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**An intelligent load shedding approach to enhance the voltage
stability of a power system**

Vadari, Subramanian Venkata, Ph.D.

University of Washington, 1991

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AN INTELLIGENT LOAD SHEDDING APPROACH TO ENHANCE
THE VOLTAGE STABILITY OF A POWER SYSTEM

By

Subramanian Venkata Vadari

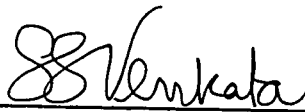
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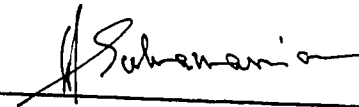
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Abstract

An Intelligent Load Shedding Approach to Enhance
The Voltage Stability of a Power System

by Subramanian Venkata Vadari

Chairperson of the : Professor S.S. Venkata
Supervisory Committee Department of Electrical
 Engineering

Load shedding can be defined as a coordinated set of controls which result in the decrease of electric load in the system. Load shedding may be initiated due to two reasons:

1. Frequency
2. Voltage

One of the differences between the two problems is - The frequency problem is a system-wide phenomena affecting the entire electrical island, whereas the voltage problem is generally localized.

The present day utility philosophy considers load shedding as a last resort in the emergency control of the system. This is understandable because the shedding of a load leads

to dissatisfied customers, decreased revenues, bad publicity, and possible litigations (depending upon the seriousness of the incident). Utilities try to avoid it as much as possible.

The objective of this dissertation is to perform an exhaustive study of the areas of load shedding and load management and recommend techniques for improvement (for the voltage problem). Two main accomplishments are presented. They are:

Expert Load Shedding (ELS), an intelligent operator's aid to help in load shedding is the result of the study of current load shedding practices, and intelligent methodologies. The method suggested in this document has been designed for implementation in an Energy Management System (EMS) environment. A prototype of the ELS has been implemented in the Dispatcher Training Simulator (DTS) which simulates an EMS environment. Preliminary results of tests performed using the ELS on an enhanced version of the New-England 345-kV system has proved very promising.

Expert Load Management (ELM) is an expert system which has been used to provide load relief (in a distribution system) in an emergency mode. Load Management (LM) is an application in the Distribution

Automation (DA) system which involves the process of controlling utility system loads by the remote control of individual customer loads. This expert system has been implemented in the EMS/DA environment and tested on the ODEC (Old Dominion Electric Cooperative) system. Preliminary results of the tests performed have proved very promising.

The main reason for the development of ELS and ELM are to enable the eventual linking of the two functions. It is the author's contention that a link between load shedding in the EMS and load management in the DA it would be possible to obtain load relief without actually tripping feeders.

TABLE OF CONTENTS

List of Figures	v
List of Tables	vi

CHAPTER 1 INTRODUCTION

1.1	LOAD SHEDDING	3
1.1.1	Present Day Electric Utility Philosophy	5
1.1.2	Utility Approach	6
1.1.3	A Brief History Of Load Shedding Incidents	7
1.1.3.1	Incident 1 [3]:	7
1.1.3.2	Incident 2 [7]:	8
1.1.3.3	Review Of Incidents	9
1.1.4	Review Of Literature Search	9
1.1.4.1	Summary Of Review	18
1.2	VOLTAGE INSTABILITY	18
1.2.1	Summary Of IEEE Working Group Findings	20
1.2.2	Review Of Voltage Related Incidents	22
1.2.2.1	Incident 1	24
1.2.2.2	Incident 2	24
1.2.2.3	Incident 3	25
1.2.2.4	Inferences From The Three Incidents	26
1.2.2.5	Industry's Wish List	27
1.2.3	State-of-the-Art Approaches	28
1.3	INTELLIGENT METHODOLOGIES	29
1.3.1	Real-Time Systems And AI	29
1.3.2	Requirements For Power System Applications	32
1.4	OBJECTIVES OF THIS DISSERTATION	33
1.5	ORGANIZATION OF THE DISSERTATION	34

CHAPTER 2 EXPERT LOAD SHEDDING (ELS) METHODOLOGY

2.1	WHY USE INTELLIGENT TECHNIQUES FOR LOAD SHEDDING ?	36
2.2	ELS DESIGN PHILOSOPHY - WHAT IS IT ?	40
2.2.1	User Interface (UI)	41
2.3	ELS FOR VOLTAGE STABILITY ENHANCEMENT	41
2.3.1	Area Identification	42
2.3.2	Reactive Power Mismatch Calculation	43
2.3.3	Modes Of Load Shedding Operation	46
2.4	THE ACQUISITION OF KNOWLEDGE	47
2.5	A TWO LAYER HEURISTIC SEARCH TECHNIQUE	48

CHAPTER 3 ELS SOFTWARE DEVELOPMENT

3.1	DTS ENVIRONMENT	53
3.2	ELS IMPLEMENTATION IN THE DTS	56
3.2.1	Integration In A Real-Time EMS.	58
3.3	DETAILS OF THE INTELLIGENT SYSTEM DEVELOPED	59
3.3.1	ELS Initialization Module	59
3.3.2	ELS Scheduled Processing	59
3.3.3	ELS Dynamics Processing	60
3.3.4	ELS Asynchronous Processing	60
3.3.5	Other System Utility Support	61
3.4	UI AND PERMITTED OPERATIONS	61
3.4.1	HABITAT{*} User Interface - A Brief Overview	62
3.4.2	Expert Load Shedding Display - A Description	63
3.4.3	Permitted Operations	66

CHAPTER 4 APPLICATION TO A PRACTICAL SYSTEM

4.1	DESCRIPTION OF THE TEST SYSTEM	69
4.2	TEST RESULTS	71
4.2.1	System Normal Operating Mode	72
4.2.2	Test Conditions	77
4.3	ELS IN ACTION	78
4.3.1	ELS In Action - Results	81
4.3.2	Inferences Drawn From Testing	82

CHAPTER 5 LOAD MANAGEMENT AS THE DISTRIBUTIVE ARM OF LOAD SHEDDING

5.1	INTRODUCTION	84
5.2	THE ODEC DA PROJECT	87
5.2.1	Load Management (LM)	90
5.2.2	Nicking	92
5.2.3	Scram	93
5.3	EXPERT SYSTEM SHELL DEVELOPMENT	94
5.3.1	Database Structure Of The Knowledge Base	96
5.3.2	The Inferencing Process	98
5.4	EXPERT LOAD MANAGEMENT (ELM)	99
5.4.1	Smart_operator:	101
5.4.2	Smart_nicking:	101
5.4.3	Smart_scram:	102
5.5	SOME EXAMPLE RULES	103
5.6	DESCRIPTION OF THE TEST SYSTEM	105
5.6.1	Test Results	105
5.6.2	Inferences Drawn	106

CHAPTER 6	CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH	
6.1	CONCLUSIONS: WHAT HAS BEEN ACHIEVED	110
6.1.1	Expert Load Shedding	110
6.1.2	Expert Load Management	111
6.2	DIRECTIONS FOR FUTURE RESEARCH	112
6.2.1	Expert Load Shedding	113
6.2.2	Expert Load Management	113
6.2.3	Combination ELS And ELM	114
REFERENCES	116

List Of Figures

1.1	Power System State Transition Diagram	2
2.1	Reactive Power Mismatch Calculation	45
2.2	Conceptual Diagram of Two-Layer Heuristic Search Technique	49
3.1	DTS - An Overview	54
3.2	ELS Integrated into the DTS Environment	57
3.3	ELS Master Display	64
3.4	ELS Master Display - Help Page	67
4.1	Overview Diagram of the Test System	70
4.2	ELS Test Results	79
5.1	The Utility System with Distribution Automation	85
5.2	ODEC System Software Overview	89
5.3	ELM: Software Design Overview	100
5.4	Test Scenario I	107
5.5	Test Scenario II	108

List Of Tables

4.1	System Generation	72
4.2	System Loading	73
4.3	Bus Voltages	74
4.4	Line Flows	76

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Dedication

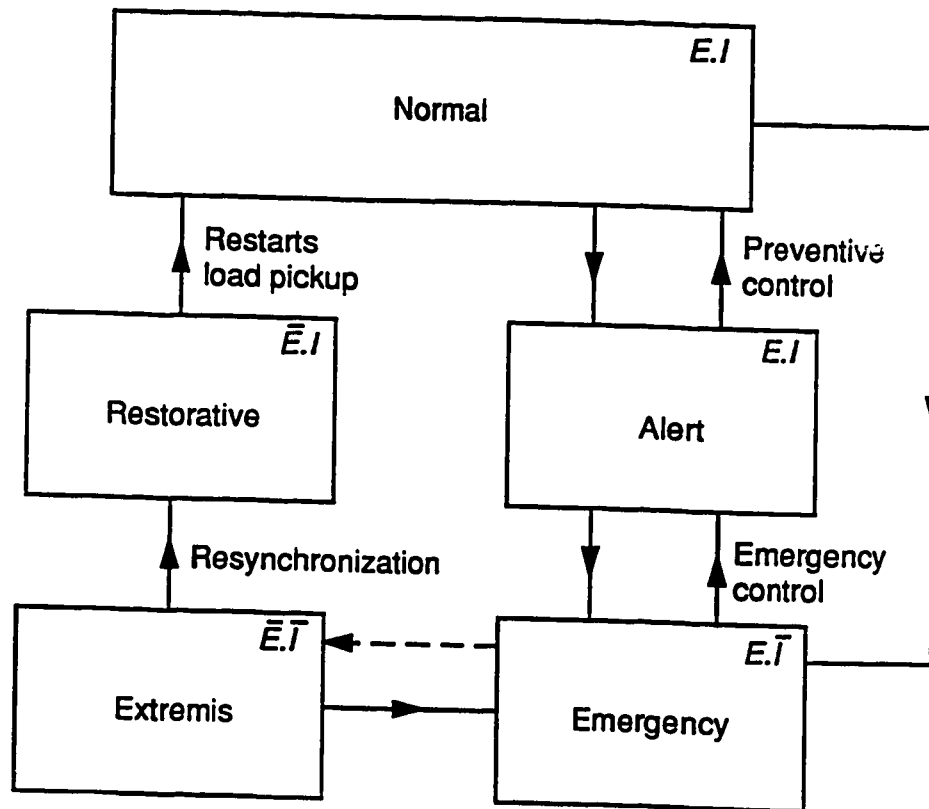
This dissertation document is dedicated to my parents Sarala and Ramachandran Vadari, my brother Viswanathan, and my sister Meenakshi whose love and affection kept me going through all the ups and downs of this dissertation work.

CHAPTER 1

INTRODUCTION

In its simplest form, a power system contains generators (which generate power), loads (which consume power) and transmission lines which transmit power from the generators to the loads. All the generators in a power system are not located in one place, and this situation is true for loads also. Thus the transmission lines form a network with generators and loads at different points. The flow of power through the transmission lines are controlled by various controllers, for example, tap-changing transformers, capacitors and others. A variety of constraints govern the actions of these controllers, one of which is the flow limit of real power on these lines.

Dyliacco [1,2] and Fink and Carlsen [3] have suggested that a power system may be operated in several different states. Figure 1-1 **Power System State Transition Diagram** names the states and the conditions under which the system exists in that state.



E = Equality constraint is satisfied
 I = Inequality constraint is satisfied
 \bar{E} = Equality constraint is violated
 \bar{T} = Inequality constraint is violated

Figure 1-1: Power System State Transition Diagram

The equality constraints (E) (shown in the figure) are the match between generation and demand (both for real and reactive power). These constraints are a fundamental prerequisite for normalcy. The inequality constraints (I) must also be observed for the system to remain in normal state. One example of an inequality constraint is that 'Flow of power through the transmission lines must be below the rated thermal or stability limits'.

When a system is in the emergency state, certain control actions are performed which attempt to restore the system back to the normal state. Load shedding has been recognized as one of them.

The theme of this dissertation stresses the following important concepts: 1) Load shedding, 2) Voltage stability, and 3) Intelligent methodologies. The objective of this first chapter is to describe these three terms more clearly and explain their significance.

1.1 LOAD SHEDDING

Load shedding can be defined as a coordinated set of controls which results in the decrease of electric load in the system. It is generally done to save the system from deteriorating to an (in) extremis [3] state from either the emergency or the alert state. It is a preventive measure

which is undertaken to protect the integrity of the power system network.

A load shedding problem can occur due to two reasons:

1. **Frequency:** Frequency problems occur when there is a generation-load (MW) imbalance. Some of the reasons for this could be the sudden loss of a generating unit or the sudden loss of a transmission line (or tie- line) which leads to an islanding situation. The major symptom is the rapid change in frequency in a few seconds.
2. **Voltage:** Voltage problems are generally due to a reactive power (Mvar) imbalance. They happen when various generating units have already reached their reactive power limits and the voltage magnitudes of some of the buses go below the desired level of 5% (say). One of the symptoms in this case is the formation of areas of low voltage. Also, one would expect relays to trip (on undervoltage) and motors to overheat (due to stalling on undervoltage). The voltage decay phenomenon occurs comparatively slower than the frequency but is equally important. If neglected, it could lead to the voltage collapse of the system [4]. The voltage problem can also occur if an overload situation exists in an area.

Voltage and frequency problems differ in yet another area. Frequency problems are system-wide phenomena affecting the entire electrical island, whereas voltage problems are generally localized. These differences also warrant the use of different methods to control them.

1.1.1 Present Day Electric Utility Philosophy

The present day utility philosophy considers load shedding as a last resort in the emergency control of the system. This is understandable because the shedding of load leads to dissatisfied customers, decreased revenues, bad publicity, and possible litigation (depending upon the seriousness of the incident). Utilities try to avoid it as much as possible.

Utilities nowadays are facing challenges of a very different nature. Loads are increasing at a faster pace than forecast by their planning experts. There are, on the other hand, no plans for any increase in generation capacity to meet this unexpected increase in load. Utilities are operating closer to their stability limits all the time with diminishing generation reserve margins. This puts tremendous stress on utility operators. Also, planners need to re-orient their thinking on the utility philosophy regarding the handling of these problems.

The Wall Street Journal has very recently reported [5] that *power shortages are expected to hit much of the U.S. especially New England, New York's Long Island, and possibly the Mid-Atlantic states as early as this summer (1988). This means rolling brownouts or blackouts in the rural and suburban areas are a distinct possibility as utilities are forced to temporarily cut off energy in one place and then another in order to avoid a systemwide blackout.*

1.1.2 Utility Approach

The differences between voltage and frequency problems (as mentioned above) lead to a difference in the approach used by the utilities to alleviate them. The Northeast Power Coordinating Council's guidelines for load shedding [6] are as follows,

1. Frequency: The frequency problem is handled by underfrequency relays which should be set to shed at least 10% of the load at a nominal set point of 59.3 Hz, and an additional 15% of the load at 58.8 Hz. These measures are designed to return frequency to at least 58.5 Hz in 10 seconds or less and at least 59.5 Hz in 30 seconds or less, for a generation deficiency of up to 25% of the load. Further, any member may initiate additional load shedding at 58.3 Hz.

