KNOWLEDGE-BASED AND INTEGRATED MONITORING AND DIAGNOSIS IN AUTONOMOUS POWER SYSTEMS.

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ABSTRACT

This paper presents a new technique of knowledge-based and integrated monitoring and diagnosis (KBIMD) to deal with abnormalities and incipient or potential failures in autonomous power systems. The KBIMD conception is discussed as a new function of autonomous power system automation. Available diagnostic modelling, system structure, principles and strategies are suggested. In order to verify the feasibility of the KBIMD, a preliminary prototype expert system is designed to simulate the KBIMD function in a main electric network of the autonomous power system.

Keywords: Expert systems, Failure diagnosis, Power systems.

INTRODUCTION

An autonomous electric power subsystem is one of the most important parts in many automatic systems, including space stations. The safety of the power subsystem depends on the working status of electrical components distributed on all hierarchical levels. Various monitoring and diagnostic measures have been used to deal with abnormalities, failures and faults in the subsystem. They include periodic manual testing, automatic monitoring and testing, and protective relaying. Continuous endeavors have been made to improve the measures; however, difficulties continue to be experienced with some faults, particularly incipient or potential failures of the electrical components.

Building a diagnostic expert system embedded in the software package for the automatic systems, a combination of artificial intelligence (AI) methodology and integrated utilization of status information opens up a new possibility to enhance monitoring and diagnostic techniques usable in the power subsystem. This is a knowledge-based and integrated monitoring and diagnosis (KBIMD) function which can serve as a new function of autonomous power subsystem automation.

This paper presents the KBIMD approach including available diagnostic modeling, diagnostic system structure, diagnostic principles and diagnostic strategies. In order to verify the feasibility of the KBIMD, a preliminary expert system prototype is designed to simulate the KBIMD function in the main electrical network of a power system.

KBIMD CONCEPTION.

The KBIMD is designed to provide continuous monitoring and diagnostics of a real-time systems. It provides an early and more complete revelation of malfunction, abnormalities and failures.

The potential benefits of the KBIMD includes efficient capability to utilize information over a wide scope of equipment, and structural, functional and behavioral knowledge of equipment, and systems. Furthermore, the KBIMD combines the experience of human experts with the computer-based approach to develop an innovative approach to the development of new diagnostic principles and methods.

I.   KBIMD STRUCTURE

The proposed KBIMD system is shown in Fig. 1. Its mainframe comprises a systems

data base (SD), an expert system (ES) and a data coupling processor (DCP). It is connected with data acquisition units, protective units and, if needed, other diagnostic subsystems. The SD contains (a) current messages of diagnosed objects, (b) historical records of the objects, (3) messages from protective relays and other diagnostic systems. The ES is the main body used to perform KBIMD. The DCP is the coupling part of the ES and SD, and performs the mapping of numerical values into qualitative values.
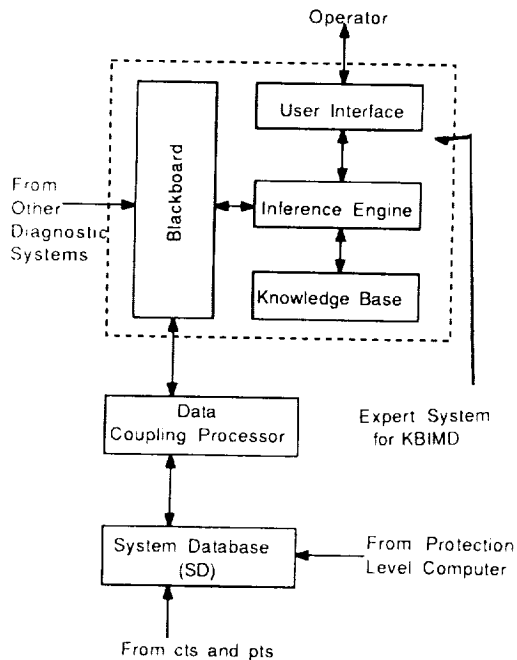

Figure 1. The KBIMD system architecture

II. KBIMD OBJECTS AND MESSAGE SOURCES.

The KBIMD objects consists of components of the electric network autonomous power system. These objects represent the diagnosed quantities of the expert system. It includes current transformers (CTs), and potential transformer (PTs). The CTs and PTs are used for monitoring and protecting relaying subsystems. They provide a source of information to the expert system and by using protective relaying between subsystems.

