

THE USE OF EXPERT SYSTEMS FOR POWER SYSTEM RESTORATION

Task Force 38.06.04

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This report was prepared by Task Force 38-06-04, which aimed at evaluating the possible contribution of expert system techniques to the bulk power system restoration problem.

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S U M M A R Y

1. INTRODUCTION

The characteristics of the Power System Restoration problem (its combinatorial aspects, use of knowledge from a wide variety of origins and of different types, number of criteria to satisfy) make it a difficult problem, for which the classical methods (such as optimisation techniques) cannot even now give a satisfactory solution. On the other hand, the use of expert systems to generate restoration plans is being considered by many research teams, and promising results have already been obtained.

The objective of the Task Force was to give a more precise evaluation of the possible contribution of Expert Systems to the Power System Restoration problem.

Three stages had been planned for the Task Force work : the first stage was a survey of already developed expert system prototypes in the field of Power System Restoration ; for the second stage, we intended to perform an in-depth comparison between different approaches on a chosen sub problem of the restoration problem ; finally, in the last stage, the aim was to make a general evaluation of the potential for practical use and further development of expert systems in the field of Power System Restoration.

The Task Force really started in August 1991, and was concluded, as scheduled, at the end of 1993. In this summary report, we will first recall the main results of the three stages of the Task Force. We will then try to give some general conclusions on the present and possible future use of expert systems for Power System Restoration.

2. A SURVEY OF EXPERT SYSTEM PROTOTYPES ALREADY DEVELOPED IN THE FIELD OF POWER SYSTEM RESTORATION¹

Nineteen expert system prototypes were analysed ; these cover a wide range of problems at the transmission level, from system restoration after a general blackout to load re-energising after a partial outage ; they also include a limited number of distribution restoration expert systems. Each system has been analysed using a detailed description form covering the following items : system functional objectives, power system representation and modelling, restoration knowledge in the expert system, knowledge engineering features, facilities provided by the system and software/hardware implementation.

Most of the systems analysed are prototypes running on simulation data, or even connected to a complete simulator. Two of them (one for partial outage, the other at the distribution level) were operational when the survey was performed (1992).

Nearly all the expert systems assist the operator during the restoration process. Most of them help the operator choose among various ways of initiating the restoration and select intermediate restoration objectives, then develop in real-time detailed restoration plans ; a number of them display for the operator the applicable, pre-established restoration procedure.

In most cases, a detailed representation of the controlled power system, including busbars, circuit breakers, lines, etc., is used. Loads are generally aggregated.

¹ A summary of this survey has been published in *Electra* (#150, October 1993)

The predominant origin of knowledge is the experts know how and operational procedures. No possibility of knowledge updating is generally included. Quite naturally, some knowledge domains such as load reconnection or path-finding are addressed by most expert systems, whereas others (such as generation management) are specific to certain types of restoration expert systems. Time reasoning and uncertainty are addressed respectively by two and four systems.

Concerning knowledge engineering features, a majority of the systems analysed are frame-based systems integrating both frame/object representation for the components of the power system and rules for the logical interrelations. Some are rule-based systems, and one is procedural, thus being able to immediately access the power system representation of the Energy Management System (EMS). A blackboard-type control mechanism is used by three systems.

The user interface development is specific for most of the prototypes analysed, the dialogue being generally mouse-driven. All but two of the expert systems have various of graphic visualisation facilities, being able to represent line/substation diagrams.

Virtually all the systems provide simulation capabilities. Eleven systems operate in a stand-alone mode, three are integrated with a training simulator and five are installed in control centres.

The user interface is, except for one system, based on a high resolution graphical interface, with various graphics standards (X-WINDOWS, GKS, WINDOWS,...). Most systems use the UNIX operating system. Two of them use VAX-VMS, and two MS-DOS on PC-based systems.

3. COMPARING THE APPROACHES ON RESTORATION STRATEGY AND ELECTRICAL CONNECTION

The aim of this stage of the Task Force activity was to perform in-depth comparison of the approaches and methods used by the different restoration expert systems. As most of the systems analysed in the first stage consider different levels in the knowledge, we chose to perform the comparison on the following items :

- what is the nature of restoration strategy in the expert systems, and how strategic knowledge is used,
- in which way the restoration expert systems address the particular sub problem of electrical connection.

The analysis was based on specific questionnaires related to these topics, completed by discussions with the system developers. It concerned eleven systems among the nineteen analysed in the first stage.

Determination of partial goals and "intelligent" sequencing of them turns out to be the cardinal topic of any restoration strategy.

Partial goals : For all systems dealing with nuclear power plants, the highest priority is given to re-energise their auxiliaries. Three systems intend to configure weakly loaded basic networks for the supply of power plant auxiliaries, and then extend them to the whole transmission network (in that case, over voltage problems must be dealt with by proper load reconnection strategy). The majority of the systems considered try however to

reconnect maximal possible load to the remaining network just after the disturbance. Priority between restored system extension and load reconnection appears to be a major strategic choice for systems dealing with general blackouts.

Sequencing : Basically, all restorative actions alternately involve sources (power plants, external networks), loads which have to be reconnected and electrical connections between them. All expert systems investigated deal with these three topics. The sequence of actions is determined by a number of criteria, such as the need to balance the active power of sources and loads, the availability of sources, their run-up times and ramping rates, the priority of certain loads, or the limitation of voltages and line currents. To take these criteria into account, a very close interrelation is needed between the knowledge base and a set of algorithms such as power flow, load modelling, generators ramping and frequency model of the power system.

The *electrical connection* sub problem was analysed in the framework of restoration strategy. Dynamic (on line) path search is realised in most of the systems analysed. Many systems use a two-layered representation of the network to control the size of the search. In the first layer, the power system is represented as a collection of stations and substations connected by transmission lines, and the goal of the search is to select the transmission lines which must be energised to connect two stations. Once these lines have been selected, the search can move down to the next layer where the detailed topology of each station and substation is represented, in order to produce detailed sequences of actions on breakers.

4. NEEDED QUALITIES AND MAIN DIFFICULTIES

4.1 Genericity : to what extent can a restoration expert system be generalised to any power system ?

When we examined the needed qualities of restoration expert systems, we found that a very important criterion was genericity. In other words, an expert system addressing only the specific problem of a given network will probably reproduce "surface knowledge" and will not easily be adapted to any other power system, while a more generic expert system will probably provide in-depth resolution of the restoration problem, and will be more easily adapted to any system. In fact, three points of view must be taken into account :

- Are the different problems solved by specific rules, tightly correlated to the power system considered, or by generic rules working on specific facts ?
- Are the necessary data available in the EMS ? If not, there will be a strong tendency to work out specific solutions; it may be difficult, for maintenance reasons, to add very elaborate and problem-specific data in the EMS data base.
- Is there a sufficiently generic data representation in the EMS ; this question is strongly correlated to other topics, such as open EMS or database portability (using for instance object oriented description).

Considering the different tasks achieved by restoration expert systems, the genericity level is not uniform. Tasks relying on network representation, such as electrical connection or network preparation before starting restoration, are processed in a generic way. The situation is more difficult with tasks dealing with sources and loads : as specific information (ramping rate, priority, etc.) must be taken into account during the restoration

process, the corresponding tasks have often been developed also in a specific way. There is however a trend towards genericity, with a clear separation between data and knowledge, even if the corresponding data are not in the EMS Database. We find the same trend towards genericity in tasks addressing the whole system at a strategic level, such as situation analysis.

Nevertheless, a certain portion of specific information and knowledge will remain in any practical and realistic case, such as agreements with certain customers, or orders to inform persons in other control centres. There is a need for editing facilities to enable the user to introduce this specific information and knowledge into the system, as they may be subject to frequent changes.

4.2 Difficulties encountered and lessons learned from the development of Restoration Expert Systems

For most restoration expert systems, difficulties were first encountered at the stage of the definition of objectives, as the global need for an aid to power system restoration had obviously to be refined. On the other hand, the prototyping process helped the users to formulate their needs in a more accurate way.

Another kind of difficulty encountered was the wide variety of knowledge which had to be formalised and introduced into the system. Very diverse facets of the problem have to be addressed. Moreover, discrepancies are often found between knowledge from different individuals. Lack of data, due to the fact that blackouts are fortunately very rare, can only be coped with by extensive simulation.

Finally, the implementation problems, and -if any- the link with the EMS itself, were not the most problematic ones for most systems (a lot of effort was needed however), provided compatibility between the databases was taken into account at the very beginning of the development.

5. CONCLUDING REMARKS

The term of Restoration Expert System covers a wide variety of applications, ranging from system restoration after a general blackout to load re-energising after a partial outage. Moreover, we have probably not completely covered this field, as we have only focused on systems of which we could have direct knowledge.

Some general concluding remarks can however be deduced from the present study.

The first conclusion is that expert system technology has experienced sufficient progress to work out the restoration problem in an efficient way. Most systems considered here are able to combine different levels of knowledge, to communicate with an external database, to integrate results of numerical models in the reasoning process. The classical path searching sub problem seems to be solved in a satisfactory way by most expert systems considered here. At a more strategic level of the resolving process, application-dependent solutions progressively leave the way to generic problem-solving methods.

The need for time reasoning, as soon as dynamic constraints of generating units have to be taken into account, remains however a challenging issue for expert system technology.

However the main difficulties encountered by restoration expert systems before they come into operation are not related to computer science or knowledge engineering. Expert systems will not, by their own technology, be sufficient to solve all the issues related to power system restoration : what kind of scenario must we cope with (e.g. full and partial black-out), what physical phenomena need to be taken into account during the restoration process (see TF 38-02-02), which data will be available during disturbed situations, how to cope with organisation and co-ordination between operating teams ?

Few restoration expert systems are operational at present ; they are mostly specific, addressing a part of the restoration problem, and realised from accurate specifications provided by the customer ; key issues from the user's point of view are verification and validation to ensure system reliability, and the possibility for the customer to maintain the knowledge base.

A new generation of restoration expert systems, more generic and flexible, is now coming. For these systems, the restoration problem is considered as a whole, but the restoration functions have to be defined very progressively : successive prototypes will help in this process, by showing to the operation teams what is possible, and helping them to define what is really needed.

Expert systems of this generation are not yet in operation, but some prototypes are getting progressively closer to this objective. Among the restoration expert systems considered by the Task Force, the major evolution experienced since the beginning of the Task Force is, for at least two of them, direct connection to a Dispatcher Training Simulator.

This seems to be a very important step in the process of making this new generation of restoration expert systems operational. In fact, the classical cycle from specification to realisation does not apply easily to the restoration problem. Due to the small number of real restoration situations experienced, and to the difficulty for the user to imagine how an innovative function will be able to perform, a gradual prototyping approach is really needed. By this way, software technology and knowledge engineering will find the best way to meet the real operational needs for power system restoration.

PART 1
A SURVEY OF EXPERT SYSTEMS
FOR POWER SYSTEM RESTORATION

PART 1.A :
SURVEY SYNTHESIS

1. INTRODUCTION

The characteristics of the Power System Restoration problem (its combinatorial aspects, use of knowledge from a wide variety of origins and of different types, number of criteria to satisfy) make it a difficult problem, for which the classical methods (such as optimization techniques) cannot even now give a satisfactory solution. On the other hand, the use of expert systems to generate restoration plans is being considered by many research teams, and promising results have already been obtained.

The first work performed by the Task Force was therefore a survey of already developed expert systems or prototypes in the field of Power System Restoration. The present part presents the results of this first stage of the work of the Task Force.

2. THE ANALYSED RESTORATION SYSTEMS

In order to prepare a list of restoration expert systems or prototypes already developed, the principle adopted was in a first step to rely on the TF members' expertise, instead of sending a questionnaire to companies, as many had already been sent by other Task Forces. The decision was not to be exhaustive, but to describe only systems on which direct knowledge was available among the TF members. A questionnaire was however established in order to obtain sufficient homogeneity and completeness in the descriptions of the different systems, but it was generally completed by TF members. In a second step, the approach was extended by sending the questionnaire to all the WG 38-06 and SC 38 members.

The resulting total list amounts to 19 restoration expert systems, which are either already developed prototypes, or in operational use.

We have sorted the systems in the following manner :

1. *Transmission level, general collapse :*

the situation addressed by such systems is the collapse of a large part or even the whole of the power system ; restoration requires the blackstart of some generating units or assistance from neighbouring utilities. Generation must always be considered in such systems, with possible subdivisions into :

- . only hydro generation,
- . thermal, or hydro and thermal generation,
- . as the preceding one, but also nuclear power plants having a significant part in the power system and due to be reconnected during the restoration process.

Other criteria may also be considered, such as long distances between generation and load, several islands to be operated simultaneously, or coordination between several control centres.

2. *Transmission level, localized incident :*

the situation addressed by such systems is the following : after a local incident, a limited area varying from some tens of MW for a small system to typically 500 to 2000 MW in the case of a large system has been deenergized, but the whole power system is in a viable state ; the main problem for such systems is to reenergize as quickly as possible the disconnected load. Some expert systems

also consider a limited amount of generation to be reconnected (generally hydro), some don't.

3. Distribution level

We should notice that the final aim of a restoration system may be to address several of these categories in the same system. However, the corresponding functions may be separated, and the proposed classification seems realistic at the present stage of development of restoration systems, even if it appears in some cases to be a little fuzzy : in the following tables, we have considered as "general collapse", systems (like DUISB) which are designed to address both general collapse and limited incident restoration problems, as they have to cope with issues which are specific to general collapse situations ; on the other hand, systems (like SRA) which are designed to address limited incident situations, but which will be extended to general collapse in a future version, have been considered in the "localized incident" category.

A general description of the expert systems of each type analysed is given in the tables in the following paragraphs. The corresponding bibliographical references will be found in attachment 2.

2.1 Expert Systems for Power System Restoration after a general collapse

The following 10 systems may be considered as general restoration expert systems.

Table 1A shows the power system considered and the part of the system to be restored, while table 1B describes the goals of the expert system, the developer and state of development, and gives references.

PROJECT	INTERNAL NAME	Power System Considered			Part of system to be restored		
		Company	Voltage levels (kV)	Total power (MW)	Load (MW)	Generation (MW)	Nb of nodes
RA : Restoration Assistant	RA	Northern states Power Company	13.8 -500	8000	5000	5000	200
A Guidance System for Power System Restoration	TEPCO	TEPCO (Tokyo Electric Power Comp)	275 -500	42000	35000	35000	60
SERIG : an expert system for power syst. restoration after a general incident	SERIG	EDF (Electricité de France)	400	70000 nucl + hydr + th	50000	50000	100
Restoration training and on-line restoration guidance system	DUISB	Duisburg and Stuttgart municip. utilities	25 - 110	300 600	250 600	300 390	40 60
Expert system to provide guidance to an operator	CHUBU	Chubu Electric Power Comp	154 -500	24000 th, hydr, nucl	20000	20000	40
System to provide a feasible restoration plan & optimize the restoration process	REC	HYDRO-QUEBEC	69 - 735	hydro	25000	25000	800
APSR Automated Power System Restoration	APSR	Atlantic Electric (New-Jersey USA)	138		Tested in real condition on a small part of the power system		
Expert System for Power System Restoration	IRPOW	Norwegian State Power Board	132-400		10000	10000	300
Expert system for generation capability dispatch during bulk power restoration	EPRI	Philadelphia Electric Company, PA (USA)	13.8-230	5000	3500	3500	60
Expert System for restoration of Power Systems	ERPS	Electricity Supply Board (ESB) IRELAND	110-400	2000	2800	2800	117

**Table 1A : Systems for restoration after a general collapse
(Power System considered)**

INTERNAL NAME	Goals of the expert system	Developed by	Dev. state ⁽¹⁾	Bibliography
RA	Assist the power system operator during restoration. Help select objectives. Design plans based on actual system status. Implement these plans. Display status of restoration.	EMPROS	Sim	[RA]
TEPCO	To give operators an appropriate restoration plan and restorative procedures. Various kinds of flexibility to modify the restoration plan automatically if unexpected events happen and to accept operators changes to the proposed plan.	TEPCO and MITSUBISHI	Sim	[TEPCO]
SERIG	Restoration of the overall system after a major failure. Priority is given to the security of nuclear plants and to the remaining system. At every stage achievement of a sustainable operating state is given a high priority. The final goal is the restoration of the demand.	LEG and EDF	Sim	[SERIG 1] [SERIG 2] [SERIG 3]
DUISB	Restoration training under real conditions (process data) On-line restoration guidance	Duisburg University	Prot	[DUISB 1] [DUISB 2] [DUISB 3]
CHUBU	Guidance to an operator	CHUBU and TOSHIBA	Sim	[CHUBU]
REC	Provide a feasible restoration plan. Optimize the restoration process.	HYDRO-QUEBEC	Sim	[REC 1] [REC 2]
APSR	Automatic restoration of a bulk power system	Atlantic Electric	Prot	[APSR]
IRPOW	Assist operators for power system restoration	ABB corporate research Norway	Sim	[IRPOW]
EPRI	Assist operators in finding feasible generator start-up sequences considering system parameters and constraints after a black-out.	University of Washington and EPRI	Sim	[EPRI]
ERPS	Identify islands and suggest restoration procedures based on state of the network	University College of Dublin		

**Table 1B : Systems for restoration after a general collapse
(Expert systems goals and development)**

2.2 Expert Systems for Power System Restoration after a localized incident

Six of the systems analysed may be considered as belonging to this class. Four of them consider the problem of a more or less limited amount of generation to be reconnected. Among them, we should notice that the SRA system will address the global restoration problem in a future version.

The following tables (2A and 2B) give a general description of the systems considered.