2. Voltage: An area may employ automatic undervoltage load shedding of selected loads to enhance power system security. It may employ automatic tie line overload shedding or shedding of selected loads to enhance the system security.

Note: From these guidelines it is clear that the voltage issue has not received adequate attention thus far.

3. Manual Load Shedding: Each area must be capable of shedding at least 50% of its load in ten minutes or less. Insofar as is practical, the first half of the manually shed load should not include that load which is part of any load shedding plan. Care should be taken that manual load shedding plans do not interrupt transmission paths. The plan should include the capability of shedding loads proportionately over the whole system, but it must also recognize that operating requirements may limit shedding to one area.

1.1.3 A Brief History Of Load Shedding Incidents

1.1.3.1 Incident 1 [3]: - One 345 kV line was out of service for maintenance. A fault occurred on a parallel overloaded 345 kV line when it sagged into a tree. Automatic reclosure was unsuccessful. Either the fault or

the attempts at automatic reclosure apparently created an electrical transient that contributed to the heating of a feed water control valve at a nearby generating unit. This unit tripped on low water level 20 seconds after the initial fault, causing a loss of 520 MW of generation. Overloading compounded by additional malfunctions, resulted in the formation of five islands. A total of 1650 MW of load was lost. Over 90% of the load was restored within 30 minutes of the initial event. Automatic load shedding was believed to be an important factor in limiting the extent of damage to the system.

1.1.3.2 **Incident 2** [7]: - On 18 April 1988, 85% of Quebec province lost electricity. A series of simultaneous short circuits during a severe ice storm has been pinpointed as the cause of the mammoth blackout. According to Hydro-Quebec, the short circuits affected all three phases of the Arnaud 735 kV substation near Sept-Iles. The sequence of events completely isolated the Churchill Falls generating station from the Hydro-Quebec system. The loss led to disruptions across the whole system leading to a complete collapse.

Hydro-Quebec reiterated that the automatic load shedding initiated by the loss of Churchill Falls did not operate as required, leading to a systemwide blackout. "A complete reliability review of this system is being undertaken," the

utility said.

1.1.3.3 Review Of Incidents - A careful review of the two incidents show that load shedding was successfully applied in the case of the first incident and not in the case of the second incident. These two incidents also show that load shedding is an important mechanism to preserve the security of the system. Also, it should be done more reliably and intelligently.

1.1.4 Review Of Literature Search

A literature search is conducted in the area of load shedding. The set of papers reviewed were published during the period 1968 - 1989 and are relevant to the area of load shedding. The techniques used range from conventional techniques to the expert system (for load shedding). A critical review of some of the key papers is presented below.

Paper #1 : An Efficient Computer Technique for Optimal Load Shedding in Power Systems (S.A. Farghal, K.M. Shebl, and A.A. Abou EL-Clä)

This paper [8] presented a load shedding strategy to be effective under emergency conditions in an interconnected power system. The three main objectives are:

1. Restoration of generation-load balance in the system.
2. Minimization of load to be shed
3. Satisfying prioritization of every load to be shed.

The problem is formulated as a multi-objective linear programming problem. The three objective functions minimized are

1. satisfy load priority during load shedding,
2. minimize amount of load to be shed at bus i , and
3. minimize the transmission line losses.

The loads at each bus are arranged such that they are given a priority number which increases with importance. The solution minimizes the amount of load to be shed at bus i , and at the same time takes care of the generation rescheduling maximize the incremental change in generation level.

The minimization of transmission losses should not be a part of the main objective function and should be secondary because of the degree of complexity introduced by it. Also, the authors have not considered voltage constraints which tend to take on great importance during emergency

conditions.

Paper #2: Optimal Load Shedding Policy for Power Systems
(L.P. Hajdu, J. Peschon, W.F. Tinney, and D.S. Percy)

This paper [9] discusses a systematic approach towards minimizing the curtailment of service in a power system after a severe fault. The problem is formulated as a static optimization problem subject to operational and equipmental constraints. The computational procedure is based on the Newton-Raphson technique and Kuhn-Tucker equations for optimization. The main objectives of this study are:

1. Supply the minimum vital local demands like auxiliaries of power plants and other industrial with high priority.
2. Ensure that the system will not deteriorate further due to overloading of one or more transmission lines.
3. Minimize the degradation of service to customers.

The solution technique suggested in this paper has merit because of certain practical implications which have been considered. However, the authors did not consider the stability problem and also did not mention selective load shedding schemes to incorporate priority of loads such as hospitals. Finally, the effects of simplification of the

objective function and the use of the decoupled power flow should be studied with more care.

Paper #3: Real Power Rescheduling and Security Assessment
(R.T. Bui, and S. Ghaderpanah)

This paper [10] presented a method which would solve the problem of real power rescheduling to satisfy a set of load changes. It also has the capability of handling line outages, generation outages, load curtailment, and maximum load distribution. The objective function tries to minimize the total transmission losses, total generation cost (assuming linear generation cost curves), and maximize the load distribution. The inequality constraints consist of limits on real power generation, real power demand, and phase angles.

The solution technique used ISML subroutines for the linear programming problem. The tests were performed on the IEEE 14-bus system. The authors claimed good computing speed and expected it to be suitable for online implementation.

The solution methodology is not very clear as the authors have not explained the components of the objective function. Furthermore, the assumptions and simplifications were not adequately justified. Also, the load curtailment did not consider the effect of reactive power imbalance.

Paper #4: Optimum Load Shedding Taking Into Account of Voltage and Frequency Characteristics of Loads (K.A. Palaniswamy, J. Sharma, and K.B. Misra)

This paper [11] presented a scheme for optimal load curtailment with considerations of the effects of generator control, and the voltage and frequency characteristics of loads. The objective function minimizes the real and reactive power curtailment keeping in mind the deviation of frequency caused by control actions. The constraints include:

1. Generation constraints: Here the effects on governor control is incorporated.
2. Load constraints: This model has both voltage and frequency dependency characteristics (exponential) of the loads.
3. System equations: These are the power-flow equations.
4. Voltage regulation constraints.
5. Transmission line flow constraints (either stability-limited or thermal-limited whichever is applicable)

In this load curtailment method, the equality constraints (1,2, and 3 above) are first absorbed into the objective function. Next, the constrained optimization problem is

converted into an unconstrained problem by incorporating the violating constraints (4 and 5 above) into the objective function using penalty factors. The objective function is then decoupled into two parts. The first part deals with voltage and reactive power, and the second part deals with real power and voltage angles. The two subproblems are solved iteratively until the required convergence is obtained. A second order gradient technique is employed for this solution.

The solution technique takes into account several factors which are important for the problem domain. However, the solution process is so elaborate that this would be a better method for detailed planning than for on-line implementation.

Paper #5: Power Mismatch Detection and Estimation for Emergency Control (N. Cukalevski, and M. Calovic)

This paper [12] proposed a centralized control strategy for the emergency control of a power system. Low order dynamic observers are proposed to estimate the magnitude of power imbalance using locally available measurements of frequency and tie-line power flows. This method is especially useful for interconnected power systems which import/export large quantities of power. This is due to the reason that the loss of a generator in such a system may not cause a large change in the frequency but may change the tie-line flow

more significantly.

The paper analysed the problem of power system emergency control during a fast developing viability crisis. An area-wide centralized control scheme, with fast structural action on demand/generation based active power mismatch detection and estimation, was proposed. The detection and estimation of power mismatch is a very important part of load shedding. This approach has merits and warrants further study because if the algorithm can be implemented efficiently, it would be of great use at the EMS center.

Paper #6: Local Load Shedding (M.M. Adibi, and D.K. Thorne)

The paper [13] presented a new method to implement load shedding in an Underground Transmission Network (UTN). Equipment overloads in UTNs are generally caused by unscheduled outages. Repairs and/or replacements of equipment in urban areas are inherently difficult and often time consuming. Hence the author felt that there was a need for a Local Load Shedding (LLS) scheme. The first order of importance in the LLS is to relieve the overloaded equipment within the time limits imposed by the equipment's short term ratings. The second order of importance is to 'minimize' the amount of load to be curtailed.

Basically the LLS scheme operates in two stages. In the

first stage, the overloaded equipment is identified, the location and amount of load to be shed are determined and the identified loads are removed. In the second stage, the same post-outage data is used to 'optimize' the UTN by adjusting voltage ratios and phase angles of transformers and regulators. The data from the 'optimized' UTN is then used to determine how much of the shed load can be restored.

UTNs are generally placed in heavily loaded urban areas where the speed of operation is critical. However, this method had certain drawbacks:

1. Load shedding is essentially a transmission level problem and it is not known how many transmission networks are underground. The problem scope is narrow.
2. The author claimed to have total control over the shedding of load, but still referred to a pre-specified load shedding list from which the loads are shed.

At this point it needs to be pointed out that this paper seems to be the best from the point of view of implementation since it has some practical considerations.

Paper #7: A Heuristic Approach to Load Shedding Scheme (S.

Shah, S.M. Shahidehpour)

This paper [14] presented an expert system approach to the load shedding problem. The authors basically start with the same set of assumptions made by Adibi [13] (see section 1.1.4.6) and also present the two-stage approach.

The quick estimate of how much to shed is based on two procedures.

1. Flow distribution: This is a procedure used to calculate the flow reduction prescribed for each line. An overload factor for a line, defined as the ratio of the overload in line 'i' to the actual real power flow in the line 'i' is used for the calculation.
2. Load Decrement: This procedure is used to determine the amount of load to be shed at each bus based on the flow reduction calculated earlier. The load to be shed at a bus 'j' is determined as the difference between the overload on the incoming lines and the overload on the outgoing lines.

The second stage which consists of the optimization of network flows for the partial restoration of some of the loads is accomplished by adjusting the phase shifter angles at the transformers.

In this paper the authors calculated the amount of load to be shed at a bus based on the differences between the incoming and outgoing overloads. This calculation seems questionable [15]. Also, in the network flow optimization stage, the authors seem to be considering only the actions of the phase shifter which seems to be inadequate and its effects limited as can be seen in their results. However, this seems to be a promising paper and has merits.

1.1.4.1 Summary Of Review - The set of seven papers [8-14] which were reviewed represent a fairly complete overview of the problem. The solution techniques vary from standard optimization algorithms (e.g. the use of linear programming) to the artificial intelligence approach. These papers have made significant contributions towards an understanding of the concepts of load shedding. However, the methods suggested in these papers do not directly lend themselves to real-time applications in an Energy Management System (EMS) environment. The requirements for EMS implementation expect the design to handle direct database accesses, user interface, and a real-time design philosophy which is discussed later in Section 1.3.1. Thus, it is the author's contention that additional research is needed in this area.

1.2 VOLTAGE INSTABILITY

The problem of voltage instability (or voltage collapse) can be simply defined as the inability of the power system to supply the reactive power (to the system) or by an excessive absorption of reactive power by the system itself [16].

The phenomena of voltage collapse [4] is characterized by a progressive decline of voltage in one or more consumer regions, a fall which accelerates after a few minutes and which is typically accentuated by the action of on-load tap changers (LTCs). This often happens due the operation of the power system close to its maximum power transfer capability (stability limit). This problem usually occurs due to disturbances or significant differences between the load forecasts and actual load. In order to preserve the security of the system, during an unusually severe situation, meaningful precautionary measures are taken. These include the locking of transformer on-load tap changer mechanism and **preventive load shedding**.

The use of preventive load shedding has already been recognized by NERC as being beneficial in preserving system security under emergency conditions. To quote the emergency operations section of the NERC operating manual [17]: ***"If a transmission facility becomes overloaded, or if voltage levels are outside established limits and the condition cannot be relieved by normal means such as***

adjusting generation or interconnection schedules, and if a credible contingency under these conditions would adversely impact the interconnection, appropriate relief measures, including load shedding, shall be implemented promptly to return the transmission facility to within established limits. This action shall be taken by the system, control area (AGC control), or pool causing the problem if that system or control area can be identified, or by other system or control areas, as appropriate, if that identification cannot be readily determined."

1.2.1 Summary Of IEEE Working Group Findings

The IEEE Working Group on Voltage Stability has been studying the problems of voltage stability. Following are some of their findings [18].

Definitions:

- o **Voltage Stability:** The ability of a system to maintain voltage so that when load admittance is increased load power will increase, and so that both power and voltage are controllable.
- o **Voltage Collapse:** The process by which voltage instability leads to loss of voltage in a significant part of the system.

- o **Voltage Security:** The ability of a system, not only to operate stably, but also to remain stable following any reasonable credible contingency or adverse system change.

Voltage problems may be initiated by one or a combination of the following:

- o Load increase (real or reactive)
- o Loss of a generator (not necessarily loss of real power in MWs)
- o Loss of shunt compensation
- o Drop in sending end voltage
- o Loss of transmission

A review of the mechanism of voltage collapse shows the following events occurring in (approximately) sequential order:

1. Residential load (active and reactive) drops, industrial load changes insignificantly, shunt compensation drops, and drop in residential load may reduce line loading.

The above may almost offset each other and the voltage would temporarily stabilize at a low value.

2. Operation of distribution LTCs to restore voltage: Residential load increases, and industrial load effectively decreases.
3. As voltage sensitive loads (for example, modern lighting) creep back, primary and secondary voltages drop further. Marginal motors on the primary may stall, bringing the voltage down further - less capacitive charging - more motors stall
4. Motor protection (relays and/or contractors) may trip many motors which relieves the situation provided that voltage does not get too high and trip lines.
5. Generators reactive contribution may be limited manually or automatically, in the process.

Thus, it can be seen that the voltage problem can be fairly complex having an extensive effect on the entire power system. This can affect the system performance significantly and therefore needs careful attention in alleviating it.

1.2.2 Review Of Voltage Related Incidents

The IEEE Working Group has also studied many incidents reported by the utilities in the area of voltage stability

[18]. Three of the more significant incidents are reported in the following sub-sections because of their relevance to this work. In addition, some conclusions which could be drawn and a list of requirements for analytical tools are also reported here.

An EDF (Electricite De France) survey of 20 voltage incidents [also in 18] provided the following information:

1. Before the disturbance

- Systems were highly loaded.
- Systems were weak because of equipment outages.

2. The disturbance

- More than half the cases were initiated by the outage of only one more element.
- Several cases were initiated by bus faults.
- In all cases, there was at least one event described as "should never occur".

3. Post disturbance

- Delay of restoration is often caused by severe mismatches between the various parts of the network.