Different fault types and symptoms are measured by the KBIMD systems.

III. PROTECTIVE RELAYING SYSTEMS.

The role of relays in dealing with electrical fault types and symptoms discussed in KBIMD are different even though they are on the same network. However, the message interchange between the two systems are of potential benefit.

IV. HUMAN OPERATORS AND OTHER DIAGNOSTIC SUBSYSTEMS

With the aid of human operators and other diagnostic subsystems, information on causes of failures are identified. This information provides the basis for developing the expert system.

COMBINATORY MODELING FOR KBIMD.

Three knowledge-based models are designed to provide intelligent diagnostic reasoning of faults. They are discussed under physical configuration model PCM, hierarchical studies model (HSM), and the cause-effect relation model (CERM) of the electric power subsystem. The illustrative network shown in figure 2 below is used as an example.

I. PHYSICAL CONFIGURATION MODEL (PCM)

A component in the subsystem can be diagnosed by the ES only when it is live. All live components constitute the live part in the electrical network of the subsystem. The PCM is used to represent the existing physically relational situation of the network, including joint relations, connected status, live status and operational status of all components in the network. It provides the KBIMD with a clear description of the live parts in the network and their changes with operational requirements.

II. HIERARCHICAL STRUCTURE MODEL (HSM).

The HSM is a hierarchical structure description of the subsystem to enable hierarchical failure-search in the KBIMD. It is organized in the following way:

Some failures have their origin in the cause-effect relationship and their discovery is based on diagnostic experience. Discrimination based on the CERM principles may be used to speed the diagnostic reasoning by directly pointing to possible failure sources.

IMPLEMENTATION STRATEGY.

Several basic strategies are used for implementing the KBIMD. The strategies may be modified to suit diverse requirements of an autonomous power system with alternating or direct power source. The strategies are divided into three major parts.

1. Failure Monitoring.

Prior to failure search by the ES, all subsystems at the highest level of KBIMD are monitored in a circular or repeated manner. The monitored electrical quantity must satisfy current and voltage balance relations. For example in Figure 4, the current balance relation using Kirchoff's 1st law gives:

$$\sum_{n=1}^{4} i_n = 0 \qquad (1)$$

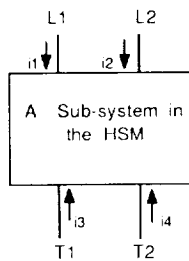where i_1 through i_4 shown in figure 4 denote the input/output port current of a given phase:

Figure 4. Ports currents of a sub-system

Similarly, for the voltage balance relations, we employ Kirchoff's 2nd law to validate voltage relations at normal conditions that is:

$$V_1 = V_2 = V_3 = V_4 \qquad (2)$$

where V_1 through V_4 are phase voltage on its input/output ports. It should be noted that the currents and voltage quantities are stepped down values obtained from current and potential transformer CTs and PTs.

B. SINUSOIDAL WAVEFORM PATTERN OF CURRENT SUM

Sinusoidal waveform pattern recognition is based on typical characteristics of alternate currents. For example, the subsystem in Fig. 4 should satisfy the following waveform pattern under normal conditions:

$$\sum_{n=1}^{4} |i_n| = \left| A.\sin(\omega_f t + \theta) \right| \qquad (3)$$

where w_f is the fundamental frequency, A and θ are real constants. Equation (3) means that a sum current of all port currents should have a sinusoidal waveform under normal conditions.

FAILURE SEARCH.

Failure search is performed by the inference engine in the expert system and advances to locate the failure in the power system. In a failure mode, it employs the service of DBFP which employs equations (1), (2), and (3) to determine whether a diagnosed system contains a possible fault source or not.

To narrow the faulty region into as small an area as possible DBSK system on the HSM is used. It narrows down the fault region into the smallest area possible. The DBEK system is used to assist the reasoning to detect possible faulty components more quickly and accurately. While the DBEK is used to verify diagnosis results and to determine the failure types. Qualitative reasoning is performed to implement description of equations (1), (2) and (3).

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II.   DATA KNOWLEDGE MAPPING.

The diagnostic reasoning in the ES is based on real-time data in the system data base which represents a stepped down version of fault quantities. To implement the diagnostic reasoning, data coupling between symbolic computation for the ES and the numerical computation is required. The implementation procedure is as shown in Fig 1.