¹ Sim : prototype running on simulation data
Prot : prototype tested in real conditions
Oper: operational system

PROJECT	INTERNAL NAME	Power System Considered			Part of system to be restored		
		Company	Voltage levels (kV)	Total power (MW)	Load (MW)	Generation (MW)	Nb of nodes
A restoration guidance system for a SCADA system	CEPCO	CEPCO (Chubu Electric Power Company)	33 - 154	3800 th + hydr	500	50 hydro	50
EKA/NOPA : an expert system for power system switching planning and restoration	NOPA	Helsinki Energy Board	110	600	600	600	
Restoration training and on-line restoration guidance system	DUISB	Duisburg and Stuttgart municip. utilities	25 - 110	300 600	250 600	300 390	40 60
SRA : Service Restoration Agent	SRA	IBERDROLA (Spain)	132 - 380	4000 typ. hydr	500	hydro	10
MARS : exp. system for power restoration after a local incident	MARS	EDF (Electricité de France)	63 - 225	10000	50-500	0	30
Expert system to provide guidance to an operator	KYUSHU	Kyushu Electric Power Company	66 - 220	14000	2000	0	45
Expert system to provide guidance to an operator	TOHOKU	Tohoku Electric Power Company	66 - 275	10000 hydro	2000	2000	30

Table 2A : Systems for restoration after a localized incident
(Power System considered)

INTERNAL NAME	Goals of the expert system	Developed by	Dev. state	Bibliography
CEPCO	Prevention of human errors in power system restoration Speed up and standardization of restorative operations Introduction of new technology to power system operations	CEPCO and MITSUBISHI	Sim	[CEPCO1] [CEPCO2]
NOPA	Assist operators for planning of switching actions and power system restoration ; the main emphasis is aimed to planning of switching actions.	Technical Res. Centre of Finland	Sim	[NOPA 1] [NOPA 2]
SRA	Focused only on local disturbances, this expert system will detect the need for restoration, evaluate the state of the network, prepare a plan for restoration and present it to the operator. It will also follow up the situation of the network as the plan is being prepared and during restoration, but using only general criteria. <u>Notes :</u> - the system is being developed under the ESPRIT programme. - it will be linked with the disturbance analysis system (LAIDA), expert system developed by Labein which has been running on line in the control centre since 1989.	Labein-Bilbao and Iberdrola	Sim	
MARS	Generate restoration plans after a local disturbance. Special attention is devoted to the structure of the knowledge base, the evaluation and correction of the consequences of proposed actions, and various levels of man-machine interaction.	Alcatel-Alsthom Res. and EDF	Sim	[MARS 1] [MARS 2]
KYUSHU	Guidance to an operator	KYUSHU and TOSHIBA	Oper	[KYUSHU]
TOHOKU	Guidance to an operator	TOHOKU and TOSHIBA	Sim	[TOHOKU1] [TOHOKU2]

**Table 2B : Systems for restoration after a localized incident
(Expert Systems goals and development)**

2.3 Expert Systems for Distribution System Restoration

Three expert systems have been considered in this category. These systems have been retained for comparison, but as the work of the Task Force is rather directed towards Power Systems at the transmission level, this must be considered as a very incomplete list of the existing expert systems in this field.

PROJECT	INTERNAL NAME	Power System considered			Part of system to be restored		
		Company	Voltage levels (kV)	Total power (MW)	Load (MW)	Generation (MW)	Nb of nodes
An expert system applied to the distribution automation system	KEPCO	KEPCO (Kansai Electric Power Comp)	6,6 - 33	no generation	.01 - 2	0	1
Restoration of outaged area in distribution network	EPFL	Services Electriques de Lausanne	6 - 20	(distribution centre)	5	0	30
Restoration Planner	RP	Puget Sound Power & Light	12	(distribution centre)	small	0	3

Table 3A : Distribution Restoration Systems
(Power System considered)

INTERNAL NAME	Goals of the expert system	Developed by	Dev. state	Bibliography
KEPCO	Optimization of load re-routing calculation, fault restoration and overload relief.	KEPCO and MITSUBISHI	Oper	[KEPCO]
EPFL	Restoration of outaged area in distribution network	EPFL-LRE (Lausanne)	Sim	
RP	Grouping customers and search for alternative feeders in a medium voltage distribution network	University of Washington		[RP]

Table 3B : Distribution Restoration Systems
(Expert System goals and development)

3. THE SYSTEM DESCRIPTION FORM

A detailed system description form (see annex) has been established in order to have a standardized description of the restoration systems, and to facilitate further comparisons. The description form is based on a general representation of the architecture of a restoration system (fig. 1) : the whole restoration system comprises the expert system itself (with a symbolic power system representation and a knowledge base), and the numerical models using the numerical power system data. The degree of integration of such a restoration system into the Energy Management System (EMS) may vary considerably (fig. 2).

The description form is composed of multiple-choice questions arranged in 7 main chapters :

- *the functional objectives of the system* : what are the intended uses of the system, for what type of incident is it designed, what functions will it provide,
- *the power system representation and modelling* : in this chapter, we make the distinction between the restoration system data base (including data for numerical programs included in the system), and the power system representation in the expert system's knowledge base. We indicate what levels of detail of the power system and which elements are modelled, also how the load, generation and network behaviour are modelled,
- *the restoration knowledge in the expert system* : what is the composition of the expertise included, how is the knowledge organized, does it deal with uncertainty or time reasoning, what approach is used to generate restoration plans, and what is the knowledge acquisition process,
- *the knowledge engineering features* : whereas the preceding chapter dealt with the nature of the knowledge included, this one describes the techniques to represent this knowledge : knowledge organization, inference mechanisms and reasoning process,
- *the facilities provided by the system* : user interface and operator interaction with the construction of the restoration plan, simulation capabilities, performance,
- *the software / hardware implementation* : hardware platform, operating system, restoration system interface with the SCADA or the simulator,
- *the practical experience, if any, with the system described.*

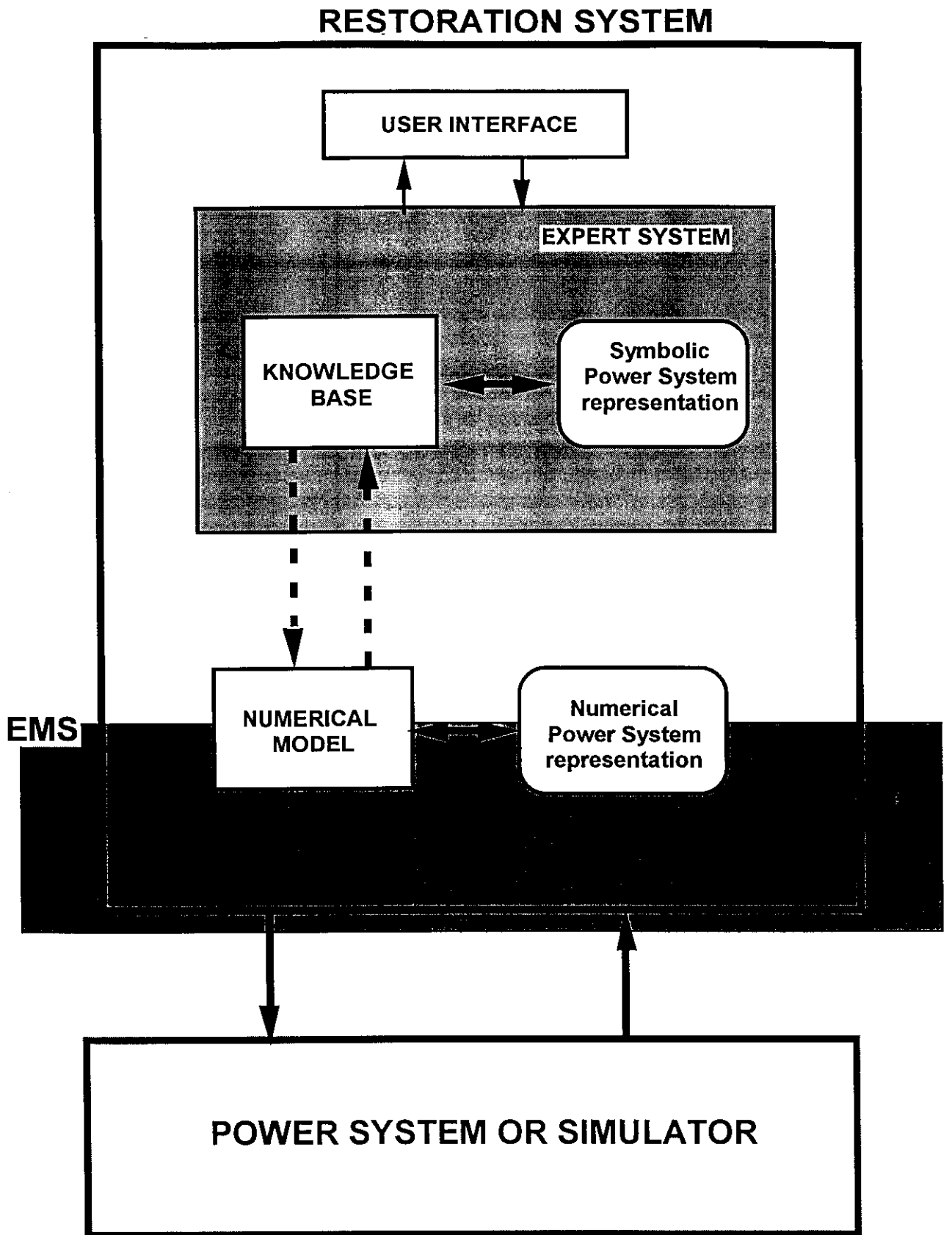
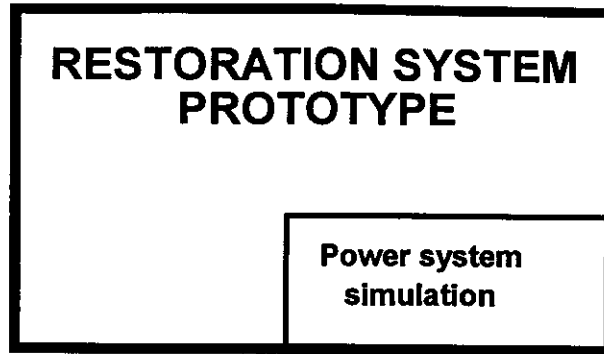
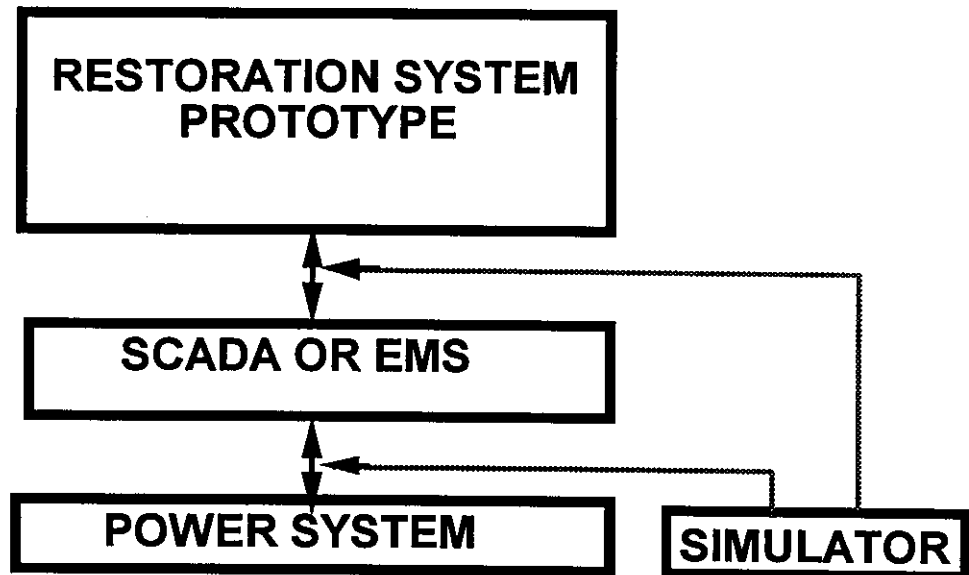


FIG 1 : POWER SYSTEM REPRESENTATIONS IN THE RESTORATION SYSTEM

①



②



③

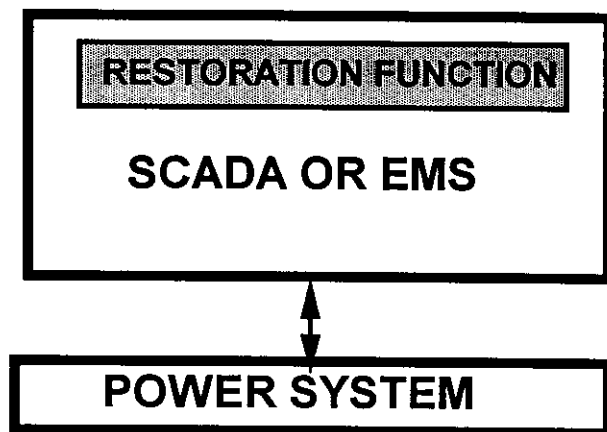


FIG 2 : DIFFERENT DEGREES OF INTEGRATION FOR A RESTORATION SYSTEM

4. A SYNTHESIS OF THE SYSTEM DESCRIPTIONS

4.1. Functional objectives of the system

The expert systems described were developed for different areas of operation (see classification in section 2). Their functional objectives show a correspondence, however. Nearly all the expert systems assist the operator during the restoration process. Most of them are used for operator training or the off-line preparation of restoration plans, in addition. The KEPCO system is different, as it is designed for automatic restoration in a distribution network.

The questionnaire offered a variety of possible functions which the systems are designed for. Each of the following answers was given by more than half of the restoration expert systems :

- develop in real-time detailed restoration plans based on the actual system conditions and the selected objectives ;
- provide a clear picture of the status of the restoration ;
- help the operator choose among various ways of initiating the restoration ;
- display for the operator the applicable, pre-established restoration procedure ;
- help the operator select intermediate restoration objectives.

The following answers were given by about one third of the restoration expert systems :

- evaluate a priori the feasibility and the merits of restoration options ;
- check the security and feasibility of plans established by the operator ;
- alert the operator when dangerous situations arise ;
- help the operator schedule resources.

Line flows and voltages are mainly used as constraints for the restoration. A majority of the systems working on the transmission level add the load/generation balance to the constraints. Few systems use dynamic stability or the standing angle as constraints.

Most of the expert systems described consider faulted network elements (lines, transformers, bus bars), broken switches and circuit breakers, and disabled substations. Several systems can handle unreliable communication links, obstructive relays or widespread damages due to natural disaster.

4.2. Power system representation and modelling

4.2.1. *General*

It is common to all systems to represent the network in two databases, the numerical one where programs such as a load flows are executed, and the "Knowledge-oriented" one, more appropriate for reasoning ; the first is, for most of the systems, more detailed. In general, the databases corresponding to large disturbance systems incorporate a wider range of high level representation.

4.2.2. *Description of the Network representation*

- **Elements represented.** It is common to all systems to include the elements required to work out the network topology : network equipment - busbars, lines, transformers, etc.- and connectivity elements, breakers and switches. Not a great level of individual detail is employed. In addition other elements are included in some systems, such as : protective relays, low voltage elements, externals, RTUs and crews.

- **Generation and loads.** The more complete representation of generation is found in large disturbance systems : this comprises Xenon and auxiliaries constraints, frequency response, ramping rates, source impedance and P-Q generation limitations. Regarding loads, they are represented as aggregates, and determined either using the pre-blackout value or using the time-related evolution of the load (typical of large disturbance systems).

- **Network behaviour.** Virtually all systems model line flows and stationary voltages in the numerical and Knowledge databases. Relays and automatisms behaviours are also included in many of the systems, provided their relevance to restoration. Some other behaviours, also important, are modelled more scarcely. It is the case of externals modelling, primary regulation, transient phenomena and stability.

- **Numerical programs.** Nearly all Restoration Systems employ a load flow program, either AC or DC. The calculation of network sensitivities is employed by five of the systems. More rare is the use of other programs, such as Optimal Power Flow, State Estimator, transient stability analysis and numerical estimation of measurements.

- **Information available from the network.** All systems acquire breakers, isolators and ground selectors status, necessary to work out the topology. In addition to those, also measurements and protective relays are acquired by many of the systems.

- **Network model generation.** Automatic generation of the database from the SCADA/simulator is strongly required, so only minimum maintenance is required on the network database (as routine maintenance is performed in the SCADA). However, special care must be taken to obtain a consistent representation.

The generation of the network is carried out automatically from the SCADA/simulator computer in 8 systems. Three employ a network editor to create the network representation, and finally 5 create it manually.

4.3. Restoration knowledge included in the expert systems

The knowledge needed for network restoration is very complex and various ; to get it analyzed more easily it can be classified according to diverse criteria :

- **The tasks and knowledge domains :** Situation Diagnosis, Sources (generation), Loads and Electrical Interconnections have to be treated in a well arranged interactive manner, tuned to the actually given situation in the network and basically depending on the given network type - "transmission" or "distribution" - as well as the restoration task - "general restoration" (after full black outs) or "partial restoration".

- **The informational types of knowledge** : Factual knowledge, describing the (static) structure of the network or its actual (dynamic) state - is network specific in any case and will be obtained mostly from the EMS database. Procedural knowledge, used for the analysis of the system in numerical or topological sense, resides on EMS information and can be formulated in generic manner in form of algorithms or logical routines ; their results have to be made accessible to the expert system. Judgemental knowledge usually consists of rules, which can either be formulated in an exact or heuristic manner. Gathered from electrical engineers' knowledge as well as operating personnel's experience, this knowledge type is the most typical one to be handled by an expert system and, due to the included heuristics, is to a high grade network specific.

- **The hierarchical levels of knowledge** : in order to reflect the way it is used, the knowledge should also be organized in hierarchical form : a general restoration Strategy is flexibilized by Tactical adaptation to the given network situation and, on the lowest level, executed by certain (switching) Operations.

Combination of these criteria results in a condensed but clearly arranged classification scheme, from which it is possible to determine the knowledge needed for restoration in general as well as to evaluate the knowledge contents of a given restoration expert system approach.

The predominant origin of knowledge is the experts know-how and operational procedures. No possibility of knowledge updating is generally included. Time reasoning and uncertainty are addressed only by a minority of systems.

4.4. Knowledge engineering features

A majority of the systems (15 systems) analysed are frame-based systems, including two object-oriented systems. 13 systems integrate both frame/object representation and rules. Three are rule-based systems, and one is procedural.

Frame-based systems use various kinds of tools and languages, whereas the rule-based systems reported here use OPS83.

Seven systems use forward chaining only, two backward chaining only, and seven both forward and backward chaining. A blackboard-type control mechanism is used by four systems.

As for reasoning process, rule-based systems including frame-based rule systems have a tendency to adopt qualitative reasoning rather than quantitative, while others have the opposite tendency. And only one system is planning to apply truth maintenance functions.