1.2.2.1 Incident #1 - Japanese system collapse (23 July, 1987):

The noon temperatures were at a record high. The end-of-lunch-hour demand which was already at a high of 38,200 MW started to increase at exactly 1:00 pm (everyone returning from lunch). The rate of increase in real power load (MW) was approximately 400 MW/min (the highest ever noted in the Tokyo system). The system voltage gradually dropped and the capacitors started to switch in. The contribution of the capacitors was overwhelmed by the reactive power (Mvar) losses causing further deterioration. In 19 minutes, the voltage in the 500 kV system dropped to 370 kV in the West and 390 kV in the Central part. Three substations were tripped with a cumulative loss of 8168 MW of load affecting 2.8 million customers.

1.2.2.2 Incident #2 - The French system (19 December, 1978):

A rapid increase in load (4600 MW in one hour) was observed between 7 am and 8 am. This was attributed to severe cold weather. This resulted in heavy transfer of power to the Paris area leading to increased reactive power (Mvar)

losses. Some of the 400 kV transmission lines became overloaded and a strong voltage deterioration was observed for about 26 minutes. The operators tried to correct the problem by blocking some of the EHV/HV (Extra High Voltage/High Voltage) LTCs and a mandatory 5% drop in voltage in some areas was ordered and the voltage stabilized at low levels. At 8:26 am, a 400 kV transmission line tripped on overload, resulting in cascaded overloads and tripping of other lines. The entire system collapsed in 18 seconds thereafter.

1.2.2.3 Incident #3 - The French system (12 January, 1987):

At 10:30 am, the operating reserve was noted at 1900 MW (7%). Three large thermal units in the Western region tripped followed by a fourth on field overcurrent protection between 10:55 and 11:42 am (the generator field is responsible for the reactive power support. Hence, the tripping of generator on field overcurrent protection indicates a severe need for reactive power in the system). Subsequently nine other units tripped between 11:45 and 11:50 am. At 11:50 am, the voltage level of the 400 kV in the Western region stabilized at 300 kV. In some areas it even dropped to 240 kV. To correct, the operators shed 1500 MW of load by tripping some 400/225 kV transformers feeding a particular region. This action stabilized the system to a new acceptable state.

1.2.2.4 **Inferences From The Three Incidents** - There were no faults or abnormal conditions which preceeded the failure of the Japanese system (incident #1). This was a slow deterioration of the system and as the voltage decreased, the air conditioning equipment (being mostly induction motor load) drew more vars as the voltage declined. Also, shunt capacitors (which have traditionally been viewed as the main source of reactive support in the case of emergencies) did not solve the problem either.

The French system on the other hand (incidents #2 and #3) exhibited a different scenario. Incident #2 showed a case where the heavy transfer of power to a load center led to line tripping, followed by a cascaded series of trippings leading to a total system collapse. Incidents #3 on the other hand, had a different set of problems, wherein four major generating units tripped causing a severe reactive power shortage. In this case, however the system was saved by shedding 1500 MW of load and thus alleviating the reactive (and real) power imbalance.

These three incidents are selected to demonstrate that load shedding applied judiciously can save the system from voltage collapse. In the case of the Japanese system, there was no disturbance to the system. The system just could not handle a reactive support at the level required of it. The first French incident was the classic case of

the severely overloaded system which just collapsed when a critical disturbance occurred. In the second French incident, good judgement by the operators (and also thorough study of the first incident) prevented the collapse of the entire system.

1.2.2.5 Industry's Wish List - The Industry (as reported by the IEEE Working Group on Voltage Stability [18]) has decided that *in spite of the efforts reported by various utilities, much of the basis of the analysis and application (of new techniques) is arbitrary and judgemental.* The industry's wish list is as follows:

1. Analytical tools

- o Accurate ways to quantify voltage stability margins.
- o Direct ways of predicting voltage collapse in complex networks.
- o Definitions of voltage related transfer limits.
- o Identification of voltage weak areas.
- o Identification of key contributing factors.

2. Planning and operational guidelines

- o Coordinating mixture of passive and active compensating devices.
- o var reserves and stability margins.
- o Coordination of protective devices.
- o Reactive compensation through generator AVR's (Automatic Voltage Regulator).
- o Guidelines for manual intervention.

1.2.3 State-of-the-Art Approaches

Voltage stability is slowly becoming recognized as a major cause of concern by the utility industry. Three different research groups are investigating this problem from different directions. The first group [19,20] is investigating the causes of voltage stability. Their focus is on arriving at suitable models for understanding the problem so that if the cause is known, then the problem can hopefully be solved. The second group [16, 21, 22, 23, 24] is investigating remedial measures to save the system if voltage collapse is imminent. The third group [25, 26] is investigating methods for recognizing the vulnerability of a system to voltage collapse.

The work presented in this dissertation falls within the scope of the second group's efforts.

1.3 INTELLIGENT METHODOLOGIES

Artificial Intelligence (AI) is the part of computer science concerned with designing intelligent computer systems, that is, systems that exhibit the characteristics associated with intelligence in human behavior - understanding language, learning, reasoning, solving problems and others [49]. Since the field first evolved in the mid-1950s, AI researchers have invented dozens of programming techniques that support some sort of intelligent behavior. Many believe that insights into the nature of human mind can be gained by studying the operation of such programs.

Whether or not they lead to a better understanding of the mind, there is every evidence that these developments will lead to a new, *intelligent technology* that may have dramatic effects on society at large.

1.3.1 Real-Time Systems And AI

In real-time computing, the correctness of the system depends not only on the logical result of the computation but also on the time at which the results are produced [28]. Real-time computing systems play a vital role in

society, and they cover a spectrum from the very simple to the very complex. Some examples of real-time computing systems include the control of automobile engines, command-and-control systems, nuclear power plants, process control plants, and others. Some examples of real-time processing in the area of power systems include alarm processing, Automatic Generation Control (AGC), emergency control (Load shedding), state estimator, and others.

The following are some of the characteristics of real-time problems [28 - 31]

- o The operating state is dynamic. The output of the real-time process will affect this operating state. Hence, it is imperative that the output must be ready before the operating state changes. Otherwise, the output of the real-time process is obsolete.
- o The problem solver must face a limited search horizon. This is due primarily to computational and/or informational limitations.
- o A related characteristic is that in a real-time setting, actions must be committed before their ultimate consequences are known.

- o A final and a very important characteristic is that, often the cost of action and the cost of planning can be expressed in common terms, giving rise to a tradeoff between the two.

Heuristic search is a fundamental problem-solving method in artificial intelligence [32]. For most AI problems, the sequence of steps required for solution is not known *a priori* but must be determined by a systematic trial-and-error exploration of alternatives. The task typically is to find the lowest cost sequence of operators that map the initial state to the goal state. A real-world example is the task of autonomous navigation in a network of roads, or arbitrary terrain, from an initial location to a desired goal location. A typical heuristic evaluation function for this problem is the airline distance from a given location to a goal location.

There are several known algorithms which perform heuristic search. One of the best known of them is A* [33]. Iterative-Deepening-A* (IDA*) [34] is a modification of A* that reduces its space complexity in practice from exponential to linear. However, the drawback of both A* and IDA* is that they both take exponential time to run in practice. As observed by Simon [35], however, it is relatively rare that optimal solutions are actually required, but rather near-optimal or "satisficing"

solutions are usually perfectly acceptable for most real-world problems. The A* algorithm will be further studied later in this dissertation.

1.3.2 Requirements For Power System Applications

The following points need to be kept in mind in developing an intelligent control system for power system applications:

1. The basic components of an intelligent system:
 - o Knowledge base
 - o Inference engine
 - o Database
 - o User Interface
2. Key factors to be considered for a good implementation (for power system applications) [36-37]:
 - o It must be compatible with, or make use of, the existing mathematical software.
 - o It must be capable of directly accessing the main real-time database.

- o The user interface planned for it should be in line with the existing user interface.
 - o It must produce a response before that response becomes obsolete.
3. Careful analysis of the problem environment. In the case of work reported here, the problem domain is within the Energy Management System (EMS) environment:
- o The system is already implemented and the technology is fairly mature.
 - o The system data (network, generation, and SCADA data) is typically placed in databases. SCADA is the Supervisory Control And Data Acquisition part of the EMS.
 - o The user interface methods are also fairly mature.

1.4 OBJECTIVES OF THIS DISSERTATION

The primary objective of this dissertation is to propose, justify, and describe the development of an intelligent approach to the load shedding problem. The following actions were taken to reach the dissertation objectives:

1. Investigate causes (what are the various power system conditions which require the shedding of load ?),
2. Perform a critical review of existing solution techniques (How is it presently implemented ?),
3. Identify new and intelligent techniques (How can the existing technique be improved ?),
4. Implement one of the new techniques and prove its improvement over existing techniques.

The shedding of a load results in the disconnection of a power system feeder. The feeder is typically the entrant into the distribution system. Load management is an application in the Distribution Automation (DA) environment and one of its functions is to decrease the load in a system without actually tripping circuit breakers. More information about distribution automation and load management is provided in Chapter 5. A logical extension of load shedding in the EMS domain is to link it to load management in the DA domain. Some preliminary results are reported in this dissertation.

1.5 ORGANIZATION OF THE DISSERTATION

The dissertation document is organized as follows: Chapter 1 provides an introduction to the whole document. Its sets

the tone of the document by explaining the important terms which form the basis of the dissertation. Chapter 2 describes the Expert Load Shedding (ELS) design philosophy and also an insight into the design methodology. The three main modules of ELS are described here. Chapter 3 describes the ELS implementation. The ELS is installed in a DTS (Dispatcher Training Simulator) environment. The implementation is described in fair detail to provide the reader with an understanding of the intricacies of software design. The application of ELS to a real power system model is described in Chapter 4. Here, the working of ELS is compared with existing techniques (to control voltage instability) to demonstrate its superiority. Chapter 5 augments chapters 2-4 in that it describes an expert system implementation to aid load management (this is in the distribution automation environment) during emergency control. Lastly, Chapter 6 presents the conclusions of this dissertation and recommendations for further research in this and related fields.

A fairly exhaustive and complete bibliography is provided at the end under Chapter 7. The bibliography covers reference material that explains most of the topics covered in this document.

CHAPTER 2

EXPERT LOAD SHEDDING (ELS) METHODOLOGY

2.1 WHY USE INTELLIGENT TECHNIQUES FOR LOAD SHEDDING ?

Power systems are characterized by a large number of variables, and the dynamics of operation under conditions of extreme stress are difficult to predict. When a severe fault condition develops in the system, the subsequent electrical stress leads to intolerable deviations from the standard 60-Hz frequency. The imbalance between the reduced available generation at 60-Hz and the system power demand leads to generator trippings and inevitable interruptions in service. This is the type of situation where events could happen so quickly, the operator may

1. lack the complete information (data) desired,
2. have insufficient knowledge, or
3. have inadequate time to digest the information to react in the best and timely fashion.

The decision-making process of how much load to shed and

where, varies from situation to situation and does not follow any algorithmic pattern. It is very heuristic in nature and involves considerable amounts of operator judgement. Very often, the key factor is the expertise of the operator handling the crisis.

Power systems are very complex systems. This complexity results in the generation of vast quantities of data which in a typical EMS is processed in various steps. Some of these steps are:

1. SCADA obtains the data and converts them from raw telemetered values into engineering units. It also performs certain data quality checks and limit checks for alarms.
2. A state estimator uses the SCADA values to estimate the state of the power system.
3. Various network applications like Power Flow, Contingency Analysis, and others use the state estimator output and perform their respective analyses.

The various manipulations performed on the data are purely algorithmic in nature and follow certain strict procedures. As a result they cannot be applied to another class of problems which are not strictly procedural.

Load shedding is used mostly in the emergency mode, when there is a significant generation-load imbalance. The present day implementation consists mainly of underfrequency relays and undervoltage relays. A number of factors need to be considered:

- o The time domain for the voltage problem is of the order of minutes, whereas the frequency problem is of the order of several milliseconds. Thus there is more time to react in the case of the voltage problem.
- o One of the main symptoms of a voltage problem is the formation of localized areas of low voltage. The low voltage area can be recognized/identified in small systems manually, but when the system is large (of the order of 1000+ buses), it is not a trivial task. It requires some 'intelligent' diagnosis capabilities.
- o Operator intervention is needed whenever load is being shed in the system. This is because indiscriminate shedding of load leads to dissatisfied customers, decreased revenues, bad publicity, and possible litigations (depending upon the seriousness of the situation). Whenever a load is shed, an explanation for the shed action is required. The use of an operator's aid fits

very well with this scenario.

A good approach for load shedding must also take into consideration some of the following dynamic information:

- o loading conditions of the network,
- o network topology,
- o source of the problem,
- o tie line flows,
- o interchange schedules,
- o equipment down for maintenance, and
- o generation reserve margin.

For a typical utility, the above mentioned list can form quite a formidable quantity of information.

Looking into the future, one can envisage power system load increasing but it does not seem to be offset by an equal or even comparable increase in generation capacity and few new transmission lines are being approved. This means that the utilities will be operating under tighter margins and closer to the limits as time progresses. This is only expected to become more critical as years pass by.

Therefore, if some pre-processing were done, to present the operators with a diagnosis of the problem and a list of suggestions, they would be in a better position to make an objective analysis. An intelligent system installed in an EMS/DTS environment, can provide a suitable solution to the voltage stability problem and still be capable of adapting to newer situations and utilizing different measures of detection. This proposed system can perform the necessary pre-processing and acts as a reliable EMS operator's assistant.

2.2 ELS DESIGN PHILOSOPHY - WHAT IS IT ?

Expert Load Shedding (ELS) is software which assists an EMS operator in performing load shedding in a power system. The main reason for the use of the term 'expert' in the name is to emphasize the difference between existing techniques and the proposed approach. Calling it an 'expert' emphasizes the following:

- o use of operator expertise in its development and
- o its capability to advice the operator to perform the right set of actions.
- o its ability to observe trends and present them in the right mode thereby allowing the operator to make a better decision.

Some of the key considerations which are taken into account while developing the initial design of the ELS are as follows.

1. Real-time design. (already enumerated in an earlier section)
2. Practical implementation. (see chapter 3)
3. Effective User Interface (UI)
4. Fast heuristic search technique.

2.2.1 User Interface (UI)

The user interface forms an important part of any power system application. The main reason for this importance is that the system is used in a control center environment by power system operators who need to be effective and efficient in their job. In the initial development stages it is imperative that the UI (at the least) is compatible with other system displays in the same environment. The UI can (at a future stage of development) also have explanation features that allow the ELS to provide the rationale behind the decision-making process.

2.3 ELS FOR VOLTAGE STABILITY ENHANCEMENT

The design has the following main function blocks.