The DCP structure performs transition from numerical values into qualitative values. The data knowledge mapping is based on selection of one of the following modes:

(a)   Three quantitative ranges of "balanced," "unbalanced," "high unbalanced" condition of three phase voltages and currents.

(b)   Four qualitative ranges, "Zero," "low," "high" and some for comparison of voltages and currents.

(c)   Three qualitative ranges, "zero," "near zero" and "not zero"from equation (1).

(d)   Three qualitative ranges "equal," "unequal" and "highly unequal" for equation (2).

(e)   Two qualitative ranges "normal" and "abnormal" in equation (3).

EXPERT SYSTEM ON KBIMD.

A preliminary prototype of the ES used to verify feasibility of the KBIMD in autonomous power systems has been designed in PROLOG[4]. Its structure, shown in Fig. 1, comprises the four ports: knowledge base, blackboard, inference engine and user interface.

KNOWLEDGE BASE

The knowledge base developed for the KBIMD consists of a fact base and a rule base. The fact base contains the fact statements which describes the behavior and records of all components. It stores qualitative knowledge of

real-time message sources and solution procedures for handling diagnostic problems.

The status and descriptions of PCM and HSM are given in the fact base. The rule base consists of IF-THEN statements. Using production rules, the basic decision-making gives diagnostic reasoning in the KBIMD. The rule base contains rules for forming and changing the PCMs and HSM. It also presents rules for CFRM, and gives description rules for DBSK, DBFK and DBEK.

II.   BLACKBOARD.

The blackboard approach uses data base for message communication between the ES and the outer units. The blackboard provides messages or order or starting or stopping rules for DCP. The DCP gives qualitative value and issues messages from other diagnostic subsystems.

The blackboard consists of blackboard Monitor (BM), Input-Blackboard (IB) and Output-Blackboard (OB). Its structure is shown in Fig. 5. BM is a part of the inference engine which maintains and controls access to the blackboard. OB is used to provide the DCP with necessary messages for selecting relevant data in the SD and performing needed numerical computation to implement the diagnostic strategies. IB is used to receive qualitative values from DCP which are necessary for performing qualitative reasoning in the KBIMD.
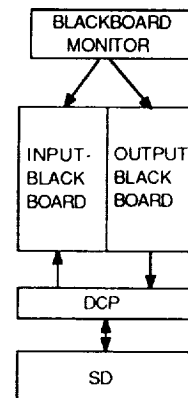
Figure 5 Blackboard structure and interaction

Inference Engine

The inference engine is the part in the ES which contains the general KBIMD problem-solving knowledge. It uses the domain knowledge in the knowledge base and performs message interaction on the blackboard. It consists of hierarchical and modular procedures, and is based on data-driven, forward chain and meta-rules methods.

The inference engine is designed to determine and evaluate the working of the ES forms and changes in the PCM and HSM. It controls and utilizes the blackboard for monitoring and starting failure search to locate possible failure. The record of diagnostic and the approach suggested for handling failure types is also given.

The inference engine and a user interface form an expert system shell constructed in a multi-level and hierarchical form shown in Figure 6.
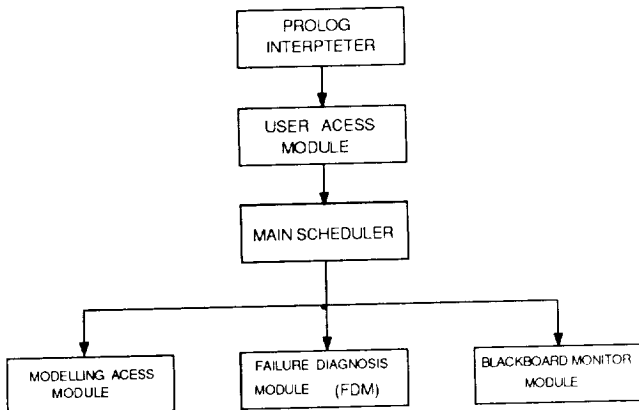

Figure 6. Modular structure of the expert system shell

Failure-Diagnosis Module (FDM) is constructed by several sub-modules, shown in Fig. 7. The KBID (Knowledge-Based and Integrated Diagnosis) scheduler is based on data-driven and meta-rules methods. Data from the main scheduler or other modules are based on reasoning steps. Meta-rules are used for scheduling of sub-modules at the lower level through ordering and utilizing of rules. As soon as a diagnosis has been completed, the

reasoning process will return from the Result Output Module to the User Access Module to report a diagnostic result to the operator.