4.5. Facilities provided by the expert systems

The different facilities were analysed with respect to the size of the power systems, separated into large (> 5000 MW), medium (between 500 and 5000) and small (< 500) load/generation systems.

Dynamic planning is mostly used by systems addressing large load/generation facilities, whereas fixed planning capabilities are mostly used by medium load/generation size systems.

Concerning the Restoration Actions Monitoring, we could find no rationale supporting the utilities choice. We assume that the choice of each organization is made accordingly with its own culture and experience. Nevertheless, it was found that the large Power Restoration Systems (PRSs) are equally dealing with :

- i) performing of "check-plan" steps, or
- ii) following "overall criteria", independent of restoration plan.

The medium-sized PRSs favor the "overall criteria" methods. Trying to outline a logical link between the replanning capabilities and the functional objectives of PRSs, we found that the link between the ability to "evaluate restoration options" and the "backtracking" as a planning feature is the most obvious.

The user interface development is specific for most of the prototypes analysed, the dialogue being generally mouse-driven. All but two of the expert systems have an important number of graphic visualization facilities, being able to represent line/substation diagrams.

Virtually all the systems provide simulation capabilities. Half of the PRSs have two simulation capabilities, i.e. :

- i) the ability to display the results of operator's input based on the current state of the network,
- ii) the ability to display the results of the proposed restoration plan.

Considering the PRSs performance, the results of the survey show a very great dispersion of the "average time to solve a standard case", i.e. : from 1 second to 2 hours. The two-hours figure represents the restoration time from a complete blackout. The one-second figure represents probably the response time for an elementary operation. Even the response time for an elementary operation cannot be considered as a standard reference, because it depends on the way the problem is divided. On the other hand, the performance is not a main issue among the objectives of this survey.

4.6. Software/hardware implementation

Most systems use the UNIX operating system. Two of them use VAX-VMS, and two MS-DOS on PC-based systems.

Interface with numerical programs is made by direct call, or by transfer files in some cases.

Eleven systems operate in a stand-alone mode which means that the interface between the expert system and the process computer is not realized.

In systems which are integrated with process computer generally the SCADA and expert systems have separate data bases. The real-time data base or part of it is copied from SCADA to the data base of the expert system. Only two expert systems have the direct access to the process computer data base.

The user interface is, except for one system, based on a high resolution graphical interface, with various graphics standards (X-WINDOWS, WINDOWS, GKS,.....).

5. CONCLUSION

Nineteen (19) expert system prototypes have been analysed ; these cover a wide range of problems at the transmission level, from system restoration after a general blackout to load reenergizing after a partial outage ; they also include a limited number of distribution restoration expert systems. Each system has been analysed using a detailed description form covering following items : system functional objectives, power system representation and modelling, restoration knowledge in the expert system, knowledge engineering features, facilities provided by the system and software/hardware implementation. The system descriptions have been analysed for each item, and correlations have been considered with the restoration problem considered and the size of the power system.

PART 1.B :
DETAILED ANALYSIS OF THE RESPONSES
TO THE QUESTIONNAIRE

Topic 1: Functional Objectives of the System

Dieter Reichelt

1.1 Introduction

The considered expert systems for restoration are designed for specific electrical networks and tasks. In order to analyse the type of network and the tasks for which the expert systems are designed, topic 1 of the questionnaire asks for the intended use of the expert system, for the types of incidents, for the functions of the system, for the constraints and for the problems the expert system can deal with. In the following an overview of the answers will be given in order to point out the correlations.

1.2 Analysis of the answers

The given answers to the questions 1.1 to 1.5 will be discussed in the following subsections. It was possible to give multiple answers for each question.

The 19 systems can be classified into 3 groups (see section 2):

- *Transmission level, general restoration:*
RA, TEPCO, SERIG, DUISBURG, CHUBU, REC, APSR, EPRI, ERPS, IRPOW
- *Transmission level, partial restoration:*
CEPCO, NOPA, SRA, MARS, KYUSHU, TOHOKU
- *Distribution level:*
KEPCO, EPFL, RP

This classification is taken into account for the analysis in the subsections 1.2.3 to 1.2.5.

1.2.1 Intended use of the final system

Nearly all (17 of 19) expert systems are designed to assist the operator during the restoration process. 11 of these expert systems are used for operator training also. In addition, 6 of them will prepare restoration plans off-line.

Exceptions are the NOPA system (preparing restoration plans and operator training, no operator assistance) and the KEPCO system.

The KEPCO system will automate the restoration process. It is the only system which can automate the restoration process. The RA system partially can automate it, however.

Except the RA, KEPCO, KYUSHU and APSR system, all systems reply to the questions which refer to the prototype status of the systems. Most of them (12) evaluate the feasibility of the expert system approach. 9 of them check the accuracy and the completeness of the knowledge base, too.

1.2.2 Types of incidents which the system is designed for

A majority of the expert systems consider the loss of supply in a limited area or the loss of supply over a wider area. More than 50 % of the systems can handle the collapse of the whole power system. Six systems (TEPCO, DUISBURG, CHUBU, REC, ERPS, IRPOW) cover all three incidents.

(See also the classification in 1.2)

1.2.3 Functions which the system is designed for

Each of the following answers

- evaluate the feasibility of the restoration process
- help the operator choose among the various ways of initiating the restoration

- help the operator select intermediate restoration objectives

is matched by about 50 % of the systems.

It is interesting that answer b): *evaluate the feasibility of the restoration process* mainly matches with the systems on the transmission level with partial restoration.

Nearly all systems match with answer f): *Develop in real time detailed*

restoration plans. 8 of them provide a clear picture of the status of the restoration. They all work on the transmission level (general and partial restoration).

The systems on the distribution level only match with answer f), except the EPFL system which fulfills answer b), too. The answers j): *Help the operator schedule resources* and k): *Alert the operator when dangerous situations arise* are fulfilled by 5 systems and 7 systems, respectively. There is a correlation as 4 systems match both answers.

1.2.4. Constraints which the system attempt to enforce

The mostly used constraints are *voltage* (12 systems) and *line flow* (15 systems). All systems on the distribution level and on the transmission level with partial restoration use the line flows as constraints.

Half of the systems take the load/generation balance into account. They all work on the transmission level.

Only a few systems use the dynamic stability or the standing angle as constraints. All these systems work on the transmission level.

1.2.5 Problems or difficulties that the system takes into account

16 systems can handle

- faulted lines
- faulted transformers
- and faulted busbars.

In addition, 15 of them can handle

- broken switches or breakers.

And 13 of them can handle

- disabled substations, too.

Exeptions are the KEPCO system which is designed for unreliable communication links, the EPFL system which at the present state can handle faulted lines only and the ERPS systems which can handle faulted lines and disabled substations. The KEPCO and the EPFL system work on the distribution level.

Obstructiv relais are taken into account by 6 systems on the transmission level, 4 of them with partial restoration and 2 with general restoration.

1.3 Overview of all answers in a table

Answer	R A	T E P C O	C E P C O	K E P C O	S E R I G	N O P A	D U I S B U R G	S R A	M A R S	K Y U S H U	C H U B U	T O H O K U	R E C	E P F L	A P S R	R P	E P R I	E R P S	I R P O W
1.1 - a)						x	x			x	x		x				x		x
1.1 - b)	x	x	x		x	x	x		x				x		x		x	x	x
1.1 - c)	x	x	x		x		x	x	x	x	x	x	x	x	x	x	x	x	x
1.1 - d)	x			x															
1.1 - e)														x					
1.1 - f)		x											x				x		
1.1 - g)					x	x	x	x	x		x		x	x		x	x	x	x
1.1 - h)		x				x						x	x				x		x
1.1 - i)				x	x		x		x		x	x	x			x	x		x
1.1 - j)					x		x	x			x	x	x			x	x		
1.2 - a)		x	x	x		x	x	x	x	x	x	x	x	x		x		x	x
1.2 - b)	x	x	x		x		x	x		x	x	x	x	x				x	x
1.2 - c)	x	x			x		x				x		x					x	x
1.2 - d)													x				x		x
1.3 - a)	x	x	x		x		x	x	x	x	x	x	x		x				x
1.3 - b)								x	x	x	x			x			x		x
1.3 - c)		x			x	x	x	x	x				x		x		x		x
1.3 - d)	x	x				x	x	x	x				x				x		x
1.3 - e)						x		x	x	x	x	x	x		x		x		
1.3 - f)	x	x	x	x	x		x	x	x	x		x	x	x		x			x
1.3 - g)		x						x	x				x						x
1.3 - h)													x						x
1.3 - i)	x		x																
1.3 - j)		x			x	x		x									x		
1.3 - k)		x			x			x	x								x		
1.3 - l)																	x	x	
1.3 - m)								x											

	R A	T E P C O	C E P C O	K E P C O	S E R I G	N O P A	D U I S B U R G	S R A	M A R S	K Y U S H U	C H U B U	T O H O K U	R E C	E P F L	A P S R	R P	E P R I	E R P S	I R P O W
Answer																			
1.4 - a)	x	x		x	x	x	x	x	x				x			x	x		x
1.4 - b)		x	x	x	x	x		x	x	x	x	x	x	x		x	x		x
1.4 - c)								x					x		x		x		
1.4 - d)		x	x										x				x		x
1.4 - e)		x			x	x		x			x		x				x		x
1.4 - f)																x	x		
1.5 - a)	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
1.5 - b)	x	x	x		x	x	x	x	x	x	x	x	x		x	x	x		x
1.5 - c)	x	x	x		x	x	x	x	x	x	x	x	x		x	x	x		x
1.5 - d)	x	x	x		x	x	x	x	x	x	x	x	x		x		x		x
1.5 - e)	x		x		x	x	x		x	x	x	x	x		x		x	x	x
1.5 - f)	x			x				x											
1.5 - g)		x	x					x		x	x	x							
1.5 - h)										x	x		x						
1.5 - i)										x	x		x						

TOPIC: 2

POWER SYSTEM REPRESENTATION AND MODELLING

Jose M. Corera and Jaime Fandino

2.1 FIRST REMARKS

It has been difficult for this topic to establish a clear correlation between the representations used and the taxonomy of the systems. At some of the points this has been extracted, but it seems that the representations used depend more on the particular approach followed by each company and on the resources and information available.

In most of the systems a duplication of databases exist, one for the numerical programs and another for the reasoning processes. The only exception is the NOPA system, which maintains only one single database for the Expert System. In general, the numerical database in the systems studied is more complex. This can be explained because the numerical database is the first one to be created, copied from the SCADA/simulator database, and requires complete information to run numerical programs. The Expert System database is generated from this one and copies only that information relevant for the reasoning.

Some systems have found appropriate not to represent all the behaviours of the network within the system, but to rely on an external program such as a network simulator (some examples are generators response, primary regulation, external behaviours, overloads, etc).

2.2 ANALYSIS OF THE DETAILED DESCRIPTIONS

2.2.1 Levels of detail

Systems intended for large and medium disturbances use a wider range of higher level representations, such as areas and substations. This is required to proceed in a more layered or structured fashion, ie first prepare a strategic plan involving regions, second detail it to areas, and so on. The plan is prepared faster and is more consistent.

In both the numerical model and the Knowledge data base the level of detail includes single elements for most of the systems, even for the most general ones.

The intermediate level consisting on a nodes-branches representation is mostly employed in the numerical database for load-flow execution.

2.2.2 Elements represented

Elements represented can be grouped in:

- HV network equipment: busbars, lines, transformers, etc.
- connectivity elements: breakers and switches
- protective relays
- low voltage elements
- externals
- RTUs
- crews

The first two are required to create an image of the network, with the adequate connections, so numerical programs can be executed and heuristic searches can be performed. Relays not only mark the limits to power flows, but also can help to diagnose the disturbance originating the blackout and to identify any equipment at fault and therefore unavailable for restoration. An updated representation of external networks is critical to solve large blackouts or disturbances near the boundaries of the system, so the external behaviour can be estimated.

The analysis of the answers show that for nearly all the systems under study both the numerical database and the ES database include busbar, lines, transformers and loads. Two distribution systems are the exception (EPFL and RP), which do not employ busbars.

Power stations and generators are only excluded from distribution restoration systems (KEPCO and RP). Reactances and capacitors are included only in 50% of the systems, and not employed in distribution.

Breakers and switches are represented extensively. Only two systems do not use them, SERIG and EPFL.

Other elements are used more scarcely. Relays are represented mostly in medium systems (5 out of 6: CEPCO, SRA, MARS, KYUSHU and TOHOKU), but only in a few of the rest (3 out of 10: TEPCO, CHUBU and EPFL). External equivalents are used in 9 of the systems for the numerical database, but of these, only in 4 for the ES database, the reason being that they are used mostly for load flow execution.

Crews are modelled only in two system for large disturbances restoration (CHUBU and EPRI), and RTUs only in two systems (APSR and KEPCO). Lower voltage elements are represented in 5 systems, in different categories.

The conclusion from the analysis shows that, except for the network equipment, the representation of the rest of the elements do not follow any general rule. Due to the complexity of the problem, system developers have taken a compromise to employ the information more readily available.

Table 2.1 displays a summary for all the systems for the above points

2.2.3 Loads

In restoration it is unpractical to model the loads directly, but to aggregate them. The number of loads is substantially reduced without any major drawback. Only three systems represent directly the feeders (two of them for large disturbances, RA and DUISB, and one for distribution, KEPCO), while most of the systems aggregate them in groups of 5 to 10 feeders, up to some tens of MW.

The value of loads is determined either using the pre-blackout value (method applied mainly in medium systems) or is estimated using the time-related evolution of the load (large disturbance systems).

2.2.4 Generation

Generation is specially critical when the system is isolated from the rest of the network: frequency fluctuations and demand unbalance cannot be compensated with interchanges from neighbouring companies, and careful generation planning is required. The more complete representation of generation is therefore found in large disturbance systems: this comprises Xenon and auxiliaries constraints, frequency response, ramping rates, source impedance and P-Q generation limitations.

Only these last two parameters are represented in systems for medium disturbances.

In the limited disturbances and distribution systems generators are represented either as a constant injection of P-Q, as a constant voltage source or even not represented at all. The reason is that for small black-outs, the amount of generated power required to restore loads is small and its distribution through all the generators active results in very low requirements.

2.2.5 Network behaviour

Virtually all systems model line flows and stationary voltages in both databases. DUISB, RA and CEPCO only include line flows in the numerical model.

Relays and automatisms follow in importance, as they are of special relevance when restoration actions are at substation and equipment detail. All medium systems include them. Only half of the large disturbance systems represent them, with preference to automatisms. At the other end, no distribution system uses this information.

The behaviour of external equivalents is considered by less than half of the systems. This can reduce the capabilities of the system, specially in the case of large disturbances when interchanges are crucial. However it must be pointed out that a poor representation of externals, or if they are poorly refreshed, can extend falsely the competence of the system. Other phenomena such as primary regulation, transient phenomena and stability are handled more rarely. Each is found in only two systems as average.

Table 2.2 gives an overview of load, generation and network behaviour; it also includes the type of disturbances addressed

2.2.6 Numerical programs

The use of a load flow program to check power flows and voltages is always necessary as a confirmation of the heuristics employed to prepare the plan.

Large systems reported to use AC load flows, and some of them also employ DC load flows, which have faster execution times. The DC load flow is more popular for medium and small disturbance systems.

Network sensitivities are calculated by five large disturbance systems (RA, TEPCO, SERIG, APSR, IRPOW). Sensitivities are a good help to avoid the execution of load flows, as they allow to estimate the load variation in other circuits when one circuit is operated, or when loads are reconnected.

Other additional features are employed only by few of the systems:

- the REC and IRPOW systems execute an OPF.
- the REC, APSR, IRPOW and SRA systems use an State Estimator
- the REC system uses transient stability simulation and electromagnetic transient simulation
- the DUISB system estimates the behaviour of measurands such as frequency and power exchanges.
- the EPFL system employs, in addition to an AC load-flow, a simplified load flow for radial networks
- the SRA system executes an heuristic and simplified SE to get a consistent picture of the network, when convergency cannot be obtained with the standard SE.

2.2.7 Information available from the network

No classification can be made within this point regarding the type of the system, from what could be concluded that each project has been influenced by the facilities it had available and the constraints imposed to the project.

It can be generalized that all systems deal with topology elements status: breakers, isolators and ground selectors. The first two are used widely, while only half receive ground selectors. This can be considered the minimum information to get a picture of the network.

In addition, measurements can help to obtain consistency with the elements status received. To keep that consistency is a major problem during disturbances. Roughly half of the systems process measurements

Protective relays indications and alarms are specially useful to analyze the history of the disturbance, and to detect limit violations. Only few systems process them, mostly in the area of medium-reduced disturbances. The use of alarms can present the additional difficulty of text processing, when the system is not coupled directly to the SCADA real time database.

2.2.8 Network model generation

Automatic generation of the database from the SCADA/simulator is strongly required, so only minimum maintenance is required on the network database (because routine maintenance is performed in the SCADA). However, special care must be taken to obtain a consistent representation.

The generation of the network is carried out automatically from the SCADA/simulator computer in 8 systems. Three employ a network editor to create the network representation, and finally 5 create it manually.

Table 2.3. Summarizes points 2.2.6, 2.2.7 and 2.2.8

KEY TO FIGURES

Systems are grouped according to the classification adopted all along the report: general disturbance, limited disturbance and distribution.

