuzzy set. The relation between two sets *X* and *Y* is known as binary relation, and is usually denoted by *R*□ *X, Y* □ . A binary fuzzy relation can be represented by a sagittal diagram. Each of the
represented by a setnodes in the
sets *X* , *Y* is of diagram.

Element *X* □ membership grades
s of *Y* with nonzeroin
R□ *X, Y* are represented in the diagram by lines connecting
□ the
respective nodes. These lines are labeled with the degree of membership.

For power systems, proposed sagittal diagrams that have sets of nodes; [set1 - sections, set 2- relays, set 3- circuit breakers]. In this paper, the authors build and generalize the sagittal diagrams for the power stations. An example for the sagittal diagrams, that of the typical generation unit model of High Dam power station was built as shown in Fig. 3. The sagittal diagrams are dependent on the causal operation of relays and circuit breaker at the instant of fault occurrence. The causal relations are represented by arrows from set to set.

The labeled relation values between the section set, relay sets and circuit breaker sets are determined statistically according to the uncertainties of operation of and the priorities of relays and circuit breakers when a fault occurs [12]. The labeled relation values between the faulted section and main protection is 0.8, backup protection is 0.7 and breaker failure is 0.55 [12], also fast protection is 0.75, generator abnormal operating condition protection which related to network is 0.65, generator backup protection for the downstream faults is 0.6, load shedding protection is 0.5. It is proposed that the labeled relation values between relays set and circuit breakers set larger than the labeled relation values between sections set and relays. If the circuit breaker is tripped by the main or backup protection relay, the breaker failure can't operate to isolate completely the generation unit by tripping all breakers. An inhibitory circle 'o' is introduced to represent this rule.

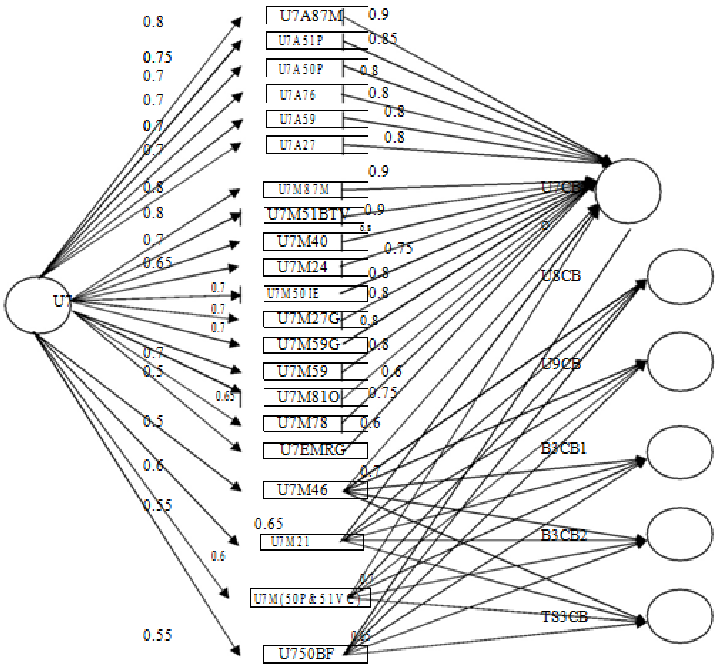

Fig. 3. Sagittal diagram for a real generation unit model in the High Dam power station

IV. Diagnosis Methodelogy

A. *Operation of Fuzzy Sets*

The intersection of two fuzzy sets *A* and *B* is specified in general by a binary operation on the unit interval that is, a function of the form

$$i : [0, 1] \times [0, 1] \rightarrow [0, 1] \qquad (1)$$

For each element *x* of the universal set, this function takes its arguments as a pair consisting of the element's membership grades in set *A* and set *B* , and yields to the membership grade of the element in the set constituting the intersection of *A* and *B* . Thus,

$$(A \cap B)(x) = i[A(x), B(x)], \text{ for all } x \in X \qquad (2)$$

There are several classes of fuzzy intersection have been proposed; their individual members satisfy all the axiomatic requirements for the fuzzy intersection. In this paper, we used the Yager class fuzzy intersection and it is defined by the following equation [14]

$$i_w(a, b) = 1 - \min\left[1, \left((1-a)^w + (1-b)^w\right)^{\frac{1}{w}}\right], \quad w > 0 \qquad (3)$$

Where *w* is interpreted as performing fuzzy intersection and union of various strengths. In this paper, $w = 3$ is chosen.