1. Area Diagnosis,
2. Reactive power mismatch identification, and
3. Load shedding

A more detailed description of these modules follows:

2.3.1 Area Identification

A low voltage area is defined as a set of connected buses (within the same electrical island) all of which have voltages lower than a pre-defined threshold voltage. Another feature of this low voltage area is the fact that it is completely surrounded by buses whose voltages are higher than the threshold. Some of the high level general rules which form a part of this module are:

1. If the voltage at a bus is less than the threshold voltage, then it is a low voltage bus. This rule is first operated on all the buses in the system.
2. If two connected buses have low voltage, then a low voltage area has been identified.
3. Rule 2 is then repeated in a recursive manner until all the connected low voltage buses have been placed in this low voltage area.

4. Rule 3 is continued until all the valid low voltage areas in the system are identified.
5. The loads in the low voltage areas are identified and ordered in the ascending order of priority. The priority number attached to a load indicates its relative importance with respect to other loads.

It must be remembered that this module is dependent upon the state of the system. Hence, it is executed only if the system state changes. The implications of this statement will be discussed in the next section.

2.3.2 Reactive Power Mismatch Calculation

At this juncture, ELS has the following information available to it.

- o Valid low voltage areas have been identified.
- o The list of buses which form the low voltage areas are available on an area basis.
- o The list of loads arranged in the ascending order of priority is also available on an area basis.

This module makes an assumption that the system has decayed to a point that the only avenue available to the system operator is to shed load. Hence, information indicating

the amount of improvement in bus voltage upon the removal of load connected to it is needed. This calculation is purely algorithmic in nature and is described below:

- o The Jacobian matrix (in the Newton-Raphson type of power flow calculation) has four terms for every bus. One of the terms is the partial differential of Q with respect to V .
- o Knowing the Jacobian matrix terms for a particular system state (or topology), the reactive load at that bus can be perturbed by 1.0 Mvar.
- o The change in voltage for this 1.0 Mvar change in reactive power injection at the load bus is then calculated. This is defined (and stored) as the reactive power sensitivity of that bus. If there is more than one physically connected load, then each of the individually connected load components will have the same sensitivity coefficient.

The components of the Jacobian matrix are dependent upon the network topology (or connectivity) of the power system. Hence, this calculation needs to be performed only if the topology has changed. Figure 2-1 Reactive Power Mismatch Calculation shows the equations depicting the process.

$$\text{Reactive power mismatch at bus } x = \frac{\text{Voltage at bus } x - \text{Threshold voltage}}{\text{Sensitivity Factor } (\gamma)}$$

Where the sensitivity factor γ is calculated as follows:

Powerflow equation:

$$[J] \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} = \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}$$

Where

- J = Jacobian
- θ = Bus voltage angle
- V = Bus voltage magnitude
- P = Bus real power mismatch
- Q = Bus reactive power mismatch

$$\begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} = [J]^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}$$

Therefore, if a bus x is perturbed by 1.0 Mvar, then

$$\begin{aligned} \Delta P_i &= 0.0 \text{ for all } i = 1 \text{ to } n \\ \Delta Q_i &= 0.0 \text{ for all } i = 1 \text{ to } n \text{ and } i \neq x \\ \Delta Q_x &= 1.0 \end{aligned}$$

Therefore, the calculated value of change in voltage at bus x due to this 1.0 Mvar perturbation at the same ΔV_x is determined to be γ .

Figure 2-1: Reactive Power Mismatch Calculation

2.3.3 Modes Of Load Shedding Operation

There are two modes of operation possible here:

- o Automatic loadshed (desirable when time is a critical factor).

In this case, ELS would automatically shed enough load to satisfy the reactive power mismatch of the low voltage area as calculated by the reactive power mismatch module. It then checks whether the low voltage areas have indeed disappeared or still exist, in which case it would start the area diagnosis again.

- o Operator assisted loadshed

In this case, ELS would merely present the information gathered by the above two modules and let the operator make a decision to shed load. If the operator does decide to shed load, then the ELS will prompt the operator for the identification of the particular load to be shed.

It can be seen that some amount of operator intervention is desirable and this is provided in a way such that the final decision to shed load always rests with the operator. Even in the case of automatic loadshed, it is the operator who decides to go the automatic mode.

2.4 THE ACQUISITION OF KNOWLEDGE

The acquisition of knowledge spans extensive consultations held with four experienced engineers. They are Dom Delaney (New York Power Pool), Jim Maurer (ESCA Corporation and formerly of Puget Sound Power and Light Corporation), Alan Karlak (ESCA Corporation and formerly of Gulf State Utilities) and Kathy Brewer (ESCA Corporation and formerly of Western Area Power Administration). The knowledge obtained from these conversations have been used towards the development of the design methodology of ELS. The consultations have been held over a period of three years from 1987 to 1990 and spans the following range of topics:

- o Present day utility protection philosophies and the deficiencies of these approaches.
- o Inadequacies of the frequency relay during undervoltage conditions.
- o Utility methods in detecting undervoltage
- o Operator requirements regarding undervoltage detection and permitted operations.
- o The respective experiences of the above mentioned 'experts' during different disturbances and their inferences.

- o Potential repercussions of deregulation in the power industry

2.5 A TWO LAYER HEURISTIC SEARCH TECHNIQUE

From the explanation provided in section 1.3.1, it is very clear that new 'rules' must be developed to implement a real-time heuristic search technique. Richard Korf [32] has enumerated many techniques in his paper, but none of them are totally sufficient in this environment. Minor modifications to Korf's A* algorithm could go a long way towards real-time implementation. An explanation of the new modified A* method follows:

A* lacks a time constraint, but such a constraint is very necessary for a real-time implementation. There is one hurdle here. A quicker answer must also have a 'confidence factor' to provide the user a measure of system confidence in the decision. A technique for the computation of this 'confidence factor' must be implemented.

Figure 2-2 Conceptual Diagram of the Two-Layer Heuristic Search Technique presents the conceptual diagram of the new heuristic search technique. As can be seen, it consists of two hierarchical layers. Both the layers consists of rules which perform a different set of functions. The selection of rules in the first layer controls the rules out of the

second layer which will be selected for the search process. The two hierarchically designed layers have different functions. The main idea behind this operating philosophy

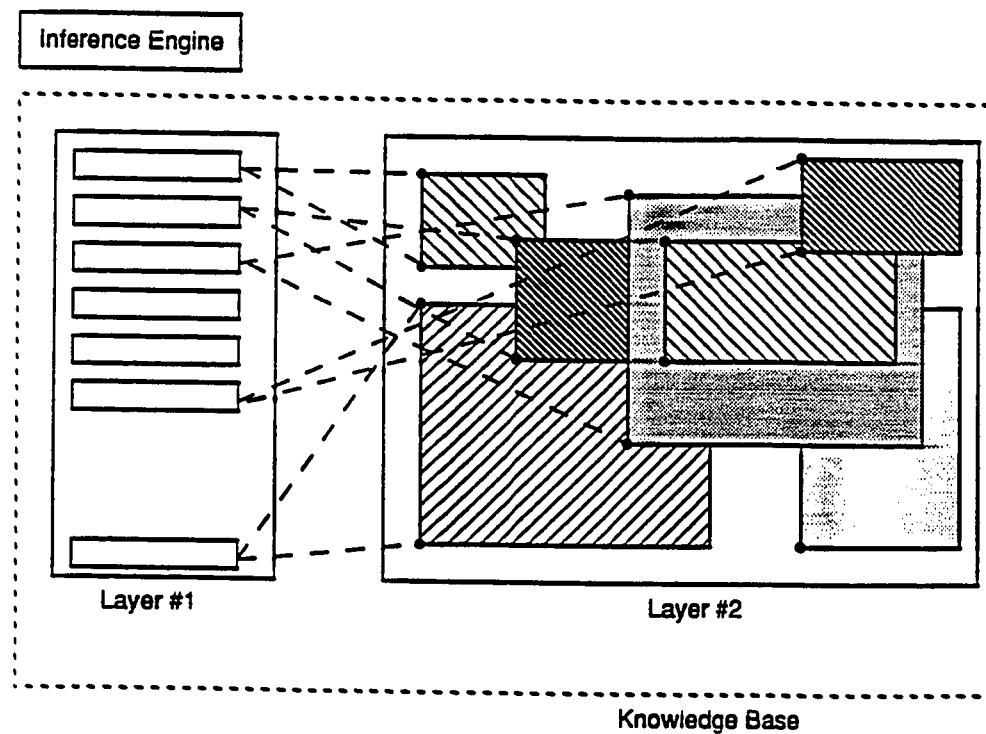


Figure 2-2: Conceptual Diagram of Two-Layer Heuristic Search Technique

is that searching through a carefully selected set of approximately 50 rules would be more efficient than searching through the entire knowledge base of say, 300-3000 rules.

The main functions of the first layer are as follows:

1. Look at the state of the system and the alarms to perform a diagnosis of the problem
2. Once the problem is recognized, it would look at its severity and determine the time (probabilistic) available before a decision must be made.
3. Provide a set of rules out of the second layer which need to be searched for the solution. This, as explained earlier, would be based on the type of problem and amount of time available for making the decision. This step would depend upon meta-knowledge (knowledge about the knowledge in the knowledge base) reasoning analysis. A new technique would be needed to encode the knowledge in the knowledge base in some form to be made available to the first layer.

4. Calculate the 'confidence factor' which would indicate the degree of confidence that ELS has on the decision.

The second layer has the complete set of rules for the decision-making process of how much and where to shed the load (that is, the actual knowledge base). This is the main knowledge base of the ELS.

CHAPTER 3

ELS SOFTWARE DEVELOPMENT

Some of the issues which are typically considered whenever a software design is provided for implementation in a production environment are as follows: 1) It must minimize the development time by capitalizing on existing software, 2) It must try to minimize the execution time, and 3) the system design must allow the eventual implementation in the real-time EMS (since this is the focus of this dissertation). The fulfillment of the issues mentioned above very often requires extensive use of system level calls.

A brief description of the production environment is now presented to provide an understanding of the implementation. By environment, the author is referring to the system within which the ELS is installed. The software system in this case is the Dispatcher Training Simulator (DTS) .

3.1 DTS ENVIRONMENT

The DTS is a software environment which simulates power system behavior and the (dispatcher) user interface [38, 39]. The DTS may be used for: dispatcher training, dispatcher evaluations, engineering studies, power system model evaluations, and offline testing of EMS functions. Very often, new applications/functions are first tested in the DTS environment, before being integrated into the real-time EMS. The DTS environment is exactly the same as the real-time environment with the addition of the power system simulation subsystem.

The DTS provides a realistic environment for dispatchers to practice operating tasks under normal, emergency, and/or restorative conditions. This is because the DTS responds in real-time just as the real power system would. Figure 3-1 **DTS - An Overview** provides a high level overview of the DTS.

As can be seen in Figure 3-1, the DTS is comprised of the following three main subsystems:

1. EMS subsystem: This is the part which exists in the energy control center. This is also the part with which the trainee will be interacting. In the figure, this includes both SCADA and AGC.

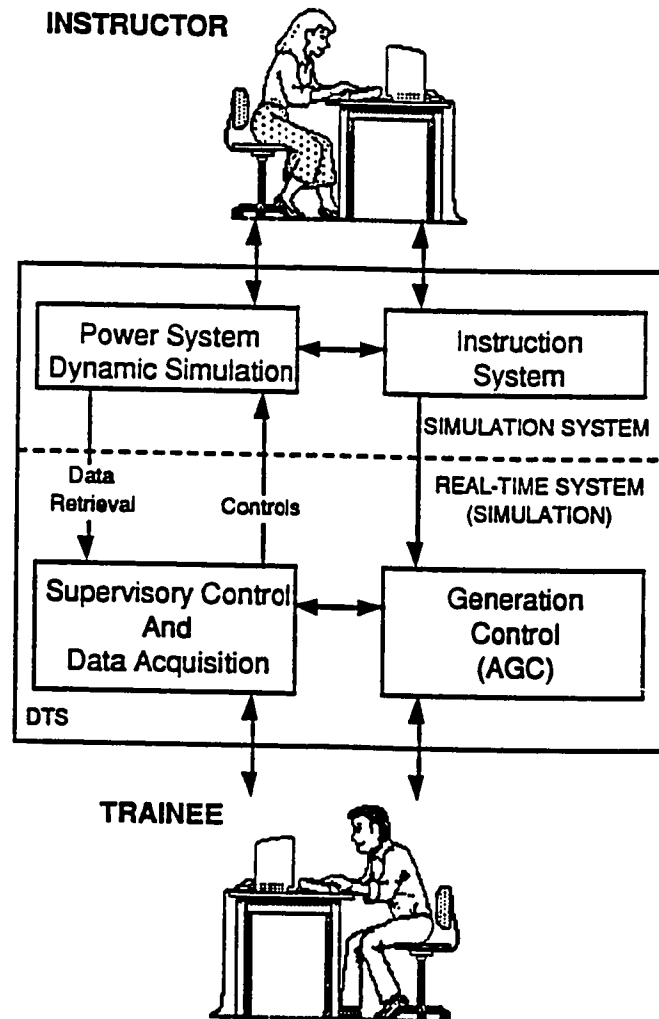


Figure 3-1: DTS - An Overview

2. Instructional subsystem: This subsystem provides the software and displays for setting up training scenarios and controlling the simulation.
3. Power system dynamic simulation subsystem: This subsystem represents the power system components such as generating units, transmission lines, transformers, and others.

The power system dynamic simulation subsystem has the following three functional modules:

1. Prime mover dynamic solution module.
In this module, the dynamics of the prime movers are solved. This includes turbines, boilers (in the case of steam turbines), and governors.
2. Network solution module.
In this module, a power flow solution is performed. Since the network state is typically in a tracking mode, this block is intelligent enough to figure out the type of powerflow solution that needs to be performed. The solution type is mainly dependent upon the change to the system since the last power flow execution.
3. Relay processing module.
This module simulates the effects of various relays. Some of the relays that are available are

over/under frequency relays, overcurrent relays, over/under voltage relays, and others. This block simulates the relay sensing, tripping and resetting mechanisms.

The non-shaded sections of Figure 3-2 **ELS Integrated into DTS Environment** present the interactions between the three functional modules of the power system dynamic simulation subsystem. In a typical configuration, the prime mover dynamics solution is executed every second. The network solution is performed once every 8 seconds or if a change has occurred in the power system to warrant a new power flow solution. Parts of the relay processing module are executed after the prime mover dynamics solution and other parts are executed after the power flow solution.