In general, the following symbols are used:

- "C" indicates company
- "R" indicates region
- "P" indicates pool
- "M" indicates municipal
- "D" indicates system database (numerical)
- "K" indicates Knowledge database (expert system)
(the two above are positioned in double columns)
- "O" is employed when no distinction is made

Regarding "Load Representation" in figure 2, the following symbols are employed:

- "N A" not applicable
- "f" feeders
- "M" MegaWatts
- "X" number not specified

	R A	T E P C O	S E R I G	C H U B U	R E C	A P S R R	I R P O W	E P R I	E R P S	D U I S B	C E P C O	N O P A	S R A	M A R S	K Y U S H U	T O H O K U	K E P C O	E P F L	R P
TYPE OF DISTURBANCE																			
limited area	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
wide area	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
entire collapse	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Size of network	C	C	C	C	C	C	C	C	C	M	P	C	C	R	R	R	R	M	C
LEVELS OF DETAIL																			
a) areas, regions	D	D	D	D	D	D	D	D	D		D	K							K
b) stations, corridors	D	K	D	D	D	D	D	D	D	K	D	K		D			D		
c) buses, branches	D	K	D	D	D	D	D	D	D	K	D	K	D	D			D		
d) single ele., busbars	K		D					D		K	D	D	D	D			D		
e) devices (switches)	D	K	D	D	D	D	D	D	D	D	D	K	D	D	D	D	D		D
ELEMENTS REPRESENTED																			
a) busbar	D	K	D	D	D	D	D	D	D	D	D	K	D	D	D	D	D		
b) line/transformer	D	K	D	D	D	D	D	D	D	D	D	K	D	D	D	D	D	D	D
c) generators	D	K	D	D	D	D	D	D	D	D	D	K	D	D	D	D	D		
d) loads	D	K	D	D	D	D	D	D	D	D	D	K	D	D	D	D	D	D	D
e) reactors, capacitors	D	K	D	D	D	D	D	D	D	D	D		D	D	D	D			
f) breakers, switches	D	K	D	D	D	D	D	D	D	D	D	K	D	D	D	D	D	D	D
g) relays	D			D	D	D					D		D	D	D	D			
h) low volt. ele.							D			D	D								D
i) externals	D	D		D			D			D	D		D						D
j) RTUs	D					D													D
k) crews				D				D											

Table 2.1 Classification of systems and elements represented (key to symbols in preceding page)

	R A	T E P C O	S E R I G	C H U B U	R E C	A P S R	I R P O W	E P R I	E R P S	D U I S B	C E P C O	N O P A	S R A	M A R S	K Y U S H U	T O H O K U	K E P C O	E P F L	R P
LOADS REPRESENTATION						N A			N A										
a) as feeders	0									0							0		
b) aggregated at HV (size)		10f	50M	10M	X		X	10M			5f	50M	30M	X	10M	10M		X	X
value=pre-blackout		0	0	0									0	0	0	0		0	0
value=cold load pick-up	0				0		0	0		0	0	0					0		
value=conserv. estim.					0								0						
GENERATION																			
a) elect. params.	D K	D	D K	D K	D K	D K	D K	D K		D		K	D K	D K		D K	D K	D K	
b) xenon constraints	D		D K				D K												
c) auxiliaries demands	K		D K	D K	D K		D K	D K	D K	D			D K						
d) frequency response					D K	D K	D	D K		D									
e) ramping rate	D K	D K		D K	D K	D K	D K	D K		D	D	K	D K						
NETWORK BEHAVIOUR																			
a) line flow	D	D K	D K	D K	D K	D K	D K	D K	D K	D	D	K	D K	D K	D K	D K	D K	D K	D K
b) stationary voltages	D K	D K	D K		D K	D K	D K	D K		D K	D	K	D K	D K			D K	D K	D K
c) relays		D		D K					D K	D K	D K		D K		D K	D K			
d) automatisms		D K		D K			D K	D K	D K	D K	D K		D K	D K	D K	D K			
e) primary regulation							K			D	D								
f) behaviour externals	D			D K			D			D K	D	K	D K						
g) transient phenomena					D K			D K											
h) stability					D K			D K											

Table 2.2 Representation of load, generation and network behaviour (see symbol signification before table 2.1)

	R A	T E P C O	S E R I G	C H U B U	R E C	A P S R	I R P O W	E P R I	E R P S	D U I S B	C E P C O	N O P A	S R A	M A R S	K Y U S H U	T O H O K U	K E P C O	E P F L	R P	
NUMERICAL PROGRAMS																				
a) AC power flow	0	0	0		0	0	0		0	0		0	0	0				0	0	0
b) DC power flow		0		0		0	0				0				0	0	0			
c) Optimal power flow					0		0													
d) Network sensitivities	0	0	0			0	0													
e) State estimation					0	0	0					0								
h) transient stab. sim.					0															
i) elec. transient sim.					0															
INFORMATION AVAILABLE																				
a) breaker states	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
b) isolator states	0	0	0	0			0	0		0		0	0		0	0	0			0
c) ground con. states	0				0		0			0		0	0							
d) measurements	0			0			0			0	0	0	0	0	0	0	0	0	0	0
e) protections indic.				0					0	0	0		0		0	0	0			
f) alarms	0			0	0	0			0	0			0	0	0	0				
GENERAT. OF NETWORK MODEL																				
a) manual		0	0			0		0								0		0	0	0
b) network editor					0						0			0						
c) auto. from process/sim	0			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 2.3 Numerical programs employed, network information available to system and model generation
(see symbol signification before table 2.1)

TOPIC 3:

KNOWLEDGE FOR RESTORATION EXPERT SYSTEMS

Gerhard Krost and Daniel Kirschen

3.1 INTRODUCTION

The knowledge which is necessary for a restoration expert system is a reflexion of the size and complexity of this problem. This section attempts to organize this knowledge according to three criteria:

- Domain
- Type
- Level

Correlation between these criteria will result in a condensed but clearly arranged classification scheme. This section concludes with some remarks about time reasoning, uncertainty, knowledge origin, acquisition and updating as they relate to the expert systems discussed in this report.

3.2 TASKS AND KNOWLEDGE DOMAINS

The network restoration problem can be divided into four subproblems which each require specialized knowledge. These subproblems are:

- **Diagnosis:** Determining the existence, nature, extent and cause of the problem.
- **Generation:** Analyzing the status of the sources of electrical power and determining the conditions under which these sources could or should be brought back in service.
- **Load:** Determining the value, location and priority of the loads which must be reconnected.
- **System:** Analyzing the status of the network and determining the connections which can be established through this network to reconnect loads and generators while respecting safety and security constraints.

The following list describes in more details the knowledge included in each domain:

Diagnosis:

- Identification of fault type
- Identification of faulty devices
- Identification of blacked-out area

Generation:

- Basic generating unit constraints (maximum and minimum active and reactive generation, etc...)
- Time-dependent unit constraints (deadline for hot-restart, etc...)
- Nuclear safety constraints

Load:

- Cold load pickup estimation
- Load/generation balancing
- Load priorities

System:

- Network constraints
- Relaying
- Network connections (paths search)
- Synchronization

The importance of these four domains depends on the task at hand: Are we dealing with a transmission or a distribution network? Is the incident a generalized blackout or a partial outage? Table 1 summarizes the importance of each domain for each restoration task.

	Transmission (general blackout)	Transmission (partial blackout)	Distribution
Diagnosis	+	++	++
Generation	++	+	-
Load	++	++	++
System	++	++	++

Table 1: Tasks and knowledge domains
 (++ indicates that knowledge in a domain is very important for a particular task, + that it is important and - that it is not very important)

As can be seen from Table 1, in the case of a generalized blackout the diagnosis aspect is somewhat secondary while the generation aspect is very important. For a distribution restoration, it is the opposite: there is no generation aspect, but it is essential to determine the nature of the problem which caused the fault. Loads and connections through the network have must be considered in both cases. For partial restorations, things are less because there may be some generation problems involved, however they are probably not as critical.

Ultimately, as practical restoration expert systems go on-line, the distinctions between the tasks of restoration are bound to become even more blurred. A system designed for a general restoration should indeed be able to handle partial restorations once the backbone of the power system has been restored.

3.3 INFORMATIONAL TYPES OF KNOWLEDGE

As seen from a computer science viewpoint, the restoration knowledge can be divided three types based on its informational content:

Factual knowledge: This knowledge can be either static (e.g. the parameters of a transformer) or dynamic (such as the voltage on a busbar.) It is almost entirely specific to a particular network and will be obtained mostly from the SCADA or EMS database. However, some facts (such as the availability of power from a neighboring utility or the location of work crews) may have to be obtained via queries from the expert system to the power system operator.

Procedural knowledge is used for tasks such as analyzing the topology of the system and scheduling operations. It usually takes the form of algorithms or logical routines and is thus fairly independent of a particular power system. This knowledge relies heavily on the factual knowledge and these two forms of knowledge must thus be closely integrated.

Judgemental knowledge usually consists of rules, which can either be formulated in an exact or heuristic manner as condition-action or condition-conclusion pairs. Gathered from electrical engineers' knowledge as well as operating personnel's experience, this knowledge type is the most typical one to be handled by an expert system. Its very nature make it highly specific to a given network. Judgemental knowledge is applied to factual knowledge which may be obtained from the database, from a dialog with the user or from the application of procedural knowledge.

Table 2 summarizes the characteristics of the various restoration knowledge types.

Knowledge Type	Examples	Appropriate Form of Representation	Storage	Primary Source of Knowledge	Generalizability
Factual Static	existence & param. of objects	object/attr. structures, data points	database	network, simulator	network specific
Dynamic	states, measurements				
Procedural	Evaluation of actual topology load flow	logical or algorithmic routines	numeric processor, knowledge base	engineers	fairly generic
Judgemental	decision heuristics	rules	knowledge base	engineers, operators	partly specific

Table 2: Informational types of knowledge

3.4 HIERARCHICAL LEVELS OF KNOWLEDGE

In order to reflect the way it is used, the knowledge should also be organized into its STRATEGIC, TACTICAL and OPERATIONAL components.

The strategic knowledge provides the guidelines which will govern the restoration of the power system from a given blackout situation to a normal state. These guidelines involve many heuristics and are the strategic knowledge is likely to be very specific to a given network.

Once a strategy has been decided, it must be carried out while taking into account the constraints and the detailed status of the system. The tactical part of knowledge is responsible for identifying unavailable equipments and finding remedies for these unavailabilities. It should also prevent overloads and oversee synchronization and other activities of the same kind. This level of knowledge may be formulated either as generic procedures or as rules which may be more or less specific to a given network.

On the operational level, sequences of switching operations have to be performed, which consist of certain sub-goals of the tactically adapted strategy (e.g. switching a path between two busbars) and which usually can be formulated in a generic manner.

Table 3 summarizes the characteristics of these levels of knowledge.

Hierarchical Level	Purpose	Primary knowledge type	Generalizability
Strategic	reactivation of power sources, selection of paths and loads	judgemental	fairly specific
Tactical	Identification of faulty devices, presentation of alternatives, synchronization	procedural	partly specific, partly generic
Operational	Switching operations, Adjustments: load/generation balance, frequency, line flows, voltages	factual	mainly generic

Table 3: Hierarchical knowledge levels

3.5 CLASSIFICATION

The three classification criteria discussed above can be combined to create a well structured and transparent classification scheme. From this classification it is possible to determine the knowledge which is needed for network restoration in general. This classification can also be used to evaluate the knowledge content of a given restoration expert system approach.

This classification is divided in four tables, one table for each of the knowledge domains (diagnosis, generation, load and system). Each of these tables is a matrix where the rows correspond to a given knowledge level (strategic, tactical, operational) and the columns to a knowledge type (factual, procedural and judgemental). Each slot in this classification contains a description of the knowledge corresponding to this slot, a reference to the questions relating to this slot in the survey and the number of expert systems of each category which include this knowledge. The first number refers to the general blackout restoration systems, the second to the partial blackouts systems and the third to the distribution systems. A total of 18 systems have been studied. 10 are for total blackouts, 6 are for partial blackouts and 2 are for distribution, which we summarize as 10/6/2.

As it can be observed from the tables, there is a good correlation between the restoration knowledge as classified and the information which was requested in the survey.

Level/Type	Factual	Procedural	Judgemental
Strategic	Evidence of a fault situation (starting point for the expert system, not asked for)	Topological evaluation of remaining network configuration for partial blackouts (not asked for)	Ability to determine the incident type (not asked for)
Tactical	Outaged network components (2.7): 3/4/1	Identification of faulted equipment (3.1): 6/5/1	Determination of options for starting the restoration (1.3): 7/3/0
Operational	Process information(2.7) alarms: 6/3/0 switch states: 10/6/1 measurments: 4/6/1	Identification of remaining sources and loads (not asked for)	Initialization of the first restoration step (1.3): 10/6/2

Table 4.1 Diagnosis

Level/Type	Factual	Procedural	Judgemental
Strategic	Power available (comm. with plant operators)	Position of selected sources in actual network topology (not asked for)	Selection of preferred source type (3.1): 9/3/1
Tactical	Availability and priority of the selected source (communication with plant operator)	Constraints (2.4.2): electric: 7/3/0 ramping: 7/2/0 nuclear: 2/0/0	Selection of a source to be reconnected under given conditions (not asked for)
Operational	Frequency, voltage (2.7): 4/6/1 availability of switching equipment (1.5): 9/6/1	Procuring synchronization conditions (3.1): 4/2/0	Proposal to synchronize the selected unit (1.3): 10/3/1

Table 4.2 Generation

Level/Type	Factual	Procedural	Judgemental
Strategic	Existence of unsupplied loads or busbars (2.7): 4/6/1	Determination of unsupplied loads (not asked for)	Proposal to resupply a load (1.3): 9/6/2
Tactical	Priorities (not asked for)	Determination of load values (2.3) model/estim.: 5/3/1 pre-blackout: 3/4/1 overload constr. (3.1): 6/6/2	Selection of the load to be resupplied next (3.1): 8/6/1
Operational	Frequency, voltage(2.7): 4/6/1 Availability of switching equipment (1.5): 9/6/1	Establishing load/generation balance(3.1): 6/2/1	Proposal to reconnect the selected load (1.3/2.2.2): 9/6/1

Table 4.3 Loads

Level/Type	Factual	Procedural	Judgemental
Strategic	Network connectivity(2.2): 10/6/2	Path search (3.5) dynamic: 3/1/1 predefined: 8/5/1 synchr. of islands: (3.1): 4/1/0	Proposal to connect points in the network (3.1): 10/5/1
Tactical	Measured values of voltage, currents, active and reactive power (2.7): 4/6/1	Enforcement of constraints: (3.1): actual: 8/5/2 potential: 7/5/1 optimization (3.5): 5/5/1	Presentation of paths (3.4): all feasible: 3/0/0 selected paths: 9/4/1
Operational	Availability of switching equipment and auxiliaries (1.5): 9/6/1	Sequencing of switching operations (3.1): 10/6/1	Proposal to switch in the selected path (1.3): 10/6/2

Table 4.4 Connections

What actually results is a summary of all the knowledge objectives being demanded during network restoration. Sources and places of storage of the particular objectives as well as their generalizability can be derived from Tables 1-3.

3.6 TIME REASONING, UNCERTAINTY, KNOWLEDGE ORIGIN, ACQUISITION AND UPDATING

It appears that only four of the general restoration expert systems considered have the ability to consider time in their reasoning:

- The TEPCO system takes into account the cold startup and ramping times of the generators
- The ERPS system considers the critical time for resupplying auxiliary power to the generators and priority loads
- The EPRI system also considers critical times using heuristic and temporal logic.
- The IRPOW system deals with dynamic priorities of generation and loads

None of the partial or distribution restoration systems considers time in its reasoning.

Uncertainty is dealt with only in the MARS, SRA, EPRI and DUISBURG system. MARS develops two alternative branches in cases of doubt and tries to realize one of them. SRA deals with inconsistencies in process information (results derived from them are assumed to be true) and with incomplete information. In case of the diagnosis part of the DUISBURG system incomplete information is intercepted by worst case assumptions. The EPRI system resets the breakers at the beginning of the restoration.

The predominant origin of knowledge is the expert's know how (15 answers) and operation procedures (16), while model- or case-based reasoning are found only in 5 cases. The knowledge acquisition mainly bases on interviewing experts (16) or evaluation of written procedures (14); theoretical studies have been performed in 8 cases.

It does not appear that the tools provided by some systems for updating the expert systems' judgemental knowledge (rule base) are intended to be used by the utilities' operating personnel.

3.7 Appendix: CONSOLIDATED RESULTS

	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8
RA	bfgijkltu	a	a	ab	eh	b	b	bfi
TEPCO	abefghijlmnopqrstv	a	b	bc	aceg	b	a	abefj
CEPCO	abegijopqrstu	a	c	c	acg	b	b	abcdefgj
KEPCO	abefijmnopqrs	a	e	b	abceg	b	b	abefj
SERIG	bcdefijklmnopqrstv	a	abc	b	eh	b	b	abefj
NOPA	abefgmqrstv	a	ae	b	aefh	b	b	abefgj
DUISBURG	abijmns	a	ace	b	degh	a	b	abcdefgj
SRA	abfijklmnopqrstu	a	ae	d	bcfh	a	b	abcegj
MARS	ijkopsu	a	abe	b	eh	a	b	abeghj
KYUSHU	aijopqrsu	a	a		ah	b	b	abefi
CHUBU	abefhijopqrsu	a	a		ah	b	b	abefi
TOHOKU	aijopqrsu	a	a		ah	b	b	abefi
REC	abefijklmnopqrstv	a	ab	ab	abegh	a	b	abdefgj
EPFL	iqr	b	ab		(d)h	b	b	cgj
APSR	abghijm	a	e	ab		b	b	abefi
ERPS	beijs	a	a	b	egh	b	a	abefi
IRPOW	abcdefgijklmnopqrst	a	a	bc	abch	b	a	cegj
EPRI	bfgijklnoprstv	a	ad	c	aefh	a	a	abefgi

TOPIC 4: KNOWLEDGE ENGINEERING FEATURES

Masakazu Kato

4.1 Introduction

In order to classify restoration expert systems from the standpoint of knowledge engineering features, three categories are considered in this analysis: frame-based systems, rule-based systems and others. Frame-based systems adopt both frame/object representation and rules, while rule-based systems adopt only the rule knowledge representation. The third group include an object-oriented system and a procedural system.

Among 19 systems reported, frame-based systems are RA, SERIG, DUISBURG, MARS, KYUSHU, CHUBU, TOHOKU, REC, RP, NOPA, APSR, ERPS and EPRI (total 13 systems). Rule-based systems are TEPCO, CEPCO and KEPCO (3 systems). Others are SRA, IRPOW (object-oriented system) and EPFL (procedural system).

The knowledge engineering features of these systems are summarized as Table 4.1 – 4.3, based on the typology stated in the first part of the report.