SIMULATION TEST EXAMPLES

Several test examples are presented to illustrate the feasibility of the KBIMD and the application of the ES. The examples are based on the electrical network configuration in Fig. 2. Simulation tests are performed in the following way:

(1) Set the ES in a waiting state,
(2) Input qualitative values necessary for KBIMD into the blackboard,
(3) Set the ES in an operational state,
(4) The ES tells failure locations as its diagnostic results,
(5) The ES explains its diagnosis through man-machine dialogue.

I. Example I

Location : VT21 (when CBB12 closed)
Failure: secondary winding of A phase in turn-turn short circuit.
Input: (1) three-phase voltages of VT21 "unbalance"
(2) the A phase voltage "low," B and C phases of VT21 "same".

Result and Explanation:

A failure inside the A phase of VT21 secondary part.
BECAUSE OF three-phase voltages of VT21 "unbalance;"
AND the A phase voltages of VT11, 12, and 22 "equal", and of VT21 "unequal";
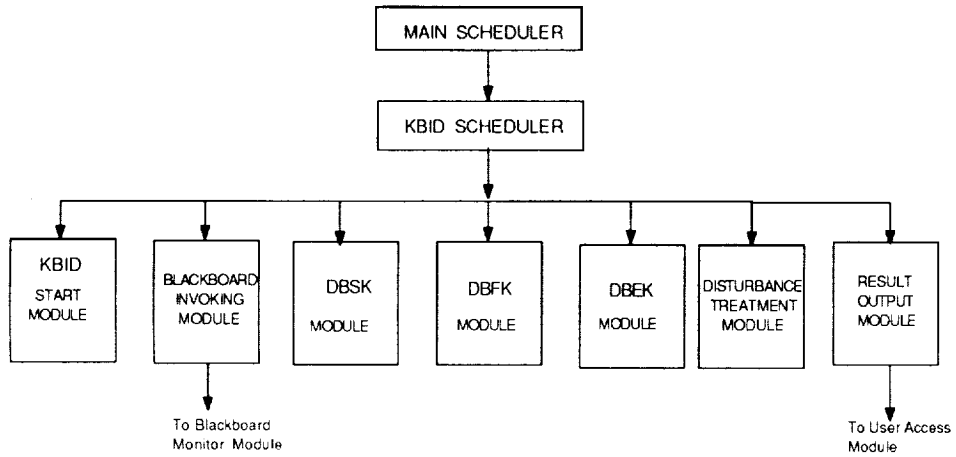AND B, C phase voltages "same" and A phase of VT21 "low".

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Figure 7. Structure of the FDM

II.	Example II	
	Location:	CT321 (when CBB34 opened)
	Failure:	secondary winding of B phase in open condition
	Input:	(1) three-phase currents of CT321 "high-unbalance;" (2) B phase current "zero," A and C phase currents of CT321 "same."

Results and Explanation:

A failure inside the B phase of CT321 secondary part.

BECAUSE OF	B phase sum current of CT311, 331, 341, 351, 361, and 321 "not zero;"
AND	the sum current of CT311, 331, 341, 351, 361 and 322 "zero;"
AND	A, C phase currents "same" and B phase current of CT321 "zero."

III.	Example III	
	Location:	Cable tie 1 (when CBB34 opened)
	Failure:	a partial discharge in C phase-ground of tie 1.
	Input:	(1) C phase currents "same," waveforms of CT451, CT452 "abnormal;" (2) C phase current waveform of CT552 "normal."

Result and Explanation:

A failure inside the C phase of Cable tie 1.

BECAUSE OF	C phase current waveform of CT451 and 452 "abnormal;"
AND	C phase current of CT451 and 452 "same;"
AND	C phase sum current of CT411,421, 431, 441, 451, and 461 "zero;"
AND	C phase sum current of CT411, 421, 431, 441, 461, and 552 " not-zero;"

AND   C phase current
waveform of CT552
"normal."

CONCLUSION.