3.2 ELS IMPLEMENTATION IN THE DTS

Figure 3-2 shows the ELS integrated into DTS. A detailed look at the figure along with the explanation provided in sections 2.3 and 3.1 provide the rationale for such a design, which is clarified below:

The area diagnosis module which identifies the low voltage areas is dependent upon changes in the system voltages and/or bus structure (topology processing). The reactive

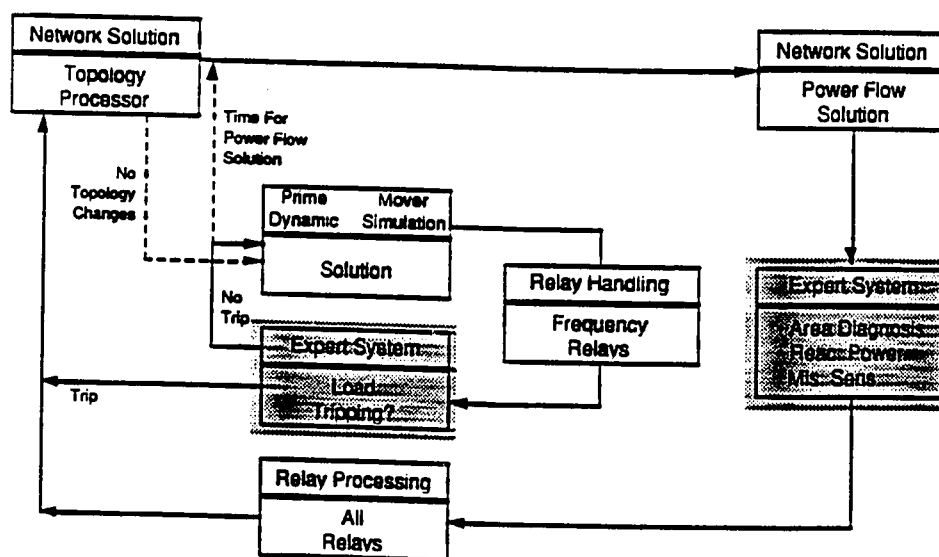


Figure 3-2: ELS Integrated into DTS Environment

power mismatch sensitivity calculation module is also governed by the same set of constraints.

Hence the calculations connected with these two modules (ELS_2) are performed after the power flow solution is completed (Network Solution_2). The dropping of the load, on the other hand does not have to be synchronized with any other process and hence is totally independent. As a result, this module (ELS_1) is executed after the prime mover dynamics solution is achieved.

Dropping of load will force the power flow solution to be executed again and hence automatically allows the reconfiguration of the topology (if needed). A new topology also forces the reconfiguration of the low voltage area and a new set of reactive power sensitivity factors are recalculated. As can be seen, ELS takes advantage of the existing software to position itself in an advantageous position and thereby save itself from unnecessary computations.

3.2.1 Integration In A Real-Time EMS.

The only DTS subsystem that exists in the EMS is the EMS subsystem. The main change for the implementation of the ELS in the EMS environment is to execute the area diagnosis and reactive power mismatch calculation after the state

estimator solution is performed. The actual load shedding, as explained earlier is a totally independent function.

3.3 DETAILS OF THE INTELLIGENT SYSTEM DEVELOPED

There are four main software modules which form a part of ELS. The following subsections describe the processing which occurs in these software modules.

3.3.1 ELS Initialization Module

This is an initializing module and the main processing that occurs here is the creation of a mailbox. The mailbox is a VAX/VMS software entity which is used for asynchronous communication between processes. Since this needs to be done only once, it is executed when the PWRFLOW process is loaded into the main memory.

One of the side issues handled in this module is get write access to the appropriate portions in the memory where the data is stored.

3.3.2 ELS Scheduled Processing

The processing which is performed in this module corresponds to that shown in the ELS_2 box in Figure 3-2. Some of the processing which occurs here are:

1. Retrieve the network topology information along with the bus voltages.
2. Diagnose the low voltage areas.
3. Calculate the reactive power sensitivity of each area in Mvars.

3.3.3 ELS Dynamics Processing

As the name implies, this routine is executed every second. The main reason for executing this routine every second is to simulate real-time (note that the ELS is in the DTS).

If the ELS is placed in automatic mode, and if some low voltage areas have been recognized, then ELS will proceed and drop enough load to satisfy the reactive power need of each low voltage area. If the ELS is placed in manual mode, then no shedding action takes place in this software module.

3.3.4 ELS Asynchronous Processing

This is the asynchronous process. If the EMS/DTS operator chooses to place the ELS in manual mode, then he/she can decide to drop a load on his/her own initiative. The set of operations that occur are as follows: The operator position's the cursor to the particular load (on the

console screen) and presses the 'SELECT' key on the keyboard. The action sets off the following chain reaction.

The use of the 'SELECT' key sends a message to the mailbox (which is described in section 3.3.1) and wakes it up. The mailbox fires up a routine which reads the cursor's position on the screen and reads the data on which it is positioned. Since the cursor is presently positioned on the load which needs to be dropped, this act provides the mailbox with enough information about the load which needs to be dropped. It then proceeds to drop the load. The system would respond to the user with appropriate alarms and messages describing the action.

3.3.5 Other System Utility Support

The above four software modules make extensive use of the system utilities like logging messages (whenever a load shed action is selected), and also sends out alarms when the load is actually shed.

3.4 UI AND PERMITTED OPERATIONS

A brief description of EASEL{*} (the user interface management system which is an inherent part of the HABITAT{*} run-time environment) is provided here before a description of the UI and permitted operations is provided.

3.4.1 HABITAT{*} User Interface - A Brief Overview

A User Interface Management System (UIMS) is designed to save time and improve the quality of communication between the machine and the user. The HABITAT-UIMS has two main components: EASEL{*} (a set of tools to support the design, implementation, and editing of pictures and displays), and RAPPORT{*} (a run-time processor that manages the interaction between the user and the system).

The display is the primary interface between the user and database. A display is defined on a two-dimensional coordinate system called display space (sometimes called "world space") which extends left, right, up and down from a central point.

RAPPORT{*} performs the following functions from HABITAT{*} displays:

- o Display Painting and refresh
- o Command processing
- o Console performance monitoring
- o User-system interface

RAPPORT{*} is an interactive system. When a user submits a command to HABITAT{*}, Rapport always responds by either

{*} Registered Trademark - ESCA Corporation

executing the commands as requested or generating a message to the user explaining why the commands cannot be executed action is necessary to correct the problem. The syntax of `RAPPORT{*}` commands is very similar to the VAX DCL (Digital Command Language). `RAPPORT{*}` commands are used to:

- o Call up specific displays, move to a specific page in a display and other display navigational commands.
- o Send a message or a specific display to another console.
- o Run, abort, stop, or wake up a specified task.
- o Start or stop performance monitoring.
- o Enter, modify or delete data from a database. It can also perform extended data entry checks which can be used to perform a variety of tasks.

3.4.2 Expert Load Shedding Display - A Description

Figure 3-3 **ELS Master Display** shows a sample page of the ELS display. As can be seen there are four items displayed here. They are:

AUTOMATIC IN LOADSHED			VPCNE1			02-FEB-1989 02:45:07		
			E L S M A S T E R D I S P L A Y					
AREA_BUS			AREA_LOAD				AREA_REAC	
AREA	BUS	BUS P.U	AREA	LOAD	REAL	REACTIVE	BUSILD	
#	#	VOLTAGE	#	ID	POWER	POWER	# IR	
					(MW)	(MVAR)	# II	
1	26	0.926	1	609	112.58	67.68	26	2
2	27	0.946	2	710	4.05	1.65	27	1
	28	0.946		611	73.45	30.13	66	2
	66	0.940	3	614	148.63	94.29	32	2
3	32	0.908	4	616	61.61	7.12	33	3
4	33	0.945		712	45.50	10.72	34	2
	35	0.946						
	34	0.945						
5	53	0.879						

Figure 3-3: ELS Master Display

1. **AREA_BUS:** This is a tabular display of the different areas and the set of buses which form a part of that area.

Explanation of data in the display: Figure 3-3 shows five low voltage areas. Area #2 has the buses 27, 28, and 66 as its members.

2. **AREA_LOAD:** This is also a tabular display of the same set of areas (identified above). In this case the set of loads which exist in that area are also displayed. The loads are ordered in order of

ascending priority.

Explanation of data in the display: Figure 3-3 shows the loads which exist in the low voltage areas. As can be seen, area #5 is not represented here. This is because, area #5 does not have a load.

3. AREA_REAC: In this table, the areas and their respective reactive power mismatch values in Mvar are displayed.

Explanation of data in the display: Figure 3-3 shows the reactive power mismatch calculated for only four areas. Here also, area #5 is not represented because it does not have a load and the reactive power mismatch calculation (as described in section 2.3.2) is dependent upon the loads available in the area.

4. ELS Mode: This is a boolean bit. If this is toggled to .Y. then it means that the ELS is now in automatic mode. If, on the other hand, it is toggled to .N., then the ELS is in manual control mode.

Figure 3-4 shows the help page of the ELS display. This figure is self-explanatory.

3.4.3 Permitted Operations

Figure 3-2 has already shown the ELS integrated into the DTS environment. The area diagnosis module and the reactive power mismatch identification module are executed at the Power Flow execution rate. The output of these two modules form the AREA_BUS, AREA_LOAD, and AREA_REAC tabular displays. At the time of execution of the voltage controlled load shedding module, the program will check if the ELS is in automatic or manual mode.

If the ELS mode is set to automatic, then it will automatically drop the loads to satisfy the reactive power requirements of the area. If, on the other hand, the mode is set to manual then the following sequence of operations happen.

- o The voltage control load shedding module will NOT automatically shed any load. This module will be bypassed, (it will go sleep until woken up by an operation on the console).
- o The operator can chose the load that should be dropped, and select it using the select key (the use of the select key will wake up the load shedding module, and give it the message that something needs to be shed. It will also give it the ID of the load to be dropped).

VPCNE1 02-FEB-1989 02:45:27

AUTOMATIC :N LOADSHED	EL S M A S T E R D I S P L A Y
--------------------------	--------------------------------

H E L P

THERE ARE THREE TABLES BEING DISPLAYED IN THIS DISPLAY. THEY ARE:

AREA_BUS: THIS TABLE SHOWS THE BUS CONFIGURATION. IT SHOWS THE LIST
OF BUSES WHICH BELONG TO EACH AREA.

AREA_LOAD: THIS TABLE SHOWS THE LOAD CONFIGURATION. IT SHOWS THE LIST
OF LOADS WHICH BELONG TO EACH AREA ORDERED IN INCREASING
PRIORITY.

AREA_REAC: THIS TABLE SHOWS THE REACTIVE POWER MISMATCH CALCULATED
FOR EACH AREA.

TWO OPERATIONS CAN BE PERFORMED FROM THIS DISPLAY.

ELS MODE: THE ELS CAN BE CHANGED FROM AUTO TO MANUAL MODE. THIS IS
DONE BY TOGGLEING TO Y/N IN THE BOX ON THE TOP LEFT CORNER.

TRIPPING IN MANUAL MODE: IF ELS IS IN MANUAL MODE, THEN LOADS CAN BE
TRIPPED BY MERELY SELECTING A LOAD AND PRESSING THE <SELECT>
BUTTON.

Figure 3-4: ELS Master Display - Help Page

- o The load shedding module will then shed the selected load.

{*} HABITAT, EASEL, and RAPPORT are registered trademarks of ESCA Corporation, Bellevue, Washington.

CHAPTER 4

APPLICATION TO A PRACTICAL SYSTEM

4.1 DESCRIPTION OF THE TEST SYSTEM

Figure 4-1 Overview Diagram of the Test System shows the enhanced New-England 345-kV test system. The test system spans two utilities: NEPOOL and ECAR. There are a total 27 substations. The system also has 67 buses (in its normal steady-state), 36 transmission lines, 32 loads points, 11 generating units, and 32 transformers. Each of the individual loads have priority values assigned to them *a priori*. The priority values range from 1 to 3. In this case, a priority value of 1 means the lowest priority and a priority value of 3 means the highest priority.

The 11 generating units of the system typically operate under Automatic Generating Control (AGC) a real-time process which automatically schedules generation at minimal cost and within certain constraints:



- o Scheduled MW flows with neighbors.
- o Scheduled frequency and time error.
- o Generating unit restrictions.
- o Area load.
- o Area generation reserves.

4.2 TEST RESULTS

This section consists of two parts. Section 4.2.1 **System Normal Operating Mode** describes the basecase conditions. The term basecase implies the normal steady-state operating conditions with no violations. Section 4.2.2 **Test Conditions** describes the scenario which was simulated to test the ELS.

It must be remembered that the test system is a real system and already has the associated protection system installed in it. The scenario has been set up such that the system will collapse on voltage instability. This also means: 1) The conditions are simulated to show a voltage collapse, and 2) the existing protection schemes are not adequate to protect the system.

4.2.1 System Normal Operating Mode

Tables 4-1 to 4-4 present the following information.

- o System generation - both real (in MWs) and reactive power (in Mvars). This is shown in Table 4-1.
- o System loading - both real (in MWs) and reactive power (in Mvars). This is shown in Table 4-2.
- o Bus voltages - magnitude (in p.u.) only. This is shown in Table 4-3.
- o Line flows - both real (in MWs) and reactive power (in Mvars). This is shown in Table 4-4

Table 4-1: System Generation

Generator Station	ID	Generated Power	
		Real MWs	Reactive Mvar
Douglas	G2	645	71
	G1	600	132
Hearn	G1	229	12
	G2	229	12
Lakeview	G1	646	134
B'Ville	1	0	501
W'Ville	1	264	-301
Chenaux	1	80	-23
Chfalls	1	371	-3
Holden	1	600	154
Nantcoke	1	406	-30

Table 4-2: System Loading

LOAD STATION	ID	POWER	
		MWs	Mvars
DOUGLAS	402	368.6	60.7
KINCARD	604	68.9	45.3
	605	43.2	8.6
	706	26.7	4.4
LAKEVIEW	38	123.7	43.8
BRIGHTON	44	146.4	27.8
CEYLON	708	260.4	70.0
HANOVER	62	305.2	29.9
PARKHILL	609	125.9	75.7
	610	84.0	30.6
	611	82.1	33.7
	710	4.5	1.8
PICTON	83	298.4	2.3
RICHVIEW	614	166.2	105.4
	616	68.9	8.0
	712	50.9	12.0
B'VILLE	715	0.0	0.0
GOLDEN	619	48.8	23.7
	620	63.4	16.6
J'VILLE	426	1.3	14.1
	427	2.7	28.2
M' TOWN	718	134.3	39.6
	720	89.6	12.9
	721	22.8	2.3
WALDEN	723	108.5	23.1
	725	98.6	20.3
CHFALLS	155	138.5	29.2
HOLDEN	160	682.8	154.6
HUNTVILL	164	127.4	17.1
MARTDALE	177	42.8	5.6
	178	43.1	4.9
NANTCOKE	183	175.3	16.6