4.2 Knowledge Representation

This is a key issue for expert systems. This representation depends on the expert systems tools or languages used. Frame-based systems use various kinds of tools or languages such as SNAP/KES, SMECI, SPOKE, NEXPERT OBJECT, KEE, TDES3, KES3.0, KAPPA-PC (tools) and lisp, prolog (languages). On the other hand, the rule-based systems reported here use OPS83. Among the third group, one uses CLOS (tool) and others are written in lisp and C (languages).

Next, we propose a classification of the systems by the number of objects (frames) and rules. As for rules, among the 16 systems which use rules, 1 system has more than 1000 rules, 7 systems have 100 – 1000 rules, 1 system has some tens of rules, and I couldn't get such information from the other 7 systems. As for objects (frames), among 15 systems which use objects, including object-oriented systems (SRA, IRPOW), 3 systems have more than a thousand objects, 1 system has 100 – 1000 objects, 4 systems have some tens of objects, and I couldn't obtain such information from the remaining systems.

4 systems adopt a blackboard-type knowledge representation. One system (SRA) is an original tool written in lisp, where the others (NOPA, MARS, IPROW) use KEE, SPOKE and CLOS respectively.

These figures are summarized as Table 4.4.

4.3 Inference Mechanism

This is closely related to knowledge representation. As most systems use rule-based inference, forward/backward chaining are the main trend. But there is one system (REC) in which message-passing is used together with rule-based inference. Chaining mechanisms can be divided into forward and backward chaining. Among the 16 systems which use rule-based inference, 14 systems use forward chaining, 9 systems use backward chaining and 7 systems use both forward and backward chaining. Of the six systems reported from Japan all use forward chaining only. DUISBURG developed in prolog and APSR written in FORTRAN77 use only backward chaining.

These figures are summarized as Table 4.5. In frame-based systems, the difference between message-passing and procedures may be said to be subtle.

4.4 Reasoning process

This section considers additional reasoning processes. Although "Quantitative" covers only uncertainty and fuzzy logic, there seems to be some confusion on "Quantitative". However according to the replies, 10 systems possess "Quantitative" features, and 13 systems "Qualitative". It may be said that rule systems including frame-based rule systems have a tendency to adopt qualitative reasoning rather than quantitative, while others have the opposite tendency.

As for other characteristics, only one system is planning to apply truth maintenance functions.

These results are summarized as Table 4.6.

	KNOWLEDGE REPRESENTATION	INFERENCE MECHANISM *	COMMENTS
RA	Frame-based Frame (1000) Rule (200)	F B P	
TEPCO	Rule-based Rule (200)	F	
SERIG	Frame-based	F B	
CHUBU	Frame-based Frame (20) Rule (100)	F P	
DUISBURG	Frame-based Frame (1000) Rule (1100)	F B	
REC	Frame-based	F B M	
APSR	Frame-based	B	
IRPOW	Others (Frame)	M	Blackboard Model
EPRI	Frame-based	F	
ERPS	Frame-based	F B	

* F : Forward chaining, B : Backward chaining, P : Procedure, M : Message Passing

Table 4.1: General Restoration Systems

	KNOWLEDGE REPRESENTATION	INFERENCE MECHANISM *	COMMENTS
CEPCO	Rule-based Rule (200)	F	
NOPA	Frame-based Frama (50 - 100) Rule (50 - 100)	F B	Blackboard Model
SRA	Others (Frame) Frame (3200)	P	Blackboard Model
MARS	Frame-based	F B	Blackboard Model
KYUSHU	Frame-based Frame (50) Rule (200)	F P	
TOHOKU	Frame-based Frame (70) Rule (240)	F P	

* F : Forward chaining, B : Backward chaining, P : Procedure

Table 4.2: Local Restoration Systems

	KNOWLEDGE REPRESENTATION	INFERENCE MECHANISM *	COMMENTS
KEPCO	Rule-based Rule (30)	F P	
EPFL	Others (Procedure)	P	
RP	Frame-based Frame (100) Rule (180)	B	

* F : Forward chaining, B : Backward chaining, P : Procedure

Table 4.3: Distribution Restoration Systems

	Rules				Frames/Objects				Comments
	≥1000	100-1000	≤100	?	≥1000	100-1000	≤100	?	
Frame-based (13)	1	5	1	7	2	1	4	3	3:Blackboard-type
Rule-based (3)	0	2	1	0	-	-	-	-	
Others (3)	-	-	-	-	1	0	0	1	1:Procedural 1:Blackboard-type

Table 4.4: Number of Frames and Rules

	Forward Chaining	Backward Chaining	Message Passing	Procedure
Frame-based (13)	11[7]	9[7]	1	4
Rule-based (3)	3	0	-	1
Others (3)	-	-	2	1

Table 4.5: Inference Mechanism

	Qualitative	Quantitative	Truth Maintenance
Frame-based (13)	9	7	1
Rule-based (3)	3	0	0
Others (3)	1	3	0

Table 4.6: Additional Reasoning Processes

TOPIC 5 :

FACILITIES PROVIDED BY THE SYSTEM

Radu Manoliu

5.1 INTRODUCTION

The Appendix 5.1 contains the basic information about the Power Restoration Systems (PRSs) which were analyzed by the Task Force 38-06-04. In order to explore the eventual common features and the correlations between the systems facilities and their complexity, we established three categories of PRSs. The Load/Generation capability of the network was considered as classification criterion. Consequently we set-up the following groups :

- . Large Load/Generation PRSs : >5000 MW
- . Medium Load/Generation PRSs : 5000 MW > L/G >500 MW
- . Small Load/Generation PRSs : L/G < 500 MW.

We are convinced that the Load/Generation parameter gives not an absolute measure of the system's complexity ; but within the framework of the available data, we believe that we can not have another better criterion to give an approximate idea of network's complexity.

Taking into account the available data, we were not able to find correlations between the elements of topology and the kind of facilities provided by different PRSs.

5.2 ANALYSIS OF THE DETAILED DESCRIPTIONS

5.2.1 Main planning and monitoring features

5.2.1.1 Dynamic or fixed planning

These features are rather well correlated with the size of the network, i.e. :

- . in the large systems category, four (4) PRSs contain dynamic planning features and only one (1) PRS (SERIC) has a fixed planning and monitoring facility ;
- . in the medium systems category, we are witnessing the negative picture of the precedent one, i.e. : five (5) PRSs include fixed planning and monitoring features, and only one (1) PRS (CEPCO) provides dynamic planning and monitoring features ;
- . in the small systems category, both PRSs are described as featuring fixed planned systems.

The correlation between the amount of the Load/Generation parameter and the nature of planning and monitoring seems rather logical : for the large PRSs, the complexity of the system is commanding a dynamic approach for network evolution planning.

5.2.1.2 Restoration actions monitoring

We could not find any rationale supporting the utilities choice for restoration actions monitoring. We assume that the choice of each organization is made accordingly with its own culture and experience.

Nevertheless, some trends may be emphasized, i.e. :

The large PRSs are equally dealing with two kinds of restoration monitoring :

- Performing of check-plan steps, or ;
- Following overall criteria, independent of restoration plan.

The medium-sized PRSs favor the "overall criteria" approach. In parallel they are also using the "check-plan-steps", as well as the "plan and check only one step ahead" methods ;

The small-sized PRSs are equally distributed between the "plan-and-check only one step ahead" and the "overall criteria" methods.

5.2.1.3 Replanning capabilities

We tried to outline a logical link between the replanning capabilities and the functional objectives of PRSs.

We found that the link between the ability to "evaluate restoration options (1.3.1)" and the "backtracking" as a planning feature (5.1 f) was the most obvious correlation we were able to acknowledge. Actually, we found 9 cases of correlation vs 4 cases of non-correlation ; in 2 cases we did not get the necessary data to make a judgement. A more detailed view of this analysis is given the following table :

	TOPIC			CORRELATION
	1.3.b.	5.1.f (B)	5.1.g (P)	
L.1 TEPCO	NO	NO	YES	YES
L.2 CHUBU	YES	NO	YES	NO
L.3 SERIG	NO	YES	NO	NO
L.4 RA	NO	NO DATA AVAILABLE		?
L.5 REC	YES	YES	NO	YES
M1. CEPCO	NO	NO	YES	YES
M2. TOHOKU	NO	NO	YES	YES
M3. DUISBURG	NO	NO	YES	YES
M4. SRA	YES	NO DATA AVAILABLE		?
M5. KYUSHU	YES	NO	YES	NO
M6. MARS	YES	YES	NO	YES
S1. EPFL	YES	YES	NO	YES
S2. NOPA	NO	NO	YES	YES
N1. KEPCO	NO	NO	YES	YES
N2. RP	NO	YES	NO	NO

Table 5.1 Correlation between Restoration Options and Planning Features

5.2.2 Operator interaction with the planning process

The analysis of this feature shows that the proposed PRSs are rather well situated regarding the features of interactive processing. Actually, eight (8) systems have at least two (2) interactive features. Because all but one of the PRSs are prototypes, it is previsible that more interactive facilities will be added in the future.

5.2.3 Description of the user interface

5.3.1 Graphic visualization

We found an important number of graphic visualization facilities. As expected, all but two (2) of the PRSs are able to represent line/substation diagrams.

Most of the systems (10 out of 15) provide a specific MMI development. Only four (4) graphic interfaces have SCADA-representations ; one of these (Duisburg) uses the same features as the training simulator.

The RA system is the only one which uses a specific development only for the prototype ; which will be transported on the SCADA environment for the final product.

The visualization of the numerical data in the inference process is provided by seven (7) systems out of 15. Only three (3) of the PRSs have explanation facilities. None of the analyzed systems is able to provide geographic representation, in spite of the fact that the technology is commercially available. It is hopeful that the PRSs for distribution networks will be provided with geographic visualization facilities, in order to facilitate crew intervention. The same comment has to be considered for the dynamic zooming facilities, which are represented only in 6 systems.

Most of the PRSs are provided with three (3) or more graphic visualization facilities.

5.3.2 User dialog facilities

The Man-Machine-dialogue is generally "mouse-driven". Only three systems are not equipped with this feature.

Another popular feature is represented by the Question/explanation-rule-content-based-facility, which is available on six (6) PRSs.

The pre-prepared explanation texts are provided by five (5) systems.

Only one system (Duisburg) uses the "verbal activated*" input for dialog purposes.

5.2.4 Simulation capabilities

All the systems, but one (Restoration Planner) provide simulation capabilities.

* "Verbal activated", means that there are predefined sets of certain keywords which can be input via the keyboard, such as "why" or "how" to get explanation, "facts" to get the informational state of the expert system and so on, displayed on the screen.

The most available feature is represented by the ability to display the results of the proposed restoration plan, which is provided by eleven (11) systems.

Half of the PRSs have two (2) simulation capabilities, i.e. : a) the ability to display the results of operator's input based on the current state of the network ; b) the ability to display the results of the proposed restoration plan.

There are also two particular cases :

- RA system is connected to the full training simulator ;
- DUISBURG system simulates the dynamic behaviour of the network

5.2.5 Performance

The results of the survey show a very great dispersion of the "average time to solve a standard case", i.e. : from 1 second to 2 hours. The two-hours-figure represent the restoration time from a complete blackout. The one-second-figure represents probably the response time for an elementary operation. Even the response time for an elementary operation can not be considered as a standard reference, because it depends on the way the problem is divided. On the other hand, the performance is not a main issue among the objectives of this survey.

Consequently, the TASK FORCE has decided (31st January meeting, New-York) not to discuss this issue in this report.

LOAD/GENERATION CAPACITY :

Large Medium Small Non Det

FACILITIES PROVIDED BY THE SYSTEM	Large				Medium				Small Non Det				COMMENTS		
	T E P C O	C H U B U	S E R I G	R A	R E C	C E P C O	T O H O K U	D U I S B U R G	S R A	K Y S U H U	M A R S	E P F L		N O P A	K E P C O
(5.3) Description of the user interface (next)	L1	L2	L3	L4	L5	M1	M2	M3	M4	M5	M6	S1	S2	N1	N2
<u>User Dialog:</u>															
(i) Pre-prepared questionnaire texts	X	X	X		X		X		X	X				X	X
(j) Pre-prepared explanation texts	X	X	X		X		X		X	X				X	X
(k) Question/explanation derived from rules contents	X	X	X		X		X		X	X				X	X
(l) Verbal input	X	X	X		X		X		X	X				X	X
(m) Mouse operated input	X	X	X		X		X		X	X				X	X
(n) Other	X	X	X		X		X		X	X				X	X
(5.4) Simulation capabilities															
(a) Show result of operator input, based on network current state	X	X	X		X		X		X	X				X	X
(b) Show results of the proposed restoration plan	X	X	X		X		X		X	X				X	X
(c) Other	X	X	X		X		X		X	X				X	X
(5.5) Performance															
Average time to solve a standard case	10 to 20 sec.	1 minute	2 hours'	≡ 2 sec for 3 stations	2 to 5 minutes	≡ 40 sec.	≡ 1 to 2 minutes	R e a i t i m e	≡ 2 minutes	≡ 1 to 2 minutes	1 to 3 minutes	1 to 5 sec.	≡ 10 minutes	10 sec.	L e s s t h a n 8 sec.

TOPIC 6:

SOFTWARE/HARDWARE IMPLEMENTATION

Jarmo Partanen

6.1 Integration of the expert system

About a half (11 systems; EPFL, TEPCO, TOHOKU, RP, MARS, SERIG, NOPA, REC, EPRI, EPRS, IRPOW) of the expert systems operate in stand-alone mode. Three systems (CEPCO, RA, DUISBURG) are integrated with training simulator and four systems (KEPCO, KYUSHU, CHUBU and SRA) with a control centre.

6.2 Hardware configuration

Most (17) of the systems are used on workstation based environment, only two systems are used on PC-based hardware. One system can be used both on main-frame computer or PC environment and one system both on workstation or PC environment.

6.3 Operating system used for expert system

Unix is the mostly used operating system. 13 systems are developed using Unix-operating system. Two systems use VMS operating system and the two PC-based systems use MS-DOS operating system. One system is based on the Aegis and one on Ultrix operating system.

6.4 Languages and tools used for expert system

Many different programming languages and tools are used in the experts systems. TDES-3 (Lisp based japanese tool) is used in three systems (KYUSHU, CHUBU, TOHOKU). C together with OPS83 is used also in three systems (TEPCO, CEPCO, KEPCO). Prolog is used in two systems (DUISBURG, RP). Lisp is also used in two systems (SRA, SERIG). The other languages and tools used are; C (EPFL), SNAP/KES (RA), Spoke (MARS), KEE (NOPA), Nexpert Object (REC), KES (EPRI), Kappa-PC (EPRS) and C++ (IRPOW).

6.5 Interface with numerical programs

The interface between expert system and numerical programs is in some systems realized via transfer files, e.g. the expert system writes the data in to the file which is used as an input data for numerical programs. In the other

systems in which the interface has realized the numerical programs are called directly as subroutines from the expert system.

6.6 Interface between expert system and the SCADA computer or the simulator

Half of the systems are operated in stand-alone mode which means that the interface between the process computer is not realized. In cases when the expert systems are integrated with process computer the basic situation is that the SCADA or simulator computer and expert system have different data bases and the expert does not have the direct access to the process computer data base. Only two expert systems (Duisburg and REC) have this kind of direct access. In other cases the real-time data base or part of it is copied to the memory of the expert system (TEPCO, KEPCO, RA, KUYSHU, CHUBU, TOHOKU, SRA).

6.7 User interface

Almost all the systems have a high resolution graphical interface, only in one system (EPRI) the text mode type interface is used. X-windows graphical standard is used in two systems. GKS (graphical kernel system) is used in three systems. The other graphical standards used in systems are KEE-graphics, Open Window, MS-DOS Windows, Multiwindows and GPR/GSR graphic systems. In some replies it was mentioned only "full graphics".

Table 6.1 Summary of software/hardware implementation

expert system	integration with process computer or simulator	hardware configuration	operating system	software tools	interface with numerical programs
RA	* integrated with simulator * A and B	*IBM RS 6000 * graphic display	* Unix	* SNAP/KES * X-Windows	* Unix sockets
TEPCO	* stand alone * B	* EWS * graphic display	* Unix	* C, Fortran * OPS 83	* using subroutine calls
SERIG	* stand alone	* PC 386 or * Sun workstation * graphic display	* Unix	* Le_Lisp * Smeci * Aida	* through files
CHUBU	* integrated with simulator and control centre * B	* AS workstation * graphic display	* Unix	* TDES-3 * GKS-graphic	* using subroutine calls
REC	* stand alone * B and C	* SunSparc station * graphic display	* Unix	*Fortran *Ease + *Nexpert Object *Open Windows	* through files
IRPOW	* stand alone	* DecStation * graphic display	* Ultrix	* CLOS, Fortran * C++	* through files
EPRI	* stand alone	* Vaxstation 3100 * text mode display	* VMS	* Knowledge Engineering System (KES)	* through files
ERPS	* stand alone * A	* 486 PC * graphic display	* DOS	* Kappa-PC * Windows	-
DUISBURG	* integrated with simulator * C	* Apollo workstation * graphic display	* Aegis	* MProlog * Apollo GPR/GSR graphic	* using subroutine calls
CEPCO	* integrated with simulator * A	* EWS * graphic display	* Unix	* C * OPS 83	* using subroutine calls

NOPA	* stand alone	* SunSparc station * graphic display	* Unix	* KEE	* through files
SRA	* integrated with control centre * A and B	* SunSparc station * graphic display	* Unix	* Allegro Common Lisp * GKS-graphic	* through files
MARS	* stand alone	* DEC or Sun workstation * graphic display	* Unix	* SPOKE * Multiwindows X11R4	
KYUSHU	* integrated with control centre * B	* Super mini-computer * graphic display	* OS/V (Unix)	* TDES-3	* using subroutine calls
TOHOKU	* stand alone * B	* AS workstation * graphic display	* Unix	* TDES-3 * GKS-graphic	* using subroutine calls
KEPCO	* integrated with control centre * B	* EWS * graphic display	* Unix	* C * OPS 83	* using subroutine calls
EPFL	* stand alone * data transfer via files	* HP Apollo * graphic display	* Unix	* C * X-Windows	* using subroutine calls
RP	* stand alone	* IBM 4341 or * PC/AT * graphic display	* Main-frame operating system * DOS	* Prolog	-

- A = selected information such as alarm or event messages are transmitted to the expert system dynamic storage
- B = content of the real-time database of the process computer is copied in part or in full to the expert system dynamic storage area
- C = expert system access directly the real-time database of the process computer

PART 2 :
STRATEGIES OF RESTORATION EXPERT SYSTEMS

by **Gerhard Krost and Daniel Kirschen**

The general aim of network restoration is to transform a power system from a disturbed state, where important elements of the system have been lost, to an undisturbed state. To achieve that aim, a certain restoration strategy is adopted, whereby the notion "strategy" means the particular proceeding in applying measures to reach a desired final situation in the power system - usually formulated in advance - from any given starting situation represented by the actual disturbance. Thus, determining a suitable restoration strategy presupposes

- a distinct and unambiguous definition of the final restoration goal ;
- the ability to rapidly and flexibly recognise the actual disturbance situation ;
- a clear understanding of the particular operative measures being available to perform the restoration as well as of the sequencing of these measures in logic and physical sense.