The discussion of fuzzy union is closely parallel to that of fuzzy intersection. The general fuzzy union of two fuzzy sets *A* and *B* is specified by a function [14]

$$u : [0, 1] \times [0, 1] \rightarrow [0, 1] \qquad (4)$$

The argument to this function is the pair consisting of the membership grade of some element x in fuzzy set *A* and the

membership grade of that some element in fuzzy set *B* . The function returns the membership grade of the element in the set $A \cup B$. Thus,

$$\mu_{A \cup B}(x) = u(\mu_A(x), \mu_B(x)) \quad , \quad \text{for all } x \in X \qquad (5)$$

The fuzzy union of Yager class is defined by the equation

$$u_w(a, b) = \min\left(1, (a^w + b^w)^{\frac{1}{w}}\right) \quad , \quad w > 0 \qquad (6)$$

4. Compare the fuzzy union for each candidate faulted section to determine the degree of membership of the faulted section.

In Fig. 4, if U7M87M, U7M51BTV and U7CB operate, the degree of membership of the faulted section Unit7 = 0.99785, another case ; if U7M78, U7M(50P&51VC) and U7CB, U8CB, U9CB, B3CB1, B3CB2 and TS3CB operate, the degree of the faulted section Unit7 = 0.73407.

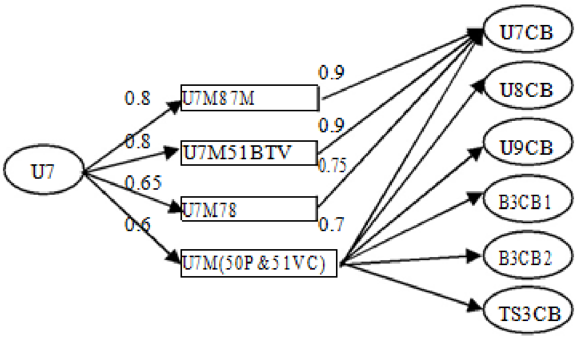

Fig. 4. Example of diagnosis with sagittal diagram

V. Case Studies

In order to testify the effectiveness of the fuzzy relation method to fault diagnosis that presented in this paper, actual faults that happened in the High Dam power station are collected from the high dam's accidents and faults archive. Fig. 6 is a part of High Dam power station. Table (I) presents some fault cases and their diagnosis it. In addition, the analyses of HPGC's analysis are given.

The diagnosis results of these cases are completely corresponding to the HPGC's analysis and also save the diagnosis time.The operation of bus bar differential (HV BB1 87H) in case 1 which is a unit protection means that the fault was on the protected bus BB1. The same situation in case 4 for operation of bus differential (B3 87H) indicating an internal fault on bus BB3. In cases 3,5 Buchholtz protections T8 63B and T13 63B are main and unit protections which respond to the gas and oil flows resulting from internal faults in the transformer T8 and T13. Finally in case 3 both the differential and Buchholtz T9 87H, T9 63B protections are operated giving high degree of certainty of having internal fault in transformer T9. Relating the expected reasons of protective relays operation in Table 1 means that proposed scheme managed to determine the faulty place correctly in Buses BB1 , BB3 and transformers T8,T9,T13.

VI. Conclusion

The proposed technique helped the operator to make the right decision in the critical situations and reduce the delay of restoring actions due to the uncertainties, incompleteness of protective relays and circuit breakers information, and also the great number of alarms and trip signals which sent to the power station's control room.

The sagittal diagrams are used to represent the fuzzy relations for generating unit, power transformer, bus bars, autotransformer and service transformer. They are used for diagnosing faulted section by the fuzzy relation operation. Misoperation of the circuit breaker is also tested. By calculating a fault section with the degree of membership and the misoperation, the proposed system presents the section's possibility of being faulty. That is, the section that has a high degree of membership is considered the faulted section.

The proposed system is tested for actual faults of the High Dam Power Generation Station to demonstrate the system performance. The tested results demonstrate that the proposed method is easy reasoning method, fast diagnosis speed, effectiveness and strong practicability of fault diagnosis methods to the real power station.

This paper presents a complete protection scheme of the different sections in the power station and the relation between them with the corresponding circuit breakers.