Table 4-3: Bus Voltages

BUS STATION	ID	KV LEVEL	P.U. VOLTAGE

DOUGLAS	3	345	1.0100
	4	345	1.0100
	5	138	1.0122
	6	22	1.0203
	7	14	1.0352
HEARN	8	345	1.0000
	9	345	1.0000
	10	14	0.9758
KINCARD	11	14	0.9758
	12	345	0.9971
	13	22	1.0013
	14	14	1.0134
LAKEVIEW	15	1	0.9993
	16	345	1.0009
BRIGHTON	17	22	1.0250
	18	345	1.0124
CEYLON	19	345	1.0171
	20	345	1.0164
	21	138	0.9621
HANOVER	22	345	1.0045
MITCHELL	23	345	1.0108
PARKHILL	24	345	1.0142
	25	138	0.9676
	26	22	0.9576
	66	22	0.9562
	27	14	0.9530
	28	1	0.9532
PICTON	29	345	1.0246
RICHVIEW	30	345	1.0016
	31	138	0.9545
	32	22	0.9091
	33	22	0.9489
	34	14	0.9485
	35	1	0.9497
	36	345	1.0500
B'VILLE	37	14	1.0956
	38	345	1.0469
COBDEN	39	345	1.0471
GOLDEN	40	22	1.0199
	41	345	1.0267
J'VILLE	42	345	1.0166
	43	138	1.0124

Table 4-3: Bus Voltages (Cont)

BUS STATION	ID	KV LEVEL	P.U. VOLTAGE
M' TOWN	44	345	1.0294
	45	14	1.0205
	46	14	1.0254
STINSON	47	345	1.0613
STRATFRD	48	345	1.0215
WALDEN	49	345	1.0473
	50	14	1.0423
	51	14	1.0429
W' VILLE	52	345	1.0150
	53	14	0.8781
CHENAUX	54	345	1.0293
	55	345	1.0293
	56	14	1.0000
CHFALLS	57	345	1.0475
	58	14	1.0200
HOLDEN	59	345	1.0500
	60	14	1.0473
HUNTVILL	61	345	1.0535
MARTDALE	62	345	1.0513
NANTCOKE	63	345	1.0500
	64	22	1.0211
REDBRIDG	65	345	1.0530

Table 4-4: Line Flows

LINE ID	STATION FROM	TO	LINE MWs	FLOW Mvars
T538	DOUGLAS	HANOVER	870	14
34560	HEARN	KINCARD	549	-2
34562	HEARN	LAKEVIEW	-104	-11
T559	KINCARD	HANOVER	408	-80
T564	LAKEVIEW	RICHVIEW	416	-16
34519	BRIGHTON	MITCHELL	-303	43
34521	BRIGHTON	PICTON	157	-80
T545	CEYLON	MARTDALE	-17	-129
34523	CEYLON	MITCHELL	-110	25
13869	CEYLON	RICHVIEW	-180	137
13822	CEYLON	PARKHILL	46	-105
34563	HANOVER	RICHVIEW	55	43
34522	HANOVER	MITCHELL	415	-103
34532	HANOVER	PARKHILL	489	-148
34528	PARKHILL	STRATFRD	236	-66
T525	PICTON	CHENAUX	-208	-25
34527	PICTON	M' TOWN	65	-39
34515	B'VILLE	COBDEN	94	114
34514	B'VILLE	GOLDEN	170	17
34506	B'VILLE	J'VILLE	-264	317
34509	COBDEN	M' TOWN	-47	139
34512	COBDEN	WALDEN	141	-21
34513	GOLDEN	WALDEN	57	-15
34503	J'VILLE	W'VILLE	-254	300
34501	J'VILLE	W'VILLE	-10	34
34568	J'VILLE	STRATFRD	-5	-58
34520	M' TOWN	STRATFRD	-229	74
T511	STINSON	HOLDEN	-9	-19
34517	STINSON	WALDEN	9	19
34502	CHENAUX	REDBRIDG	95	-102
T540	CHENAUX	CHFALLS	-324	44
34542	CHFALLS	MARTDALE	1	-41
34504	HOLDEN	REDBRIDG	-95	-49

The intent behind displaying this information is to provide an understanding of normal operating conditions of the test system. For example, Table 4-3 shows that the voltages of the buses under normal operating conditions are well within the pre-specified threshold of 0.95 p.u.

4.2.2 Test Conditions

The following scenario has been simulated in the DTS on the test system.

Note: The situation is created specifically for the purposes of testing ELS. It may or may not have any connection with actually existing conditions on the New-England system and has no relationship to any incident.

A cold winter Monday morning (02-Feb-1989) is taken as the test day. At 7:30 am, the reactive power demand in Mvar starts increasing very rapidly. There are no rate of change readings but the values of loads at the Golden, Chfalls, and Holden stations shown in Figure 4-1 **Overview Diagram of the Test System** peaks at the following values:

- o Golden (load ID = 619) 53.4 (MW) and 125.9 (Mvar)
- o Golden (load ID = 620) 69.5 (MW) and 218.2 (Mvar)

- o Chfalls (load ID = 155) 160.4 (MW) and 533.8 (Mvar)
- o Holden (load ID = 160) 793.4 (MW) and 479.6 (Mvar)

The voltages start to drop to as low as .89 pu at these stations. At 8:30 am, the Automatic Voltage Regulator (AVR) at the Chfalls Plant (Unit #1) turn off when the reactive demand peaks at 124 Mvars. At 8:45 am, the AVR at Holden Plant (Unit #1) also turned off for the same reason. Chenaux Plant (Unit #1) tripped on overexcitation and the entire system collapsed in about 35 seconds.

On post-mortem it is noted that the voltage relay at Holden picked up the low voltage at 8:45 am. However, since its time delay has been set at 60 seconds, the system collapsed before any action could be taken.

4.3 ELS IN ACTION

Figure 4-2 **ELS Test Results** shows the various low voltage areas found. Since the low voltage areas are dynamic in nature, this represents one snapshot of the situation. As can be seen, six low voltage areas are identified (See Section 3.4.2 for the description of the display items). The figure also shows the following information in each low voltage area:

AUTOMATIC IN LOADSHED			VPCNE1 E L S M A S T E R D I S P L A Y					02-FEB-1989 08:43:08		
AREA_BUS			AREA_LOAD					AREA_REAC		
AREA	BUS	BUS P.U.	AREA	LOAD	REAL	REACTIVE	BUSILD	AREA	REACTIVE	
#	#	VOLTAGE	#	ID	POWER	POWER	IP	#	POWER	
					(MW)	(MVAR)	IR		MISMATCH	
							II		(MVAR)	
1	21	0.938	11	708	243.40	65.41	21	1	36.32	
	25	0.942		614	155.35	98.55	32	2	24.92	
	31	0.933		616	64.39	7.44	33	3	16.99	
	35	0.929	12	609	117.67	70.74	26	4	14.00	
	32	0.890	13	710	4.23	1.72	27	5	258.38	
	33	0.928		611	76.77	31.49	66			
2	26	0.908	14	712	47.55	11.20	34			
3	27	0.928	15	160	617.99	539.90	59			
	28	0.928								
	66	0.921								
4	34	0.928								
5	47	0.839								
	59	0.723								
	60	0.701								
	65	0.820								
6	58	0.937								

Figure 4-2: ELS Test Results

- o The set of buses in each low voltage area along with their p.u. voltages
- o the loads associated with each area along with their values and priorities and
- o the reactive power mismatch for the area in Mvar.

As can be seen in the figure, low voltage area #1 contains the buses 21, 25, 31, 35, 32, and 33. There are three loads in this area and they are connected to buses 21 (load ID 708), 32 (load ID 614), and 33 (load ID 616) in order of priority. The reactive power mismatch for this area is 36.32 Mvar. The figure also shows area #6 which actually is a generator bus with no load. This is a case of the generator reaching its Mvar limit and being regarded as a P,Q (load bus). However, since it did not have any load to be shed, there is no reactive power mismatch calculated for that area.

Two simulation runs of the test case are performed. The voltage threshold of tolerance is placed at 0.95 pu. In the first test run, ELS is placed in manual (advisory) mode. No load is dropped, and the system collapsed as described earlier. In the second test run, ELS is placed in automatic mode.

4.3.1 ELS In Action - Results

ELS has made the following inferences in the case of area #1:

Area #1 has the low voltage buses 21, 25, 31, 35, 32, and 33 in it. The loads LD 708 (priority #1), LD 614 (priority #2), and LD 616 (priority #3) are identified as existing in this low voltage area. The reactive power mismatch calculated for this area is 36.32 Mvar. The dropping of load LD 708 (which is the lowest priority load in this area) will provide a load relief of 65.41 Mvar. This load relief is greater than the calculated mismatch of 36.32 Mvar and hence LD 708 is the only load dropped in this area.

A similar reasoning has gone into identifying the loads to be dropped for the different low voltage areas. The actions and the corresponding messages/alarms logged are shown below:

- o Loads Dropped

Load ID = 708 - (243.4 MW, 65.41 Mvar)

Load ID = 609 - (117.67 MW, 70.74 Mvar)

Load ID = 710 - (4.23 MW, 1.72 Mvar)

Load ID = 611 - (76.77 MW, 31.49 Mvar)

Load ID = 712 - (47.55 MW, 11.20 Mvar)

Load ID = 160 - (617.99 MW, 539.90 Mvar)

- o Messages issued

DTS309 I: Removed - LD 708 at ST CEYLON by ELS
DTS309 I: Removed - LD 609 at ST PARKHILL by ELS
DTS309 I: Removed - LD 710 at ST PARKHILL by ELS
DTS309 I: Removed - LD 611 at ST PARKHILL by ELS
DTS309 I: Removed - LD 712 at ST RICHVIEW by ELS
DTS309 I: Removed - LD 160 at ST HOLDEN by ELS

Once the loads are dropped, there is no low voltage area diagnosed. Once the reactive demand dropped, the loads which are previously shed, are restored manually.

4.3.2 Inferences Drawn From Testing

The following inferences can be drawn from the tests that have been conducted in the previous sections:

- o The ELS observes the entire system and presents a higher level overview of the problem areas of the power system.
- o The ELS display provides information (or advice in a very primitive form) to the operator. This allows the system operator to understand the situation and if needed, make an assessment regarding its importance or seriousness.

- o The operator can notice trends in the system. Some of the following examples are possibilities:
 - The operator can observe if the number of low voltage areas are increasing or decreasing.
 - The operator can also observe if the number of buses in each area is increasing or decreasing.

Trends of this nature allow the operator to diagnose a move towards a stable system or an unstable system.

- o ELS also allows the operator to make correct decisions. Also, if the operator desires, he /she can place it in automatic mode at any instant, and then ELS would go ahead and shed the appropriate loads.

This action of ELS is in sharp contrast to the undervoltage relays which function as following:

- o Monitor voltage locally, that is, at a particular point in the system.
- o The relays settings are set (in the field). This means that they cannot be changed depending upon the current operating conditions.

CHAPTER 5

LOAD MANAGEMENT AS THE DISTRIBUTIVE ARM OF LOAD SHEDDING

5.1 INTRODUCTION

Distribution Automation (DA), a term introduced in the mid-seventies, can be loosely defined as the remote or automatic control of functions required by electric power utilities for the operation of their distribution systems [40]. Over 140 individual DA functions have been identified [41] for exploration and possible implementation. Included in this list are functions such as data collection (meter reading, tamper flags, status), load management, voltage and reactive current (or var) control, system configuration, dispersed generation control, and protection relaying. Additional benefits such as increased safety come from the operation of the DA system. The DA system as seen today must contain a mix of automatic routines with planned human monitoring and intervention. The user interface allows the minimization of confusion in viewing one-line diagrams, locating trouble spots, or finding faulted areas [42]. Figure 5-1 The

Utility System with Distribution Automation shows how DA fits into the utility system.

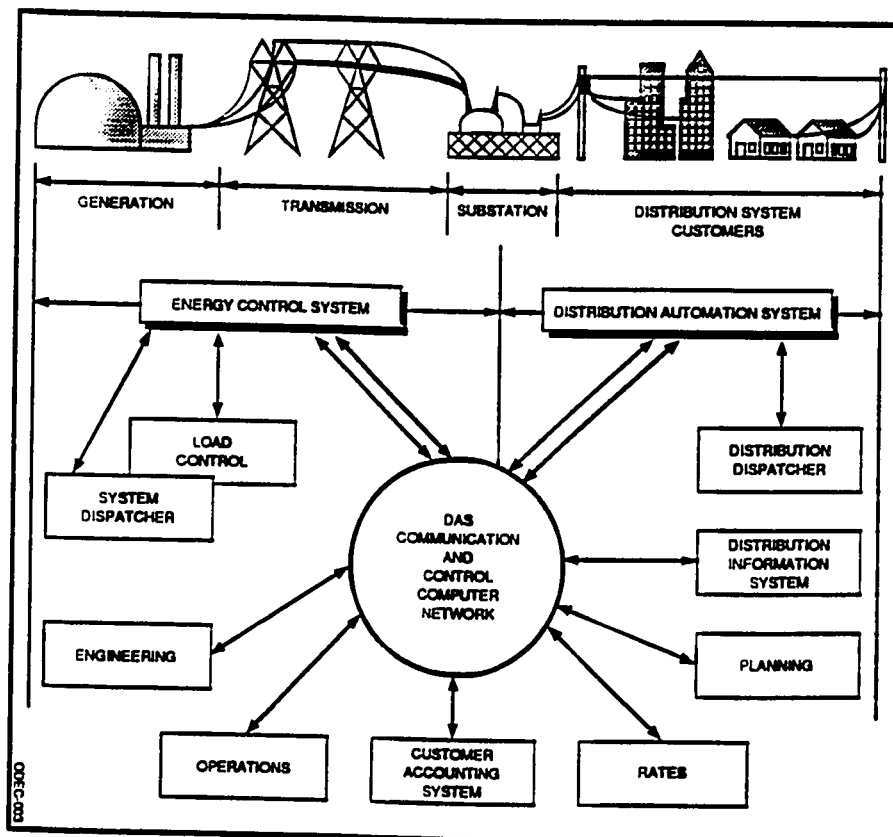


Figure 5-1: The Utility System with Distribution Automation

Load Management (LM) involves the process of controlling utility system loads by the remote control of individual customer loads. Control includes suppressing or biasing automatic control of cycling loads, as well as load switching. LM can also be effected by inducing customers to suppress loads during utility selected daily periods by means of time-of-day rate incentives. Execution of load management provides several possible benefits to the utility and its customers. Some of the benefits are as follows:

- o Maximizing utilization of the existing distribution system can lead to deferrals of capital expenditures.
- o Minimizing the requirement for more costly generation or power purchases by suppressing loads.
- o Relieving the consequences of significant loss of generation or similar emergency situations by suppressing load.
- o Reducing cold load pickup during re-energization of circuits using devices with cold load pickup features.

Expert system applications in power systems have made tremendous strides in the last decade and will continue to

do so as time progresses. Many applications including some online implementations have come into existence [43]. However, application of expert systems in the DA area have been lagging those in the EMS area. A summary evaluation of the state of the art in application of expert systems in DA is provided in [44].