In the following, some general remarks on these subtopics of restoration strategies are given and the particular approaches adopted by 11 out of the 19 restoration expert systems under the review of CIGRE TF 38-06-04 are evaluated in more detail, basing on the results of a questionnaire specifically related to restoration strategies. This questionnaire, prepared for the second step of the task force work, entails the comparison of some restoration expert systems with special respect to their particular proceeding. It has been answered for the following systems : CHUBU, EPFL, DUISBURG, KYUSHU, MARS, NOPA, RA, SERIG, SRA, TEPCO and TOHOKU; it should be remarked that the CHUBU, KYUSHU and TOHOKU systems are implementations at different utilities, but originating from the same manufacturer. Further, the EPFL system is the only one designed for pure medium voltage distribution networks.

1. RESTORATION GOAL

Of course, the goal of restoration is to re-configure the power system to an undisturbed state. But what does "undisturbed state" mean ?

Seen from the customers' point of view, the restoration goal can be defined as the full (undisturbed) re-supply of all loads. In 7 of the 11 more closely investigated expert systems this criterion is applied; it can be derived from the status of switching equipment and measurement values which in their turn immediately are available from the network control system (SCADA/EMS). The fulfilment of all loads' re-supply can either be checked at the end of a fixed sequence of restoration measures or - dynamically - during the restoration actions, thus terminating the procedure if reached.

Seen from the viewpoint of power system operators, on the other hand, the undisturbed state of the network might be indicated by :

- configuring the network to a "normal" topology, bearing in mind that the definition of this "normal" state is somewhat precarious due to routine disconnections for maintenance work etc.;
- re-configuring the network topology to that which existed before the disturbance occurred; this requires a very careful flashback on what was the situation before the disturbance, and it will cause problems if some equipment became unavailable during the disturbance ;

- restoring the source situation before the disturbance. But what about a lost thermal plant, the power of which is substituted from the interconnected network after the disturbance; will the restoration then require the plant to be re-synchronised or an alternative one run up (which might be a question of hours), despite the fact that the power system is in full service ?
- dynamic finding of a new network state which besides the full re-supply of customers provides sufficient (e.g. n-1) security ; this would require an integration of contingency analysis into the restoration procedure.

As it can be seen from these topics, the definition as well as the realisation of possible restoration goals is much more complex than expected. Thus, it is easily explainable that the majority of expert systems desire the goal of full customers' supply. Only the TEPCO system is oriented to reach a pre-defined "normal state" (whereby unavailabilities are dynamically taken into account), the SRA system tries to restore the pre-disturbance configuration except faulted equipment and tripped thermal generation, and the RA system targets to reconnect all main transmission lines and to restart the major plants.

2. DETERMINATION OF THE ACTUAL SITUATION AT RESTORATION BEGINNING

There is a great variety in possible network states, which actually might result from the occurrence of a disturbance; corresponding to the definition given in the report of the first step of CIGRE TF 38-06-04 work they can be roughly grouped into :

- *total blackout* which is the collapse of almost all the power system; the restoration in this case requires the black start of some generating units or the assistance of a neighbouring utility ; this situation is covered by 11 out of the 19 reviewed expert systems;
- *partial blackout* which is the loss of supply over a wide area, but a large portion of the power system remains operational; 13 of the investigated expert systems deal with this situation;
- *local disturbance* followed by the loss of supply in a limited area, covered by 15 out of the 19 expert systems.

It is obvious that each of these very different disturbance types entails a particularly adapted restoration procedure (e.g. black start is only demanded in the full blackout situation). On the other hand, 13 of the 19 expert systems under regard deal with more than one disturbance type, thus requiring the ability to distinguish the actually given type; only the KEPCO, MARS, NOPA and RP systems exclusively cover local disturbances, and the APSR, EPRI and SERIG systems solely deal with total blackouts and thus do not need to differentiate before restoration beginning.

Practically, in the majority of 8 out of the 11 expert systems which have been analysed more closely ("strategies" questionnaire), the determination of the actual breakdown situation is performed via the identification of unsupplied busbars (respectively areas), and in 4 systems (NOPA, DUISBURG, SRA and TEPCO) by an additional disturbance type classification; it is

noteworthy that in the case of the other 3 Japanese systems (CHUBU, KYUSHU, TOHOKU) such a classification has been stated to be desirable.

A certain preparation of the network before restoration beginning might contribute to a more secure restoration by avoiding critical states and at the same time by making the actual situation to be surveyed more easily by the operator.

Therefore, several expert systems provide for splitting one voltage level of the power system into islands ("vertical splitting"): in the MARS system such islands are pre-defined by automatic devices on the French network, in the SERIG system vertical splitting takes place independently of the expert system, too, and in the TEPCO, CHUBU, KYUSHU and TOHOKU systems the splitting is done dynamically depending on the actual situation.

In the DUISBURG system, when a total blackout has occurred, the opening of all breakers is initiated before the start of restorative actions; this has been explicitly desired by the utility staff. The advantage of obtaining a defined initial state is contradicted by the unnecessary waste of auxiliary energy - whose replenishment especially in disturbance situations is not guaranteed - as well as the additional time delay for the switching operations, especially if they are performed manually by the operator. As a supplementary effect of opening all breakers, the separation of the different voltage levels (110/25/10 kV in the DUISBURG case) is obtained, which is called "horizontal splitting" of the network; but to achieve this aim, opening of the breakers of all coupling transformers solely fully suffices, which is induced in the case of the SRA system.

A combination of both vertical and horizontal splitting is applied in the written restoration recommendations of several German utilities operating the 380/220 kV supergrid.

3. RESTORATIVE MEASURES

Basically, all restorative actions are alternately related to :

- sources (power plants, external networks),
- loads which have to be reconnected and
- electrical connections between them,

and all expert systems under investigation deal with these three topics. At a first glance, the chosen sequence of addressing them is dominated by the demand to balance the active power of sources and loads. But there are further criteria which considerably influence the performance of the sequence adopted, such as

- availability of sources, their run-up times and ramping rates,
- necessity to prefer certain loads (e.g. houseloads of nuclear plants),
- the limitation of voltages, line currents and reactive power,
- the actual topology of the remaining network

and so on. With respect to these, the "intelligent" sequencing turns out to be the cardinal topic of any restoration procedure. It should be explicitly emphasised, that the notion "intelligent" does not mean "optimal" : due to the high dimensionality of objectives and the combinatorial variety, the calculation of a global optimum is practically impossible, and a reduction to a small number of objectives (e.g. minimising the total time demand or smoothing the voltage

profile etc.) would fully neglect all the other aspects. Therefore, the use of an expert system, which diminishes the combinatorial variety by the use of approved heuristics without necessarily cutting the scope of objectives to be taken into account, proves to be an adequate solution; or, in other words, restoration is one of the most rewarding areas of expert system application in network control.

But how is this sequencing implemented in the particular expert systems; how is the adequate restoration strategy derived ; which measures and which objectives are taken into account ?

3.1 Partial goals

The priority between partial goals related to sources, loads and interconnections is addressed in a specific way in each of the expert systems. The majority of 7 systems try to reconnect maximal possible load to the remaining network after the disturbance first. Two systems (NOPA and RA) care for the auxiliaries of thermal power plants first, while the SRA and SERIG systems give priority to the auxiliaries of nuclear power plants; the RA system also gives a high priority to the nuclear auxiliaries in case their emergency generators have not started properly. The SERIG, SRA and RA systems intend to configure a (weakly loaded) basic network for the supply of power plant auxiliaries. In addition to that and before restoring load, the SRA will try to restore the transmission network.

The first approach is based on the assumption that there is still some power available after the disturbance (which is not necessarily true in the case of a total black out). The third approach could probably cause problems in the case of very long distances or pure cable networks due to reactive power; these circumstances can be taken into consideration either universally through the application of a power flow or heuristically by implementation of rules.

3.2 Sources

Generally, an adjacent network will be the first choice of primary power source for a collapsed and islanded system. Even if there is no bulk power available, the inertia and stable voltage of an external network will considerably alleviate the restoration, specifically at the beginning with very low own generation. Regarding further sources, hydro generation and gas turbines (if present) will be selected next, and the thermal units will follow ; but this sequence may be overruled in specific cases, e.g. where some thermal plants are provided with the ability to run under houseload conditions after having tripped and are thus immediately available for re-synchronisation.

In the case of local disturbances or distribution networks, it usually suffices to exclusively consider interconnected networks as power sources ; in principle, their availability and limitation has to be regarded, but there are no time constraints. While on the distribution level (EPFL) the availability of power can be assumed if the feeding transformer is energised (which usually can be ascertained by the network control system), in all other expert systems (SERIG excepted) this has to be asked for at the control centres of power plants or neighbouring utilities and to be communicated to the expert system by user's dialogue.

After partial or full black outs, the first step must be a selection of the primary source for restoration. This can be done by either default (under pre-assumption of the particular availabilities, EPFL) or dynamically at run time under consideration of the actually given

states of power plant units and tie connections. The latter has been realised or is at least intended in all other expert systems under regard: 9 out of 11 systems deal with limited availabilities of sources in general ; many of them choose from various source types (10 systems handle neighbouring networks, 8 thermal plants, 7 hydro generation and 4 combustion turbines), globally taking into account the particular times to get them (re)-synchronised, and some consider the topological location of the sources related to the actually connected network, too. The ramping rates of thermal plants are explicitly regarded in the CHUBU, NOPA and TEPCO systems.

3.3 Loads

As stated above, the full re-supply of customers is aspired to as the ultimate goal by most of the expert systems considered. Thus, 8 out of 11 systems reconnect maximal possible load to those substations which have been re-energised ; in doing so, 5 of them additionally consider the priorities of predetermined loads. The NOPA and SRA systems try to optimally match the load to be selected with the actually available power, and two other systems regard this procedure as desirable. In any case, the problem remains to reasonably determine the recovery values of the particular loads to be expected. Hence, 6 of the 11 systems rely on the pre-blackout values, and 3 operate on fixed values attached to each load, which are pre-estimated in a conservative manner. Modelling the time behaviour of loads after reconnection is stated as being desirable in 3 cases.

3.4 Power balancing

The equilibrium between generation and consumption is a vital consideration, especially during restoration. Taking this into account in adequate manner, requires a very close interrelation between the expert system and a set of algorithms such as power flow, load modelling, generators' ramping and frequency model of the power system as a whole. Only the TEPCO and the CHUBU systems match the actually measured frequency and power flow results, while in two other implementations (NOPA and DUISBURG) this balance is based on an estimation which is represented heuristically in rules ; the TOHOKU and RA systems designate one of these two methods as desirable, in SERIG the expert system verifies that each network has sufficient primary margin, and the remaining two systems, dealing with local disturbances (MARS) and distribution networks (EPFL) only, assume a given generation (feeding transformer for EPFL) capacity which certainly complies with the full amount of recovering load.

4. ELECTRICAL CONNECTIONS

4.1 Path determination policy

The electrical network consisting of lines, transformers, busbars and switching equipment provides for the interconnection between power sources and loads. Therefore, the performed switching actions have to agree with the adopted sequence of source selection and load reconnection by creating certain paths between generation and customers. Two basic forms of procedure are applied in the expert systems under regard :

- a) Dynamic (on line) path search, realised in 8 and under development in 1 out of the 11 analysed systems ; this search process can reflect diverse criteria, such as minimisation

of switching operations (RA, SRA, CHUBU, KYUSHU, TOHOKU and NOPA) or constraints in voltages (RA and SERIG), line currents (EPFL, MARS, NOPA and SRA) or - e.g. - reactive power.

- b) Suggesting pre-defined plans for path switching (realised in 2 systems), either based on experience (DUISBURG) or on pre-estimation of the practicability (TEPCO) with respect to line/transformer loads.

The approach a) offers greater flexibility, especially in the case of changes to the network topology e.g. by installation of new equipment, but requires close and frequent interaction with the process data model of the network; solution b), on the other hand, offers the opportunity to limit the variety by the inclusion of heuristics into the rules which provide for the path proposals, but causes problems with respect to the knowledge base maintenance.

4.2 Path generation procedure

The flexibility which is normally built-in to an electric power network is such that the number of connections (or paths) which could be created through that network is enormous. A blind search for a restoration path would produce an extremely large search tree in any practical size network. Techniques must thus be developed to avoid a combinatorial explosion in this search.

It is generally agreed that the first technique which can be used to control the size of the search is to use a two-layered representation of the network. In the first layer, the power system is represented as a collection of stations and substations connected by transmission lines. The goal of the search in this layer is to select the transmission lines which must be energised to connect two stations. Once these lines have been selected, the search can move down to the next layer where the detailed topology of each station and substation is represented. At this level, the purpose of the search is to determine the switching operations which must be performed within each substation to establish the electrical connections between the incoming and outgoing lines, between a line and an energised busbar or between a line and a "target" busbar.

While this decomposition considerably simplifies the problem, the number of connections which can be done within a single substation remains very large. The search must again be limited by using heuristics. These heuristics can be introduced in several ways :

- a sophisticated model of each substation can be built and used in conjunction with rules describing the principles of switching operations to determine directly the path which an experienced operator would establish ;
- a simple search can be combined with pre-determined switching patterns to speed up the process ;
- a "cost" could be assigned to the operation of the various types of devices and a "best first" (A*) type search can be used to try to determine the path which minimises the total "cost" of establishing a connection between two points in the substation. By adjusting the costs assigned to the various types of devices, it should be possible to obtain a path similar to the one which would be created by an experienced operator. It should be noted that the details of a system based on this approach have not yet been described in the technical literature.

It should also be noted that there are two aspects to the determination of a connection path within a substation: finding the switching devices which must be closed (or which must remain closed) and finding the switching devices which must be opened (or which must remain open). While the determination of the list of switches which must be closed is very similar to the determination of a shortest path in a graph, the determination of the switches which must be opened is considerably more heuristic. A couple of examples illustrate the types of problems that are encountered :

- an EHV disconnector should usually not be left open because closing it at a later time may require a significant reconfiguration of the substation,
- it is usual practice to open the breakers on the low voltage side of a transformer instead of opening the breakers on the high voltage side.

The MARS system uses an approach somewhat different to the decomposition described above. In this system, the next station to be re-energised is first selected based on its importance in the network. This importance is based on whether it can be re-energised from a neighbouring station or if it can help re-energise a neighbouring station. Then, focusing on the selected station, MARS chooses the best way to re-energise it, taking into account the available devices and specific preference rules.

5. STRATEGIC PROCEEDING

5.1 Forming the strategy by sequencing

The actually chosen sequence of measures and actions as discussed above will reflect the adopted restoration strategy. In principle, such a sequence can either be determined with respect to the given disturbance situation in advance, or it can be formed or at least influenced dynamically during the restoration actions, based on the actual network situation at any moment during the restoration ; actually it appears that all expert systems under regard are oriented to the second approach. Likewise, the desired target configuration of the network can be determined either before restoration beginning (TEPCO, CHUBU, KYUSHU, TOHOKU, SERIG, SRA and DUISBURG) or adaptively during the procedure (EPFL, MARS, NOPA and RA). To reflect the procedure adopted by the particular expert systems most purely, the individual answers on the corresponding topics of the questionnaire, which actually have quite different levels of detail, are substantially cited in the following:

In the CHUBU, KYUSHU and TOHOKU systems, after a fault diagnosis the possible sources are evaluated, a final network configuration is estimated, a switching sequence is determined and all possible substations are re-energised. The reconnection of loads is performed according to their pre-determined priorities taking care not to cause overloads. In the case of the CHUBU system, abnormal voltages are also avoided and some definite substations are re-energised first to secure a maximal number of power sources most quickly.

The procedure of the TEPCO system is split up into four phases: recognition of the current state and determining faulted components, designating premises to make restoration plans, determining a target configuration of the network and generating action sequences to reach the target.

An identification of the current network situation is the first step of the SRA system, too. After that, a target configuration is elaborated and the first part of the plan is established : restoration of a basic network by closing breakers, thus providing for power to critical auxiliaries. Having resupplied maximum possible load, configuration changes (i.e. busbar changes) are carried out and doubtful equipment is incorporated after having suggested the corresponding tests, in order to have more power available to restore loads. It is intended to operate the target network without violations ; thus, re-scheduling of generation is involved.

The EPFL system first tries to find the faulted area and then to re-energise it, and at the same time to suppress all overloads by load transfer.

In the MARS system priorities on substations to be re-energised are determined ; for each substation the choice of actions is determined at each step by evaluating the different possible actions.

The NOPA system re-energises all blackout areas if possible, first by use of the national grid connection and then by use of their own thermal plants.

In the RA system the restoration is decomposed into a set of objectives. Some of these objectives are predetermined (e.g. restarting the generating units) and some are created dynamically (e.g. creating backup paths for ensuring the security of the system). The strategy embedded in the RA is reflected in the order in which it recommends that the various objectives be pursued. This order is determined dynamically and is revised after the completion of each major step of restoration. Since it is very likely that the restoration will not be carried out as planned, RA is designed to perform cycles. Each cycle corresponds to a major restoration step and consists of the following phases:

1. the operator selects an objective with the help of the RA ;
2. RA establishes a detailed plan for achieving this objective
3. the operator reviews and modifies this plan if necessary
4. RA assists the operator in the execution of this plan

Once phase 4 is completed, the cycle is repeated for the next major step until all the restoration objectives have been accomplished.