APPENDIX A

A.1 Generators Protections

21 Distance / impedance
24 Over excitation volts per hertz
27 Undervoltage
27G Stator ground 3rd harmonic undervoltage
40 Loss of excitation
46 Phase unbalance / negative sequence
50IE Inadvertent energization
50BF Breaker failure
50P Phase instantaneous overcurrent
51P Phase time overcurrent
50P/ 51VCCalled 50P / 27
51BTV Transverse percentage differential
59 Overvoltage
59G Stator ground
76T DC Overcurrent
78 Out of step
81O Overfrequency
87M Longitudinal percentage differential

TABLE I
RESULTS OF ACTUAL FAULTS AND THEIR DIAGNOSIS

Case	Date and Time	Operated Relays	Tripped CBs	HPGC's Analysis	Fuzzy Diagnosis Result	
					Operated Relays	The Faulted Section and Membership Degree
1	22/11/2007, 14:55	HV BB1 87H	B3 CB1, T13 CB, L1 CB1, L2 CB1	Differential relay – right operation	HV BB1 87H	The faulted section is HV BB1, 0.791992.
2	22/11/2007 17:06	T9 87H, T9 63B	U9 CB, B3 CB1, B3 CB2, TS3 CB	Differential & Buchholtz relays – right operation	T9 87H, T9 63B	The faulted section is T9, 0.997847.
3	23/07/2006 16:48	T8 63B	U7 CB, U8 CB, U9 CB, B3 CB1, B3 CB2, TS3 CB	Buchholtz relay – right operation	T8 63B	The faulted section is T8, 0.791992.
4	06/07/2005, 14:14	B3 87H	U7 CB, U8 CB, U9 CB, B3 CB1, B3 CB2, TS3 CB	Differential relay – right operation	B3 87H	The faulted section is B3 BB, 0.791992.
5	02/04/2005, 20:02	T13 63B	T13 CB, T13CB1, TS2 CB,	Buchholtz relay – right operation	T13 63B	The faulted section is T13, 0.791992.

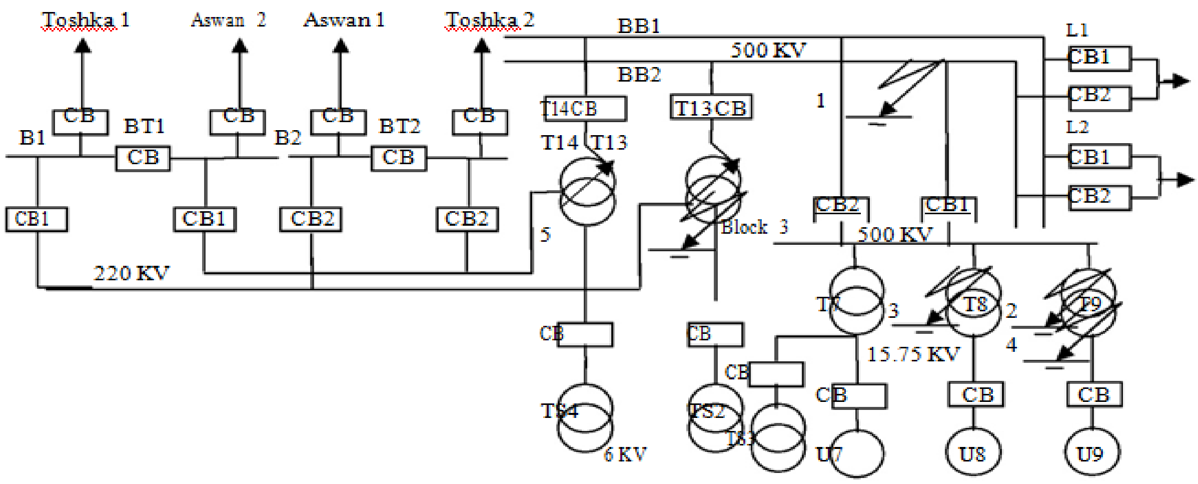

Fig. 6. A part of High Dam power station

A.2 Power Transformer

51N I, II Ground time overcurrent stage 1, 2
87T Harmonic restrained percentage differential
87H Unrestrained high set instantaneous differential
63B Main transformer Buchholtz
KNB Bushing leakage current
WT Oil temperature

A.3 Service Transformer

50P I, II Cut off overcurrent stage 1, 2
51P I, II Maximum overcurrent stage 1, 2

63B Service transformer Buchholtz 63BTC Tap changer Buchholtz

87H Harmonic unrestrained differential

A.4 Autotransformer

24 Over excitation volts per hertz
46 I, II Negative sequence stage 1, 2
50P/51P I, II Overcurrent stage 1, 2
63B Transformer Buchholtz
63P1 Transformer pressure relief
63P2 Tap changer pressure relief
67NP I, II Directional earth fault stage 1, 2 at high side 500 kv
67NS I, II Directional earth fault stage 1, 2 at low side 220 kv
67 I, II Low side directional overcurrent fault stage 1, 2
87T Transformer differential
87NP Restricted earth fault at high side
87NS Restricted earth fault at low side
96P Tap changer protective relay
WT Winding temperature
OT Oil temperature

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