This chapter has two main objectives. The first objective is to present the development details of an expert system shell. The implementation of the shell is in its early stages and is expected to improve (and become more general) as time progresses. The second objective of this chapter is to present the load management expert system which was developed using the shell (mentioned above). The present implementation of the expert system aids the DA operator during emergency conditions. The expert system was developed in an EMS/DA environment and tested on an actual DA system.

5.2 THE ODEC DA PROJECT

The Old Dominion Electric Cooperative's (ODEC) DA system was chosen as the test utility. ODEC is an electric cooperative located in Virginia which consists of 12 member sites. The utility functions purely as a distribution system and buys power from Virginia Power and Delmarva Power. The DA project is organized hierarchically with a

central DA center also called the Coordinating system and each of the members called the member systems. An overview of the software design can be seen in Figure 5-2 ODEC System Software Overview.

Each system (either at the member site or at the coordinating site) is divided into three main parts.

- o Engineering system: This includes the application programs such distribution SCADA, Load management, Load forecast, Historical data retrieval and collection. There also exists a software interface (EMETCON{**}) which controls the load control field devices.
- o Utilities and Services: This includes services such as alarms, reporting functions, and other utilities which gather data for the various trending devices.
- o Basic System Components: In addition to the computer operating system, this includes a comprehensive software environment for the development and support of real-time information systems.

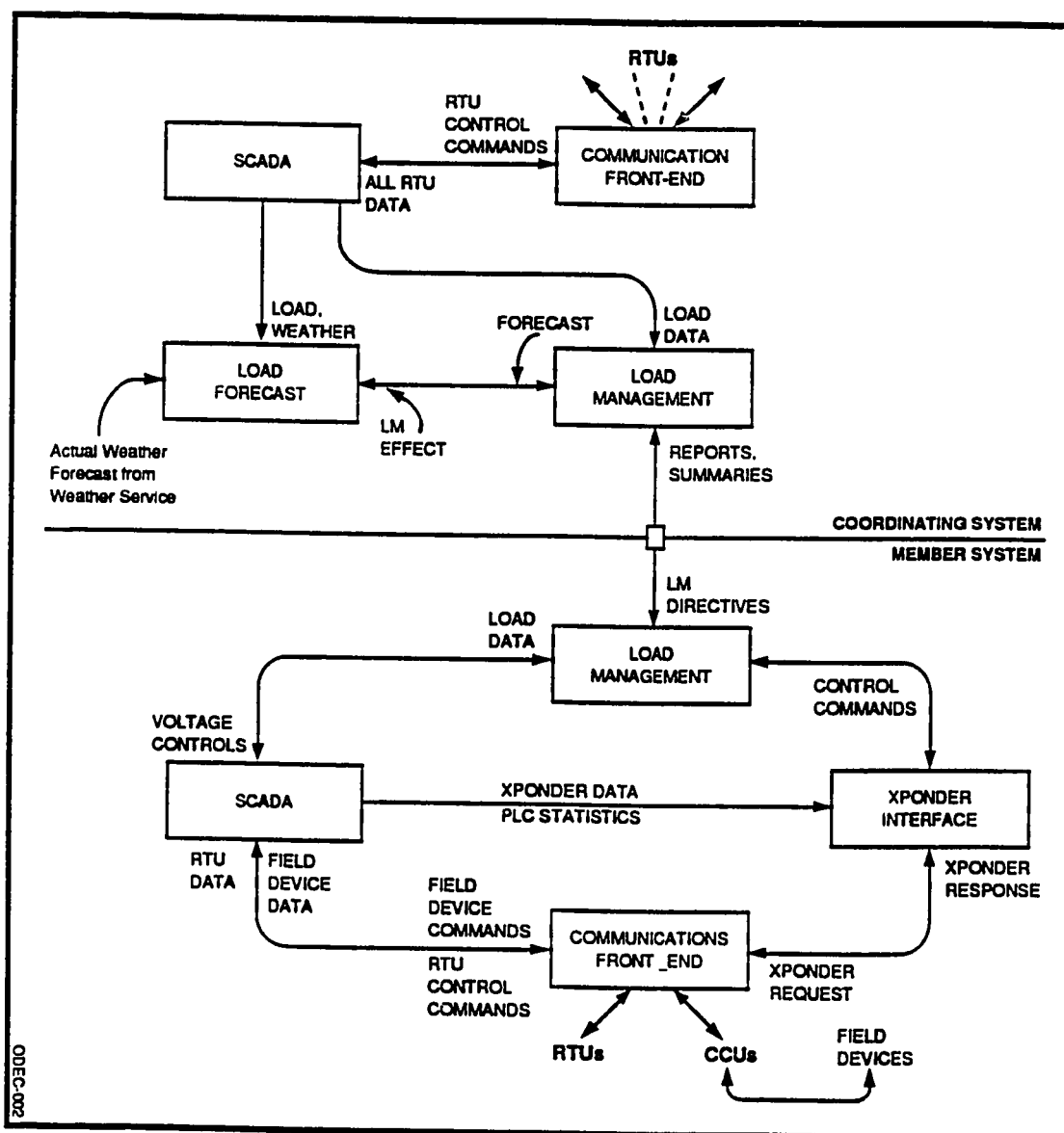


Figure 5-2: ODEC System Software Overview

This environment is called HABITAT{*} [45] and consists of the following:

- A DataBase Management System (DBMS) for developing and managing data structures in real-time environments.
- A user interface management system fully integrated with the DBMS.
- Software utilities to support development of run-time applications.

5.2.1 Load Management (LM)

The present implementation of LM provides an algorithmic approach to minimizing the monthly coincident peak (MW demand) and thus the cost of power purchased. This is because ODEC is charged based upon the peak demand. It uses the output of a load forecast program as its input and (for those hours forecasted to have the potential to be the peak for the month) provides a strategy to minimize the peak. The strategy is then passed to the EMETCON{**} interface which in turn controls the load control devices in the field. Emergency procedures for shedding load (Scram) are available as well as a means of testing the potential worth of different load shedding strategies (Nicking) [46]. The sub-functions Nicking and Scram are

both described in greater detail below.

The effect of the LM strategy on the load is passed back to the load forecast program. In this way, load forecast can update its model without having the result of LM included in the adaptation.

The LM implementation is organized in a hierarchical fashion in that the coordinating system is responsible for overall system optimization and controls are passed to the member systems for local implementation. The software at the coordinating system recognizes the two different suppliers and separately optimizes for each group. The resulting controls are passed on to the member systems for review and implementation. Each member system can choose to implement one of the following:

- o automatically implement the instructions from the coordinating system,
- o manually change them to something else, or
- o replace them altogether.

The various reporting functions keep track of the decisions taken.

5.2.2 Nicking

'Nicking' is a method used to calculate the amount of load available or the energy saved due to load management. Upon request by the operator, one or more load groups at an operator-specified substation is temporarily shed in order to evaluate the potential for load reduction. This function automatically performs the following sequence of activities:

1. record the most recently telemetered load at the selected delivery point,
2. shed the selected load groups (or reduce voltage group) for one 5-minute period,
3. record the new level of load at the delivery point for the 5-minute period of load "nicking",
4. re-connect the shed loads (or return voltage level to nominal for voltage nick),
5. record the new level of load at the delivery point for this 5-minute period of restored load,
6. average the the two non-nicking intervals (first and last 5 minute intervals) and subtract from it the load during the 5 minute period of load nicking, and

7. display the average load while not nicking, the load while nicking, and the difference which represents the amount of available controllable load.

5.2.3 Scram

Scram is a function used by the utility when there is a need to reduce load suddenly. There could be a variety of reasons for a utility to invoke the Scram function. They could be one or a combination of the following:

- o Severe generation/load mismatch. This could happen due to many reasons. Some of them are: 1) A purchase transaction got suddenly terminated due to tie-line failure or an emergency in the utility selling power, or 2) a sudden failure of one of the generators and reserve requirements not being met.
- o Economics: In some cases, the utility may be buying power at a rate which was determined by a certain value of peak MW transfer. If the operator found that the (short term) forecasted peak would be greater than the pre-determined value, then the scram function could be invoked for peak-shaving.

- o Operator demand: The ODEC operator could invoke the scram function due to an emergency in the utility's control area itself.

Some of the load management possibilities are:

- drop a class (for example, small water heaters) of water heaters
- drop a class of air conditioners or
- drop all loads under load management.

The Scram function is presently done manually wherein the operator selects a certain load class and performs an action which then proceeds to drop all the loads in that load class or drops all load classes which drops all of the loads under load management.

5.3 EXPERT SYSTEM SHELL DEVELOPMENT

An Expert System (ES) has been defined [27] as a computer system or program which incorporates one or more techniques of Artificial Intelligence (AI) to perform a family of activities that traditionally would have to be performed by a skilled or knowledgeable human. The knowledge necessary to perform at such a level and the inference procedures used can be thought of as a model of an expert in a specialized field or domain of interest.

In order to satisfy the three main points mentioned in section 1.3.2 *Requirements of an Expert System for Power System Application*, two possible approaches can be considered: use a standard expert system shell, or develop a new one in HABITAT{*}. The former approach presents the advantages of a standard product. However, it has the following disadvantages:

- o development of mapping programs to allow the ES to access data in the HABITAT{*} databases,
- o data maintenance problem of maintaining some data in two places: HABITAT{*} database and the ES shell's internal database,
- o non-compatible user-interface between the two systems, and
- o no direct access to the use of mathematical software already available in the DA system.

The use of the latter alternative of developing a primitive expert system shell in HABITAT{*} does not have the disadvantages mentioned above. The rule base would exist in HABITAT{*} (the same environment in which the DA system has been implemented). An implementation of this kind automatically allows the user to view the rules (and modify them) by using the standard user interface management system supported by HABITAT{*} [47]. This implementation

also allows the inferencing system to display the reasoning behind the decision making process using the message logging subsystem. The main disadvantage here is the effort involved in the development of a shell from scratch.

5.3.1 Database Structure Of The Knowledge Base

The structure (a hierarchically organized form) is shown below:

RULE

```

|
|__CONDITION (or set of conditions connected to
|              each other with boolean expressions)
|
|__ACTION (or set of actions connected to each
|              with boolean expressions)

```

Where, 'RULE', 'CONDITION', and 'ACTION' are records which contain a number of fields. For example: the structure of the CONDITION record is :

FIELD_CONDITION: The name of the actual field in the database which needs to be tested.

RECORD_CONDITION: The name of the actual record in the database which needs to be tested.

FLAG_CONDITION: If the field is a boolean set of bits, then this will contain the name of the mask.

ID_CONDITION: If a particular record needs to be tested, then this will contain the ID of the record.

COND_CONDITION: Conditionality to be tested. This could be one of - 'GT' (greater than), 'GE' (greater than or equal to), 'LT' (lesser than), 'LE' (lesser than or equal to), 'EQ' (equal to), 'SET' (if the boolean bit is set), 'RESET' (if the boolean bit is reset).

VALUE_CONDITION: The actual value being tested.

Example: CONDITION record data:

FIELD_CONDITION: ID

RECORD_CONDITION: SEASON

COND_CONDITION: 'EQ'

VALUE_CONDITION: 'SUMMER'

Actual Condition: "If Season is summer"

A comparison of the CONDITION record and the example show how the information provided in the condition record identifies the actual field in the database which needs to be tested.

If more than one condition needs to be tested, then the appropriate number of condition records are inserted (one for each condition) and they are connected to each other by boolean expression. The design assumes that the person creating the rules database has a certain amount of knowledge regarding the structure of the database which is being tested (in this case, the load control database).

The action part of the rule contains the action which needs to be performed. This structure also identifies the database field (directly) that needs to be modified and the modification. In this area, the philosophy behind the design of the ACTION record is very similar to that of the CONDITION record. If more than one action needs to be taken at the same time, they are also connected together by a boolean expression.

5.3.2 The Inferencing Process

At this stage, the rule base is one long contiguous set of rules. The inference engine performs two passes over the rule base. In the first pass, it uses the forward chaining method (data driven) and goes through the rule base identifying the set of rules whose 'condition' (or set of conditions) has tested true. The selected rules are then placed in the conflict set. In the second pass, it goes through the conflict set and applies certain 'rules' of

conflict resolution. The design of the 'rules' of conflict resolution are such that only one rule is finally selected and 'fired' (its action part is implemented).

5.4 EXPERT LOAD MANAGEMENT (ELM)

In the DA control room, an operator typically uses past experience of how much load there is to drop under each load class. He/she then mentally prioritizes them based on knowledge of season, time-of-day, day-of-week and other heuristic knowledge. One example of heuristic knowledge is: an operator may not want to shed air-conditioners in the summer except as a last resort.

ELM models the knowledge and experience of the operator. As a new rule is placed in the knowledge base, it can immediately utilize that knowledge. This is exactly how an operator learns either through experience gained from a new scenario or when he/she has to adapt to a new policy/corporate contract. ELM also gathers real-time data about available loads at different times of the year/day that can be shed. It then automatically incorporates this data into the decision mechanism of the SCRAM function. As the real-time system changes, or more load/load classes become available, the database is automatically adjusted for that and hence available to ELM.

Figure 5-3 **ELM: Software Design Overview** shows three main components: 1) Smart_operator, 2) Smart_nick, and 3) Smart_scam. They are described in greater detail in the sub-sections below.