The autonomous electric power system is one of the most important parts in many automatic systems. Malfunctions, abnormalities and incipient or potential failures in the autonomous electric power system have been a difficult problem to address. With the application of expert system technology and integrated utilization of information, this paper suggests an approach of knowledge-based and integrated monitoring and diagnosis (KBIMD) to deal with the failures in autonomous power systems. The paper presents:

(1) The KBIMD basic conception and available system structure scheme of the KBIMD,

(2) Combinatory modeling for the KBIMD which is performed through a combination of a physical configuration model, a hierarchical structure model and a cause-effect relation model.

(3) Combinatory diagnosis principle for the KBIMD which is performed through a combination of diagnosis based on first principles, structure knowledge, function knowledge and experiential knowledge,

(4) Basic implementation strategies for the KBIMD,

(5) A preliminary design of the prototype expert system used for the KBIMD.

The paper gives simulation test examples to illustrate the feasibility of the KBIMD and the prototype expert systems.

Further research will be necessary to advance the KBIMD suggested here to practical application in autonomous power systems. It should include:

a   Development of information integration utilization methodology

b   Development of diagnostic principles available to no-electric parts in autonomous power systems

c   Knowledge-based recovery after completion of a diagnosis process

d   Full design and implementation of a practical KBIMD system.

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point in 3-space. The simulation proceeds by determining the surface to which the leaking fluid will drop, found by dropping a perpendicular from the leak point. The gradient at the point where this perpendicular intersects the topmost surface under the leak point determines the direction the liquid will take. The path of the liquid from this point is determined computationally, until a level is reached from which, in intuitive terms, there is "nowhere to go but up"; more formally, until the minimum point or plane of an upward concavity is encountered. At this stage the algorithm proceeds to simulate the mounting fluid level, creating a new horizontal plane a small increment Δx above the above-mentioned (local) minimum, and determining the intersection of the new plane (called a *level*) with the planes that form the side of the upward concavity. If this intersection contains points that are outside the plates that form the concavity (it suffices to check points in the intersection of the level and the edges of the concavity), then we have found a level at which the fluid will spill out of the concavity. The spill point is determined, treated as a new leak source, and simulated in the same manner as the preceding sources. Otherwise, a new plane Δx above the previous one is created to represent the advancing fluid level, and the process iterates.

When a new level-representing plane is generated, it is determined whether it intersects the space occupied by a component. If so, a possible propagation path from the original leak to the component is recorded. The effects of failure of the component that was reached can then be propagated further along the functional dependency net.

It should be noted that the paths thus determined are *possible* rather than predicted propagations. Whether such a propagation actually occurs depends on numerous factors such as leak flow rate, amount of fluid available, etc. In most cases of malfunction such factors can only be approximated; furthermore, the amount of time required for these possible events to occur, and in some cases even the ordering of the event sequences, is not predicted by the simulation. The predictions made by the simulation are thus inherently *qualitative* in nature.

The above description of the simulation procedure, while conceptually straightforward, glosses over a large number of computational complexities. The physical world is a complicated place, with behavior determined largely by local interactions. Attempting a qualitative simulation of three-dimensional events based on non-local computations entails a large number of special cases, most of which had to be found the hard way. It is surprisingly difficult, for example, for the simulation to establish and keep track of which side of a plane the fluid path belongs. Alternate representations based on local rules, as described in [Gardin] and [Taylor], were considered but tabled on the grounds of computational intractability.

CONCLUSION

We envision the final form of the spatial simulation system described above as part of an interactive pilot aid system that allows the human to remain in the loop, rather than attempting to solve all problems of diagnosis, prognosis, and recovery planning within the program. The motivation for this orientation lies in our belief that attempting to construct a completely autonomous system would confine its scope of operation to "toy problems", an ever-present bane of AI systems. It is expected that the operator will have the capability of posing a wide variety of queries to the system, including queries regarding possible physical or functional fault propagation paths. The system will provide answers based not only on database retrievals, but also on qualitative simulations such as the one described in this paper, as well as an array of alternate qualitative and quantitative reasoning techniques.

The reasoning processes of AI programs are typically based on deductive inference mechanisms. A number of powerful techniques for such inferencing have been developed, but tend to suffer from representational difficulties, particularly the frame problem. As discussed in [Sloman], reasoning based on analog rather than Fregean representations can offer a way around many of these problems.