In case of the DUISBURG system, a disturbance type classification at the beginning (full black out, islanding, partial or local disturbances, ...) activates a corresponding set of rules, which entails the fundamental sequence of restoration objectives such as providing for power from an external network, re-energising a substation, running up a gas turbine or providing for an electric interconnection between substations ("strategic level"). The treatment of these objectives is adapted to the actual network situation (availabilities) and to the operator's objections by presentation of alternatives ("tactical level"), and on the "operational level" the particular switching operations in the substations including load reconnection or further actions (telephone calls to external control centres e.g.) are initiated. The restoration is terminated if all objectives have been performed and all loads are re-supplied.

The main strategy of SERIG is to re-energise most of the extra high voltage network, and then to reconnect most of the load. SERIG models mainly the first step ; re-energising of load is performed in that step only to obtain correct states of network. For the first step, the

strategy is to build regional networks, following a pre-defined decomposition of the whole network. To reach that aim, it takes into account :

- security and dynamic behaviour of nuclear plants ;
- reconnection of small networks ;
- extension and strengthening of networks ;
- taking care of the correctness of different network states, mainly concerning voltage.

When the regional networks are rebuilt, they are reconnected between themselves. There are four different levels of strategy:

- global strategy ;
- choice of a kind of action ;
- detailed choice of action ;
- how to perform an action.

5.2 Impeding conditions

During the restoration, the problem might occur that the procedure offered by the expert system is hampered by unavailabilities of equipment or by refusals of the operator. In this case, only the EPFL and SERIG systems fail ; all the other ones embrace this topic with their dynamic procedure: 6 systems (CHUBU, KYUSHU, TOHOKU, NOPA, RA and SRA) make use of the approach of searching for an alternative by topological processing, 2 systems (MARS and DUISBURG) provide heuristically approved alternatives in their rules, and the TEPCO system modifies the target configuration correspondingly.

Another question is, what would happen if the network state unexpectedly changes, e.g. by tripping of lines or transformers, or by unscheduled switching of the operator, or, in a more spectacular scale, by the expansion of a local disturbance up to an outage of several substations. Here, the particular expert systems conduct as follows: DUISBURG, MARS and NOPA have fixed their procedure to the situation analysed at restoration beginning. TEPCO, CHUBU, KYUSHU, SRA and TOHOKU immediately stop the procedure, reset and begin afresh, including the diagnostic and scheduling phases ; this approach is easy to realise and makes sense when the restoration has not proceeded very much. Only RA is able to dynamically adapt its procedure to the new state, which, of course, is the most efficient approach and thus stated as to be desirable for the CHUBU, KYUSHU, TOHOKU, NOPA and DUISBURG systems, too.

To avoid unexpected tripping or expansion of the disturbance, a look on the system's security during restoration is indicated. Therefore, the 4 Japanese, the RA, SERIG, SRA and DUISBURG systems try to prohibit the occurrence of overloads and abnormal voltages ("violations"), NOPA aims to care for the security, too, and the RA system additionally recommends the creation of backup paths. An evaluation of the given security with respect to a contingency analysis is not implemented anywhere so far; anyway, during restoration a network is usually operated far away from a (n-1)-secure state.

PART 3.A :
GENERICITY OF RESTORATION EXPERT SYSTEMS

by Gerhard Krost

1. PROBLEM STATEMENT

1.1 What we mean by "genericity"

The perspectives of further restoration expert system development and the acceptance of such systems for practical application strongly depend on their adaptability to any given power system and on their maintainability. Therefore, one intention for the third phase of task force work was to elaborate on what portion of the information and knowledge implemented in the restoration expert systems under regard was of generic kind and what portion was specific to the power system. The following three points of view can be taken into account in this discussion on genericity:

- A) Are the different problems solved by specific rules, tightly correlated to the system considered, or by generic rules working on specific facts ? This question is linked to the issue of surface knowledge (of the operators of a given power system) versus in-depth knowledge (which is more universal, as it relies upon physical phenomena occurring during restoration.
- B) Are the necessary data available¹ in the EMS ? If not, there will be a strong tendency to work out specific solutions; moreover, we notice that it may be difficult, for maintenance reasons, to add very elaborate and problem specific data to the EMS database.
- C) Is there a sufficiently generic data representation in the EMS ? This question is strongly linked to other topics, such as "open EMS", and will not be specifically addressed here.

1.2 Information types and storage

Principally, the required information can be stored

- a) in the expert system's knowledge base - e.g. in form of rules describing logical coherence
- b) in form of procedural programs representing algorithmical dependencies
- c) in a database containing information about the existence, behaviour or state of the power system's components.

In practical cases, a first approach can be to implement database information of type c) in a special database,

- which is subordinated to the expert system itself (e.g. in object oriented order) thus providing easy expert system access
- which has to be set up individually for the given power system, thus being extremely network specific
- and which can also be supplied with actual EMS information (such as states or measurement values) via some data transformation and transfer.

¹ In this paper, data availability is considered from the data processing point of view, and not from the point of view of data transmission in disturbed situations ; in other terms, we address here the problem of data availability in the EMS for the application software, not the question of the validity and availability of data transmitted from the real power system to the EMS.

This results in a double network data representation with all the well known disadvantages, and a high degree of specific information stored in the expert system's database.

Another approach is to base the expert system's needs of power system data (c) immediately on the already existing database of the EMS system which contains the data model of the power system (stock of objects, topology) as well as all actual states, measured values and so on. When the EMS database is directly accessed, data transformation for the expert system's conveniences is necessary, too, but a considerable amount of power system specific information remains outside of the domain of the expert system and is maintained and actualised in any case with the already existing EMS system.

Algorithmic procedures (type b) such as load flow, topology evaluation and so on are usually formulated in generic manner and thus do not increase the power system specific information contents in the domain of the expert system.

The rules of a knowledge base (a) can be individually formulated in either a generic way or else specifically related to the conditions of a given network or utility at wish. Basically, a certain portion of specific rules can be replaced by a combination of generic rules and search procedures through the database (simple example: "In case of a blackout, you must first rely on power plant P as a source" \implies "In case of a blackout, you must search in the database for a near hydro plant and rely on this as a source"). That way, the network specific information (i.e. the existence of the hydro plant) will be found in the database, and if the database is the existing one of the EMS system, there is no need to provide any additional network specific information for the expert system at all. Thus, immediate access of the expert system to the EMS data is of essential importance for the genericity of practical expert system implementations.

1.3 Proceeding

It was intended to base the investigation of genericity on the set of restoration expert systems reviewed by the task force since the first phase of work. To get an overview, but to avoid the use of another detailed questionnaire at the same time, a table was prepared referring to some fundamental topics of the restoration strategies report (phase two of task force work) asking for the form of implemented knowledge (rules - procedures - data, see above) and their particular genericity (power system specific-generic). The analysis presented here is based on eight answers which have been received for the RA, TEPCO, EPFL, DUISBURG, SRA, MARS, SERIG systems and collectively the CHUBU, KYUSHU and TOHOKU systems. We may notice that the answers of these 10 systems differ widely, making any general tendency difficult to point out.

2. GENERICITY OF THE DIFFERENT FUNCTIONS IN A RESTORATION EXPERT SYSTEM

2.1 Situation analysis

As can be seen from the strategies report, the majority of restoration expert systems deal with more than one disturbance type, which presupposes the ability to determine the given one. Actually, the CHUBU, KYUSHU and TOHOKU systems try to find out the faulted area (or the unenergized buses) by use of generic rules. In the TEPCO and DUISBURG systems a fault type classification is carried out. TEPCO uses a procedure specifically

adapted to the power system under regard and DUISBURG presently uses rules, which are 50% network specific and 50% generic. The SRA uses 30% generic rules and 70% generic procedures to determine the fault situation in the power system; the actual status of the network is evaluated by generic procedures running on EMS data. MARS, SERIG, RA and EPFL do not analyse the fault situation at all.

2.2 Preparation before restoration beginning

Except for EPFL and SERIG, all systems regarded here provide for preparation of the power system before beginning of restorative measures. In the case of the MARS system, this preparation is performed outside of the expert system by on-site automata which split the network into predefined islands. The Japanese systems - TEPCO, CHUBU, KYUSHU and TOHOKU - provide for splitting the network into islands whose actual configuration dynamically depends on the actual disturbance situation. The splitting conditions are formulated generically, in case of TEPCO as a procedure and in case of the CHUBU, KYUSHU and TOHOKU systems in data form. The RA and DUISBURG systems deal with rules for preparation, whereby the generic rule set of RA operates on power system specific data and aims in selecting the appropriate restoration option and the DUISBURG rules are formulated in generic manner, but comprise the utility specific philosophy of opening all breakers on 110-kV and 25-kV levels before restoration beginning. In the SRA system the different voltage levels are separated (horizontal splitting) depending on the results of generic procedures, which in their turn operate on a LISP-based network representation.

2.3 Sources and loads

Due to the fact that EMS systems usually deal with detailed power plant and load data quite sparsely, this information has to be provided by the expert systems themselves in many cases, thus considerably increasing the portion of their power system specific contents. The CHUBU, KYUSHU and TOHOKU expert systems provide for selection and reconnection of sources and loads by application of power system specific procedures; TEPCO operates with generic rules (whereby it is assumed, that the specific information about the characteristics of sources and loads is stored in the EMS database), and the DUISBURG system presently uses power system specific rules, which are going to be replaced by generic selection and reconnection procedures.

When the expert system is integrated to a restoration training simulator (which applies to the DUISBURG and some other expert systems under regard), all detailed power plant and load data, which are requested for modelling these components in the simulator and which are represented in a special region of the EMS database, are at the same time available to the expert system. Thus, the level of generalisation in the expert system's rules can be significantly increased.

The SERIG system makes use of specific rules, which essentially care fore the operating conditions of the nuclear plants in restorative state of the power system; for both the SERIG and MARS systems, the reconnection of loads is handled by generic rules. In case of the SRA the sources/loads reconnection is performed by use of generic procedures running on a LISP-based network representation; the ranking of loads' priorities is stored in a specific configuration file. For the RA system a generic search procedure for sources operating on EMS data has been developed, and the EPFL system has a generic load reconnection procedure only.

2.4 Electrical connections

All expert systems considered here provide generic methods for electrical connection: for EPFL, CHUBU, KYUSHU, TOHOKU and DUISBURG generic path search procedures have been developed, while the SERIG and MARS systems make use of generic rules. The TEPCO and RA systems combine generic rules and generic procedures with a percentage of about 80/20 in case of TEPCO and 50/50 in case of RA. In the MARS system, the consequences of actions are tested with respect to overloads.

In contrast to the sources and loads situation, the information required to perform electrical connections in the power system is usually available from the EMS database. Thus, the methods provided can rely on EMS data.

2.5 Power balance

Presently, this feature is implemented only in four of the expert systems considered here: The SERIG system makes use of generic rules. TEPCO and CHUBU provide an intersection between the actually measured frequency and power flow results - which is, of course, a procedural approach - formulated specifically for the TEPCO system and in a generic manner for the CHUBU system. In the case of DUISBURG, a generic procedure for that purpose is under development, while the present state provides an estimation which is represented heuristically in the expert system's rules.

2.6 Unavailabilities and faulted equipment

All the expert systems considered here except EPFL and SERIG are able to deal with unavailable or faulted equipment; this primarily refers to the devices establishing electrical connections - transformers, lines etc..., whereby the information concerned is generally available from the EMS system. This problem is treated in a generic manner in all systems through a mechanism which finds alternative routes for electrical. Thus the type of implementation (rules - procedures) fully corresponds to that one which is described for the electrical connections in § 2.4. Unavailabilities of sources (power plants or neighbouring networks) are generally handled in a different way consistent with the selection of sources and loads described in § 2.3.

3. DISCUSSION AND SUMMARY

Ten restoration expert systems - developed and implemented for a particular power system each - have been analysed more closely with regard to their genericity (which is also related to maintainability e.g. in case of power system reconstruction or improvement).

These attributes primarily depend on the portion of power system specific information included and secondly on the manner in which this information is formulated. It is assumed that data (i.e. factual information) can be changed most easily (and in case of EMS data it is a matter of maintenance anyway). On the other hand, the adaptation of higher level information (such as rules) which contain network specific information themselves is a much more complicated enterprise. Of course, rules are quite easy to be formulated due to their orientation to natural language, but the check of their correctness and consistency is very hard to perform especially in the case where an already existing and qualified rule set has to be improved.

For these reasons (reflecting the three viewpoints A), B) and C) given in § 1), it would be desirable to create expert systems relying on generic rules only, which can be qualified once and which can either directly access power system specific (EMS-)data or make use of (analytical) procedures, which in their turn are formulated in generic manner and operate on power system specific (EMS-)data. In that way, all power system specific information would be condensed in (factual) data form thus offering the potential to be specifically adapted to a given power system; in the case of power system improvement, EMS data would anyway be subject of data maintenance, and no separate or additional actualisation procedure would be necessary.

In the practical case of restoration expert systems, however, this situation is only partially given: the subtask of establishing electrical connections including the presentation of alternatives in case of faulted or unavailable equipment (§ 2.4 and § 2.6), can almost fully be solved by the application of generic rules and procedures based on existing EMS data; this philosophy has been quite uniformly applied for all expert systems considered here.

Detailed information about generation and loads, on the other hand, (such as ramping rates, contractual agreements and so on), is not available or is only sparsely available from the EMS database. In accordance with viewpoint B) of § 1, this information is represented in the expert systems themselves, in many cases in the form of specific rules (i.e. rules addressing particular devices) or as power system specific data which can be accessed by rules or procedural programs in the expert system's environment; here, the approaches which have been found in the expert systems under review differ very much, and there is no uniform tendency. When the restoration expert system is integrated into a training simulator, a considerable portion of detailed load and source data - which is needed for the simulation, but is not available from a real EMS system - can also be made accessible to the expert system, thus further reducing specific information to be stored within the expert system itself and at the same time giving an idea about the potentialities of "open EMS" - viewpoint C) of § 1.

Nevertheless, a certain portion of specific information might remain in any practical and realistic case, which cannot or is not intended to be formulated in EMS data form at all; this comprises, for example, contractual agreements with certain customers, preferences or limitations related to components of the power system under regard - such as limitation of short circuit power in certain topological states -, orders to persons or other control centres by telephone calls and so on.

Therefore, it appears desirable for future expert system development, to provide user-friendly editing facilities, which enable the utility personnel to enter power system specific information (which might be of considerable importance for the applied restoration strategy) in a syntax close to natural language or in any other way which does not demand any knowledge about the structures and formats internally used by the expert system.

Another problem is the introduction of such specific rules without conflicting the generic rules already existing. One approach to this difficulty could be "case based reasoning", which can deal with both generic and specific cases within the same framework. Its applicability to power system restoration remains to be investigated.

The high proportion of specific information implemented into power system restoration expert systems does not only depend on the fact that the reviewed prototypes have each

been developed for one particular power system. Rather, the complexity and diversity of the problem of restoration itself, which means the operation of the power system under extreme and strongly restricted conditions, require a considerable amount of information which is specific to the particular network under regard and, of course, its surroundings.

Conversely, if power system restoration could be exclusively based on the portion of information which is usually available from any EMS system, the expert system could, of course, be kept in a quite generic form, but the part of the restoration problem addressed by the expert system would essentially be reduced to path switching.

Thus, open and flexible handling of a certain portion of power system specific information is required by restoration expert systems. Corresponding capabilities for entering and storage are also required. In case these are provided, the need for data which are not available from the EMS database does not mean that it lacks genericity.

Table of answers

<i>Name</i>	<i>Subtask of Restoration Expert System</i>						
	<i>Situation Analysis</i>	<i>Preparation before restoration</i>	<i>Selection / Reconnection of sources</i>	<i>Selection / Reconnection of loads</i>	<i>Path search for electric connections</i>	<i>Generation/ Load balance</i>	<i>Reaction vs unavailable or faulted equipment</i>
RA	-	R/s	P/g	-	R,P/g	-	R,P/g
DUISB	R/s,g	R/s	R/s,P/g	R/s,P/g	R/s,P/g	R/s,P/g	R/s,P/g
EPFL	-	-	-	P/g	P/g	-	-
SRA	R,P/g	P/g	P/g	P/g	P/g	-	P/g
CHUBU	R/g	D/g	P/s	P/s	P/g	P/g	P/g
KYUSHU	R/g	D/g	P/s	P/s	P/g	-	P/g
TOHOKU	R/g	D/g	P/s	P/s	P/g	-	P/g
TEPCO	P/s	P/g	R/g	R/g	R,P/g	P/s	R,P/g
SERIG	-	-	R/s	R/g	R/g	R/g	-
MARS	-	P,D/g	-	R/g	R/g	-	R/g

R : implemented in rule form

P : implemented in form of a (logical or numerical) procedure

D : implemented as data of EMS or network model

s : specifically adapted to the power system under regard

g : generic (i.e. adaptable to any given network)

PART 3.B :
EVALUATION OF THE DIFFICULTIES ENCOUNTERED
TO DEVELOP A RESTORATION EXPERT SYSTEM
AND TO PUT IT IN OPERATION

by Jose Corera

Note: no reference has been made to particular systems, as confidentiality was requested by some of the contributors.

1. ORGANISATIONAL MATTERS

For all the systems the end users belong to a different department/organisation than that of the developers; however, very good collaboration is reported, and enough expertise was provided by the customers.

For most of the systems, demonstrations to the end users were needed, in order to refine the knowledge and performance. This was due to the broad range of functionalities a Restoration System is assumed to provide.

The fact that blackouts are scarce has affected the provision of resources for at least one of the systems. The development had lower priority for the customers than other applications.

2. OBJECTIVES DEFINITION

For some of the systems, no clear specification of objectives from the final user existed, except the wide one "a system to support the restoration work by the operators". One of the system development teams carried out an analysis of operator's decision making process during restoration, thus creating their own specification. Similarly and due to this lack of concrete data, the nature of another of the systems evolved along the project, as feedback was received from the customer.

At the other extreme, one of the systems had a too concrete specification, leading to a too specific development; this system is now being improved by raising the abstraction level.

Another system is reported not to have found particular difficulties in getting the specification for the system.

Finally, one of the systems is reported to have a too fuzzy target definition in the sense of the type of blackout scenario to be addressed.