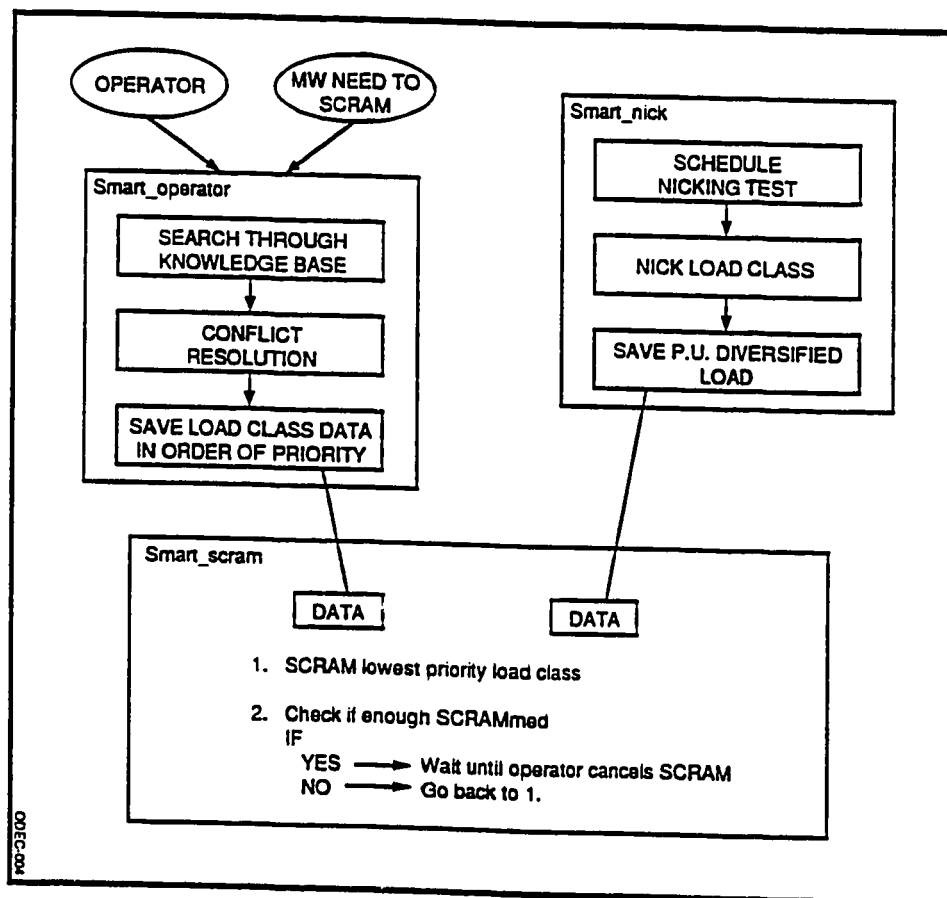


Figure 5-3: ELM: Software Design Overview

5.4.1 Smart_operator:

The main function of the expert system is to prioritize the available load classes based on knowledge programmed into the knowledge base. A sample set of rules are provided in Section 5.5 - *Some Example Rules*. As operating procedures and/or contracts change, more rules can be added to the knowledge base and will be available to the Smart_operator inferencing logic.

5.4.2 Smart_nicking:

The nicking test has been modified to allow it to automatically gather and store information. The changes are as follows:

1. The nicking test now allows system-wide nicking of an entire load class (e.g. large water heaters) at a time.
2. The process manager now repeatedly executes the nicking test at a specified interval. If the interval is set at say, every 5 hours, nicking test values for each hour would be available in 120 hours (24 hours x 5) provided other load reduction actions are not taking place. Each load class is staggered for start times. For example; Large Water Heaters (LWH) are nicked in hours 1(day 1), 6, 11, 16, 21, 2(day 2) etc. ; Average

Water Heaters (AWH) are nicked in hours 2(day 1), 7, 12, 17, 22, 3(day 2) and so on.

3. The real-time per unit diversified load values from the nicking test are accumulated and stored in the database. These values are calculated by dividing the load reduction of a given load class by the number of devices controlled. Examples of this output are shown in Section 5.4.3 - *Test Results*. Each entry is stored by load class, season, day-type (day of week), holiday, and hour of day. A weighted average is used to combine the old value with a new one. $N(\text{oldvalue}) + (1-N)(\text{newvalue})$ where $0 \leq N \leq 1$.

Values may be manually entered into the database to correct values taken when the normal number of devices are not controllable (due to equipment maintenance, failure, etc.).

5.4.3 **Smart_scram:**

This is started by the operator or as an option automatically based on a need for immediate load reduction. Once it is triggered, it calls `smart_operator` which uses the knowledge available, to prioritize the available load classes. The following sequence of operations take place after this:

1. look into the nicking test database for the first load class (in priority order) and retrieves its diversified load for the current season, day-type, holiday (true/false), and hour-of-day,
2. determine the number of available devices for the load class and calculate the available load (MW) that can be SCRAMmed for this load class,
3. compare the available load (in this load class) with the total MW needed to be SCRAMmed. SCRAM the load just identified,
4. if more load is needed to be SCRAMmed, go to the second load class in priority order and continue until enough load has been SCRAMmed, and
5. wait until the operator cancels SCRAM or as an option, cancel SCRAM automatically.

5.5 SOME EXAMPLE RULES

An example set of rules is presented in this section:

1. IF
 SEASON IS SUMMER AND
 DAY IS MONDAY AND
 HOUR OF THE DAY IS LESS THAN 17:00

 THEN

SET PRIORITY OF AIR CONDITIONERS TO 15
SET PRIORITY OF SMALL WATER HEATERS TO 10
SET PRIORITY OF AVERAGE WATER HEATERS TO 7
SET PRIORITY OF LARGE WATER HEATERS TO 3

2. IF

SEASON IS WINTER AND
DAY IS MONDAY AND
HOUR OF THE DAY IS LESS THAN 8:00

THEN

SET PRIORITY OF SMALL WATER HEATERS TO 10
SET PRIORITY OF AVERAGE WATER HEATERS TO 7
SET PRIORITY OF LARGE WATER HEATERS TO 3
SET PRIORITY OF AIR CONDITIONERS TO 1

3. IF

SEASON IS WINTER AND
DAY IS MONDAY AND
HOUR OF THE DAY IS GREATER THAN OR EQUAL TO
8:00 AND
HOUR OF THE DAY IS LESS THAN OR EQUAL TO 17:00

THEN

SET PRIORITY OF SMALL WATER HEATERS TO 3
SET PRIORITY OF AVERAGE WATER HEATERS TO 7
SET PRIORITY OF LARGE WATER HEATERS TO 10
SET PRIORITY OF AIR CONDITIONERS TO 1

4. IF

SEASON IS WINTER AND
DAY IS MONDAY AND
DAY IS A HOLIDAY AND
HOUR OF THE DAY IS GREATER THAN OR EQUAL TO
8:00 AND
HOUR OF THE DAY IS LESS THAN OR EQUAL TO 17:00

THEN

SET PRIORITY OF SMALL WATER HEATERS TO 10
SET PRIORITY OF AVERAGE WATER HEATERS TO 7
SET PRIORITY OF LARGE WATER HEATERS TO 3
SET PRIORITY OF AIR CONDITIONERS TO 1

5.6 DESCRIPTION OF THE TEST SYSTEM

The DA system had the following components:

- o Load classes:
 1. Large water heaters (LWH).
 2. Medium water heaters (MWH).
 3. Small water heaters (SWH).
 4. Air-conditioners (AC)
 5. Voltage control (VC).
- o Seasons:
 1. Spring
 2. Summer
 3. Winter
 4. Fall
- o Day-types:
 1. Monday
 2. Tuesday
 3. Wednesday
 4. Thursday
 5. Friday
 6. Saturday
 7. Sunday
- o Hour-of-day: 1 through 24.
- o Holiday

5.6.1 Test Results

A comparison between the existing nicking/scram and the ELM technique is difficult. This is because, in the existing system, both of these are performed manually and hence totally depend upon the operator's decision. However, in this section, the author will show results which attempt to prove that the expert system works.

Assumptions: To facilitate testing, the load variations

are simplified through each day. Also, the variations of loads on Monday through Friday have been made similar to Saturday and Sunday. Only Monday-Friday are given below.

Note: The numbers given are for testing purposes only, and do not represent values obtained from the field.

Two scenarios were tested. The first scenario was a monday afternoon in summer. The second scenario was a monday morning in winter. Figures 5-4 **Test Scenario I**, and 5-5 **Test Scenario II** presents the following information in sequential order:

- . Input data
- . Output of Smart_operator
- . Output of Smart_nick
- . Output of Smart_scram.

5.6.2 Inferences Drawn

At this point a comparison between the present mode of operation and the ELM mode must be explained.

The output of SMART_OPERATOR provides the list of available load classes in order of priority. This module essentially performs the reordering based upon certain knowledge (heuristic in nature). This feature is entirely new. It

did not exist earlier. The improvement in nicking (as evidenced in SMART_NICK) automated the nicking process (this was done manually earlier) and made a full 24-hour range of (current) data available for each load class.

Input Data

Season = SUMMER
 Day-type = monday
 Time-of-day = 15:00 Hrs
 Holiday = .false.
 MW to be dropped: 20 MW

Output of Smart_operator

Rule base output = AC(15), SWH(10), AWH(7), LWH(3)
 (The values in parenthesis are the newly assigned priority numbers)
 Number of devices per load class = LWH(20000), AWH(50000),
 SWH(20000), AC(20000).

Output of Smart_nicking test (summer):

Load Class	Diversified Demand (KW/device) for each hour (Monday-Friday day-type)						
	1 - 5	6 - 7	8	9	10 - 16	17-18	19-24
LWH	0.4	0.5	0.6	0.5	0.4	0.5	0.4
AWH	0.3	0.4	0.5	0.4	0.3	0.4	0.3
SWH	0.2	0.3	0.4	0.3	0.2	0.3	0.2
AC	0.0	0.3	0.4	0.3	0.2	0.2	0.0

Output of Smart_scam

ELM first shed LWH: Load relief: $20000 * 0.4 = 8$ MW

Total relief: 8 MW

ELM then shed AWH: Load relief: $50000 * 0.3 = 15$ MW

Total relief: 23 MW

Since the required MW relief was 20 MW it stopped at this point.

Figure 5-4: Test Scenario I

Input Data

Season = WINTER
 Day-type = monday
 Time-of-day = 07:00 Hrs
 Holiday = .false.
 MW to be dropped: 30 MW

Output of Smart_operator

Rule base output = SWH(10), AWH(7), LWH(3), AC(1)
 (The values in parenthesis are the newly assigned priority numbers)
 Number of devices per load class = LWH(21000), AWH(52500),
 SWH(20000), AC(20000).

Output of Smart_nicking test (winter):

Load Class	Diversified Demand (KW/device) for each hour (Monday-Friday day-type)						
	1 - 5	6 - 7	8	9	10 - 16	17-18	19-24
LWH	0.4	0.5	0.6	0.5	0.4	0.5	0.4
AWH	0.3	0.4	0.5	0.4	0.3	0.4	0.3
SWH	0.2	0.3	0.4	0.3	0.2	0.3	0.2
AC	0.0	0.1	0.2	0.2	0.2	0.1	0.0

Output of Smart_scram

ELM first shed AC: Load relief: $20000 * 0.1 = 2$ MW
 Total relief: 2 MW
 ELM then shed LWH: Load relief: $21000 * 0.5 = 10.5$ MW
 Total relief: 12.5 MW
 ELM then shed AWH: Load relief: $52500 * 0.4 = 21$ MW
 Total relief: 33.5 MW
 Since the required MW relief was 30 MW it stopped at this point.

Figure 5-5: Test Scenario II

Finally, SMART_SCRAM uses the outputs of SMART_OPERATOR, and SMART_NICK and drops just enough load to satisfy the load (MW) demand. In the present implementation of SCRAM the operator would actually position the cursor to the load class which he/she wanted to drop and 'SELECT' it.

{*} HABITAT, EASEL, and RAPPORT are registered trademarks of ESCA Corporation, Bellevue, Washington.

{**} EMETCON is a registered trademark of ABB Corporation.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

6.1 CONCLUSIONS: WHAT HAS BEEN ACHIEVED

Since there are two main pieces of work reported in this dissertation, their achievements are reported separately:

6.1.1 Expert Load Shedding

The issue of load shedding was studied in great detail. The present utility practices and their deficiencies were pointed out. Different possibilities for improving the state-of-art were studied and analysed (this included a literature search). A design for an intelligent operator's load shedding aid was developed for implementation based upon certain key criteria and a prototype was implemented and tested on a study system.

The results obtained from testing ELS on a study system prompted the author to improve the implementation and go all the way towards full-scale implementation and testing of the ELS in a real-time EMS/DTS environment and test it

on an enhanced version of the New-England 345-kV system. Initial test results have been valuable and some of following conclusions can be made:

- o Existing undervoltage protection methods are not adequate to protect the power system from voltage collapse.
- o ELS provides an overall system-wide viewpoint allowing the operator to spot trouble spots and notice trends. Some of the trends that can be noticed from the ELS master display are: spread of voltage weak areas, change in reactive power need in each voltage weak area, and others.
- o ELS allows the operator to operate it (ELS) in either an automatic or advisory mode thereby maintaining flexibility.

6.1.2 Expert Load Management

In this work two main accomplishments have been reported:

1. A design for an expert system shell to be implemented in a real-time database management system.

2. Results of the implementation of an expert system (designed using the shell presented above) to aid load management in emergency situations.

The following conclusions can be arrived at from the ELM implementation in the ODEC project environment:

- The Nicking test has been automated to provide better data to allow Scram to exercise better judgement before making a decision.
- Heuristics obtained from consultations with the system operators have been used to pre-prioritize the available list of load classes based upon system conditions.
- Scram can now be placed in an automatic/advisory mode allowing the operator to scram the most eligible load class to obtain the needed load relief.

6.2 DIRECTIONS FOR FUTURE RESEARCH

Any dissertation work should point towards possibilities for future research in this and other related areas. Some directions for future research are described in this chapter. The author is already making progress in some of these areas.

6.2.1 Expert Load Shedding

The area of voltage stability is receiving increasing interest in research circles and some of the leading research areas have been presented in section 1.2.3 *State-of-the-art Approaches*. Two research areas have been targeted for future research. The first area is the understanding of the cause of voltage instability [19, 20]. The second area is the work done by Tom Overbye and his associates at Madison Gas and Electric [25, 26]. The second area is being reviewed with more interest because of the possibilities for its use in training an Artificial Neural Network (ANN) to provide an online analysis of the voltage security of the power system.

The author has already been experimenting with the use of a combination Artificial Neural Network/Expert System approach for voltage stability enhancement [50]. However the work is still preliminary in nature and more material will be presented in future as warranted.

6.2.2 Expert Load Management

Preliminary results from testing the expert system ELM on a DA system have shown promise and sufficient cause for further development. Three main areas have been targeted for further research.

- o Expanding the design of the expert system shell to make it completely general. The authors' aim is to provide an environment for expert system development in any HABITAT{*} installation.
- o Expanding the rule base of ELM. Some of the areas currently under investigation are problem detection, diagnosis and automatic correction (either with or without operator intervention). This will obviously require further interaction with the 'experts' in the DA area and will be an ongoing process.
- o Automatic Smart_restoration of load classes to back out of scram situation.

6.2.3 Combination ELS And ELM

It must be recognized that at a very fundamental level, both load shedding and load management (LM) provide load relief. Typically load shedding is used as an emergency measure whereas load management is used more for economic purposes (SCRAM being an exception). However the two applications are still separated between the two control areas (EMS and DMS) with essentially manual (operator-to-operator) communication between them.

It is the author's contention that the two could be linked

with automatic/operator advisory links in such a way that the load management application (in the DMS environment) could be used as the distributive arm of load shedding. This achieves a very important step in emergency control. When the EMS requires load relief the load shedding application would calculate the amount of load relief needed and pass this value on to the DMS center. There the ELM function could then activate the SCRAM (SMART_SCRAM) function to scram the LM loads.

What this essentially achieves is the availability of load relief without actually tripping circuit breakers. This, in effect takes load shedding to a whole new dimension.

(*) HABITAT, EASEL, and RAPPORT are registered trademarks of ESCA Corporation, Bellevue, Washington.

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