As conclusion to this point, it must be remarked that most of the suppliers had to carry out additional work in defining the functional requirements for the systems, as the customer could not provide an adequate specification. This can be considered common to all innovative applications.

3. RESTORATION KNOWLEDGE

The introduction of *generic* restoration knowledge extracted from the users has been considered very convenient within the systems. The use of knowledge specific to the target network is not desirable due to the future maintenance problems; however, in some cases it was necessary.

Discrepancies at the level of detailed knowledge are encountered in most of the systems, either because that knowledge was obtained from different individuals, or because it was obtained from the early dates in the project and the opinions had changed, etc.

Most of the systems have been tested using a network simulator to validate restoration knowledge. This has been crucial to overcome the lack of scenarios from real operation.

4. PRACTICAL IMPLEMENTATION

One of the systems -and this can presumably be extended to the others- quotes the effort to introduce restoration knowledge as "huge", due to the many facets of restoration.

Two specific implementation problems are reported by systems built in a generic way :

- how to deal with substation configurations without affecting the core of generic knowledge, and
- how to introduce utility-specific restoration knowledge without conflicting with the generic rules already existing.

The convenience of a robust network representation is recommended by one of the system developers to ease the overall implementation. However, the same developer also mentions the difficulties caused by the use of a mixed hard/soft environment, recommending as far as possible a single language development.

As a next target for research, and as a means to ease knowledge acquisition and diminish maintenance expenses, the investigation into machine learning or automatic knowledge acquisition is suggested in one of the contributions. However, the main difficulty is the lack of appropriate disturbance scenarios. The use of domain specific shells for power system restoration can be of great advantage.

5. INTEGRATION INTO SCADA/SIMULATOR¹

In general terms, most of the systems are integrated with the EMS or a simulator, but only two of the systems are running on real time network data.

Integration has been easier for developers familiar with SCADA/EMS applications -i.e. suppliers of SCADA systems-, although quite a lot of effort was still needed.

¹ Integration into SCADA is addressed here from the software developer's point of view. We do not deal in this paper with issues related to integration to the process (the power system) itself, such as real time data availability in disturbed conditions.

Two systems report that development was based from the very beginning on the actual EMS/simulator data structures, thus final integration was not problematic.

Those systems using the same Database of the EMS -the system does not have its own copy of the network database- have avoided the need of translation, making the development easier. At the other end, at least one of the systems implementing its own database reports the complexity of interfacing both databases, as they are written in different languages -C in the control system, LISP in the restoration expert system.

Still some systems run on simulated data, or use their own network simulator.

6. EXPERIENCE WITH THE SYSTEM/RECOMMENDATIONS

What follows is a list of recommendations from the various systems (included in brackets is the number of systems to which the recommendation applies) :

- the employment of a user interface familiar to the operators is important (1). This includes the use within messages of a language familiar to them (i.e. when referring to network elements). The system should perform reliably, to gain the operator's acceptance.
- fast prototyping is essential for expert systems development; the use of special tools required for data and knowledge based maintenance is suggested(1). However, this poses a delicate problem when integrating those non standard tools into the Dispatch environment
- flexibility is important for a decision making support system for restoration: i.e. to modify the plans under operator suggestion, under unexpected events in the network, etc. (1)
- maintainability is a weak point for various systems; this was sacrificed in order to achieve fast responses, or to support very specific network dependent requirements. Increase the generic content (2)
- not all the inference/explanation capabilities of the system were used. A simplification is recommended (1)
- the use of a restoration system for operator training proves to be very beneficial, thanks to the transparent reasoning (2)
- more testing needed with the simulator (2)
- many aspects of restoration have still to be added (1)
- no problem with the tools used (1)
- no major problem with integration of the system, but the effort is time-consuming (1)
- data maintenance is avoided by the use of EMS database data (2)
- excellent performance for real time use (3)
- good for other users (1)
- a more algorithmic approach would be convenient

7. CONCLUSIONS

The general experience reported by the developers is positive, and the scope of the systems developed is wide, reaching most of the facets of restoration. The intervention of the end users from the first stages of the project, and extensive testing of the systems is the key issue for the success of this technology, still not as mature as power applications software. Finally, the use of advanced tools, required to deal with a problem of this nature, has made integration of the systems problematic.

It must be pointed out that this report does not address maintenance experience by end user - so far maintenance refers only to maintenance by the developers, as the systems are quite young. Also operator acceptance in real cases has been not tackled, as most of the systems run on simulated data.

Answers received from :

- Duisburg (Dr. Krost, Germany)
- Kyushu, Chubu, Tohoku (Dr. Kato, Toshiba, Japan)
- Tepco (Dr. Matsumoto, Mitsubishi, Japan)
- Restoration Assistant (Dr Kirschen, Empros, USA)
- MARS (Heilbronn, EdF, France)
- SERIG (Heilbronn, EdF, France)
- SRA (J. Corera, Iberdrola, Spain)

ANNEX 1 :
SYSTEM DESCRIPTION FORM
USED FOR PART 1

DETAILED SYSTEM DESCRIPTION

Name of the restoration system :

Date :

Author :

Notice 1 : For each question, check all the applicable answers and detail if necessary

Notice 2 :

In the following, we will distinguish between :

- the restoration system or "the system" : the whole software/hardware system developed for restoration,
- the different parts of the restoration system, which generally comprise :
 - . the expert system, including the knowledge base and the inference and control mechanisms ; the knowledge base itself comprises the restoration knowledge (expertise) and the process representation (generally symbolic) directly referred to by the restoration knowledge.
 - . the numerical models working on a data base which constitutes the power system representation for the models.
 - . the user interface
 - . interface mechanisms between the expert system and the numerical models, between the expert system and the user interface, and between the restoration system (expert system and/or data base) and the power system (process or simulator) real time data.

0. **DOES THIS OVERALL STRUCTURE APPLY TO THE CONSIDERED RESTORATION SYSTEM**

- a Yes
- b No

If not, please specify

1. FUNCTIONAL OBJECTIVES OF THE SYSTEM

1.1. Indicate all the intended uses of the final system :

- a Preparing restoration plans off-line
- b Training the operators to restoration
- c Assist the operators during the restoration process
- d Automate the restoration process
- e Other (please specify)

If the described system is a prototype, describe also its intended uses towards the final system :

- f Final checking before putting the system into operation
- g Evaluation of the feasibility of the expert system approach to restoration
- h Basis for the detailed specification of the final system
- i Checking of the accuracy and completeness of the knowledge base
- j Other (please specify)

1.2. Indicate all the types of incidents for which the system is designed :

- a Loss of supply in a limited area after a local disturbance
- b Loss of supply over a wide area, but a large portion of the power system remains operational
- c Collapse of almost all the power system. The restoration requires the blackstart of some generating units or the assistance of a neighbouring utility
- d Other (please specify)

1.3. Indicate all the functions for which the system is designed :

- a Provide a clear picture of the status of the restoration
- b Evaluate a priori the feasibility and the merits of restoration options
- c Help the operator choose among various ways of initiating the restoration
- d Help the operator select intermediate restoration objectives
- e Display for the operator the applicable, pre-established restoration procedure
- f Develop in real-time detailed restoration plans based on the actual system conditions and the selected objectives

- g Check the security and feasibility of plans established by the operator
- h Implement detailed plans developed by the operator
- i Implement detailed plans developed by another module of the expert system and reviewed by the operator
- j Help the operator schedule resources (manpower, active generation capacity, reactive power reserves, etc...)
- k Alert the operator when dangerous situations arise
- l Coordinate the activities of the crews in the substations
- m Others (please specify)

1.4. What constraints does the system attempt to enforce ?

- a Voltage
- b Line flow
- c Dynamic stability
- d Standing angle
- e Load/generation balance
- f Others (please specify)

1.5. Indicate all the problems or difficulties that the system takes into account :

- a Faulted line
- b Faulted transformer
- c Faulted busbar
- d Broken switch or circuit breaker
- e Disabled substation
- f Unreliable communication link
- g Obstructive relay
- h Widespread damages due to natural disaster (hurricane, earthquake...)
- i Others (please specify)

2. POWER SYSTEM REPRESENTATION AND MODELLING

2.1. Indicate what are the levels of detail represented in the system

2.1.1. In the restoration system data base (see notice 2)

- a Areas, regions or islands
- b Stations, substations and corridors
- e Busses (nodes) and branches
- d Single elements, busbars
- e Devices (busbars, switches, lines, transformers, etc...)
- f Other (please specify)

2.1.2. In the expert system knowledge base (levels of detail manipulated directly by the expert system. see notice 2)

- a Areas, regions or islands
- b Stations, substations and corridors
- e Busses (nodes) and branches
- d Single elements, busbars
- e Devices (busbars, switches, lines, transformers, etc...)
- f Other (please specify)

2.2. Indicate which of the following elements are represented in the restoration system :

2.2.1. In the data base

- a Busbars
- b Lines and transformers (lumped elements/distributed constants, intensity limitations)
- c Power stations and generators
- d Loads
- e Reactances and capacitors
- f Breakers & switches (lumped switches, detailed switching, ground connectors)
- g Automatic devices, relays
- h Lower voltage levels elements
- i External area equivalent
- j Remote terminal units, substations computers
- k Crews
- l Other (please specify)

2.2.2. In the expert system knowledge base

- a Busbars
- b Lines and transformers (lumped elements/distributed constants, intensity limitations)
- c Power stations and generators
- d Loads
- e Reactances and capacitors
- f Breakers & switches (lumped switches, detailed switching, ground connectors)
- g Automatic devices, relays
- h Lower voltage levels elements
- i External area equivalents
- j Remote terminal units, substations computers
- k Crews
- l Other (please specify)

2.3. Load modelling

Please answer the following questions :

- Does the restoration system model loads :

- a By representing the distribution feeders
- b By aggregating them at a higher voltage level ?

In the latter case, what is the average size of an aggregate ?

- How does the restoration system determine the value of a given load ?

- c It uses the pre-blackout value
- d It uses a cold load pickup model, with time-related behaviour
- e It uses a conservative estimate
- f It uses another method (please elaborate)

- what are the voltage and frequency behaviour modelled in the expert system ?

2.4. Generation modelling

Which of the following characteristics of generating plants are modelled in the restoration system :

2.4.1. In the data base

- a Electrical parameters (please detail)

- b Xenon constraints (for nuclear power plants)
- c Auxiliaries demand and constraints
- d Frequency response
- e Ramping rate
- f Others (please elaborate)

2.4.2. In the expert system knowledge base

- a Electrical parameters (please detail)

- b Xenon constraints (for nuclear power plants)
- c Auxiliaries demand and constraints
- d Frequency response
- e Ramping rate
- f Others (please elaborate)

2.5. Network behaviour

Indicate which of the following physical phenomena are implicitly or explicitly modelled by the system :

2.5.1. In the data base

- a Line flow
- b Stationary voltage levels
- c Protective relays
- d Automatism (lack of voltage, service restoration, load shedding...)
- e Primary regulation
- f Behaviour of external network (external equivalents)
- g Transient phenomena
- h Stability
- i Others (please elaborate)

2.5.2. In the expert system knowledge base

- a Line flow
- b Stationary voltage levels
- c Protective relays
- d Automatism (lack of voltage, service restoration, load shedding...)
- e Primary regulation
- f Behaviour of external network (external equivalents)
- g Transient phenomena
- h Stability
- i Others (please elaborate)

2.6. Indicate all the numerical programs which can be called or otherwise relied upon by the restoration system :

- a Ac power flow
- b Dc power flow
- c Optimal power flow
- d Network sensitivities
- e State estimator
- f Transient stability simulation
- g Electromagnetic transient simulation
- h Other (please specify)

2.7. Indicate what are the measurands/indications available from the process (or simulator) database

- a Breaker states
- b Isolator states
- c Ground connector states
- d Measurands
- e Protection indications
- f Alarms

2.8. Miscellaneous

Indicate how the network model is generated :

- a Manually
- b With a specific network editor
- c Automatically from the process computer or system simulator

3. RESTORATION KNOWLEDGE IN THE EXPERT SYSTEM

3.1. Indicate and detail all the areas where knowledge is represented in the expert system

- a Identification of faulty devices
- b Selection of an initial source of power
- c Taking into account security constraints for nuclear power plants
- d Taking into account operational constraints for nuclear power plants (for instance : need for a quick power increase)
- e Selection of islands to be reconnected
- f Balancing of load and generation
- g Generating unit starting procedures
- h Generating unit operation procedures
- i Design of connection paths through the network
- j Sequencing of switching operations
- k Identification of potential voltage problems
- l Correction of potential voltage problems
- m Identification of actual voltage problems
- n Correction of actual voltage problems
- o Identification of potential line overloads
- p Correction of potential line overloads
- q Identification of actual line overloads
- r Correction of actual line overloads
- s Selection of loads to be reconnected
- t Estimation of the cold load value
- u Relaying problems
- v Synchronization of islands
- w Others (please specify)

3.2. Is the knowledge organized into hierarchichal levels ?

- a Yes
- b No

Please detail (for instance goal generation strategy, completion of individual operations,...)

3.3. What is the general approach to restoration ?

- a Heuristic search
- b Hypothesize and test
- c Case - based
- e Procedural
- f Other

3.4. If the expert system decomposes the restoration process into intermediate objectives, does it :

- a Determine all the feasible objectives ?
- b Choose or recommend an objective based on its intrinsic importance ?
- c Choose or recommend an objective based on global criteria such as an estimate of the time to completion of restoration ?
- d Use another approach ? (Please elaborate)

3.5. If the expert system develops detailed plans of operations, does it :

- a Minimize the number of operations required to execute each of these plans (switch openings, switch closings, tap adjustments, etc...) ?
- b Optimize the voltage profile ?
- c Optimize the branch flows ?
- d Rely on optimizations performed off-line ?
- e Use heuristic criteria ?
- f Explicitly optimize some other criterion ? (please explain)

does it use :

- g An algorithmic topology processing program
- h A heuristic search
- i Another approach (please elaborate)

3.6. Does the expert system deal with uncertainty and inconsistant information ?

- a Yes
- b No

If yes, explain how :

3.7. Does the expert system deal with time constraints ?

- a Yes
- b No

If yes, explain for which constraints and how :

3.8. Knowledge origin and acquisition

Knowledge origin :

- a Expert's know-how
- b Operation procedures
- c Model-based reasoning
- d Case-based reasoning

Knowledge acquisition :

- e Interviewing of experts
- f Written procedures
- g Theoretical studies
- h Others

Knowledge updating facilities :

- i Yes (please detail)

- j No

4. KNOWLEDGE ENGINEERING FEATURES

4.1. Indicate how the knowledge is represented and organized from the viewpoint of the expert system

Is the Knowledge represented and organized into :

- a Worlds
- b Composites
- c Knowledge sources
- d Classes
- e Objects
- f Facts
- g Rules
- h Other (please elaborate)

Indicate the approximate number of each one.

4.2. Inference mechanism

- a Forward chaining
- b Backward chaining
- c More sophisticated mechanism
(if any, describe the control mechanism)

4.3. Characteristics of the reasoning process

- a Qualitative
- b Quantitative (incertitude, fuzzy logic)
- c Involving temporal reasoning
- d Involving truth maintenance functions
- e Involving dynamic data updating
- f Other (please elaborate)

5. FACILITIES PROVIDED BY THE SYSTEM

5.1. Indicate the main planning and monitoring features

- a Dynamic or
- b Fixed planning
(during the preparation of the plan -partial or complete- is the network evolution taken into account, or is planning prepared only from a snapshot of the network ?)

→ Restoration actions monitoring :

- c Check plan steps are performed accurately and network evolves to the expected situation in the plan
- d Plan and check only one-step-ahead : suggest one action, wait till the action is performed, check results...
- e Independent of plan, only overall criteria followed

→ Replanning capabilities :

- f Backtracking
- g Partial plan amendment under change in the premises of the plan

5.2. What is the operator interaction with the planning procedure ?

- a Introduction of additional information (ie. new elements in fault)
- b Amendment of strategic planning and detail planning
- c Display results of intermediate steps

5.3. Describe the user interface

→ Graphic visualization :

- a Geographic representation
- b Line/substation diagrams
- c Synoptic representation

- d Employment of same representation as SCADA or
- e Specific development

- f Dynamic zoom and other facilities
- g Numerical data (time shapes etc...) having been considered for the inference process
- h Logic coherences of the expert system's decisions (explanation)

→ User dialog :

- i Pre-prepared questionnaire texts
- j Pre-prepared explanation texts
- k Questionnaire/explanation texts on line derived from rules contents

- l (Short term) verbal input
- m Mouse operated input
- n other (please elaborate)

5.4. Simulation capabilities

- a Based on the current state of the network, show the result of actions input by the operator
- b Show the result of the proposed restoration plan
- c Other (please elaborate)

5.5. Performance

Average time to solve a standard case :

6. SOFTWARE / HARDWARE IMPLEMENTATION

6.1. Is the expert system

- a Operating in stand-alone mode
- b Integrated with a training simulator
- c Integrated within a control center

6.2. What hardware platform is used for the expert system ?

6.3. What operating system is used for the expert system ?

6.4. What language or tool is used for the expert system ?

6.5. How does it interface with numerical programs ?

6.6. Describe the interface between the expert system and the process (SCADA) computer or the simulator. In particular :

- a Is selected process information such as alarm or event messages transmitted to the expert system dynamic storage ?
- b Is the content of the real-time database of the process computer copied in part or in full to the expert system dynamic storage area ?
- c Does the expert system access directly the real-time database of the process computer ?
- d Is another mechanism (or a combination of the above mechanisms) used ?

6.7. Implementation of the user interface

Type of display :

Graphics standard :

7. **PRACTICAL EXPERIENCE WITH THE PROTOTYPE/
SYSTEM**

7.1. **What are the means employed for testing the system ?**

- a Tested with hand-prepared cases from a file
- b On-line with a network simulator...
- c Recalling past perturbances
- d Do use of "figured out" cases
- c Other

7.2. **What is the experience from the system ; please highlight
the do's and dont's of the approach form the following
points of view ?**

- Development and installation of the system

- Performance of the system

- Maintenance

- Handling by the operators

8. **ANY OTHER COMMENT**

ANNEX 2 :
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OF THE SYSTEMS ANALYSED

BIBLIOGRAPHICAL REFERENCES

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