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THE CONTROL OF POWER SYSTEMS DURING DISTURBED AND EMERGENCY CONDITIONS

U.G. KNIGHT

Study Committee 39 (Power System Operation and Control)

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CHAPTER 1

BACKGROUND

Cigre has supported studies into the control of power systems during disturbed conditions since the mid 1970's. Much of the work has been done under the umbrella of the Study Committee on power system operation and control - Study Committee 32, responsible for planning and operations until 1978, Study Committee 32 responsible for operational work only from 1978 to 1982 and Study Committee 39, again operational work only since 1982.

Each of these Study Committees from 1973 until 1986 supported a Working Group (WG 01) on Emergency Control (the term often used for the control of power systems during disturbed conditions) which met about twice a year. A number of papers were produced on topics supported by the Study Committee and their contents, outlined below, have been used in the preparation of this brochure. In chronological order, the papers were:

"A survey of control strategies in emergency", (1).

This paper published at the request of the Chairman of Study Committee 32, Mr. M. Valtorta, summarised the replies to a questionnaire on strategies used by utilities to contain the effects of abnormal disturbances. The questionnaire was addressed mainly to countries with representatives on WG 01 and replies were received from 12 countries, representing 25 utilities.

The topics studied for each utility included:

(i) the security criteria used in operation

(ii) the likely actions taken to prevent a disturbance spreading through the system; sequences of actions in order of priority for various contingencies were summarised. The analysis included the probable worse effect of various contingencies and the priorities for the different containment actions for each type of contingency;

(iii) a similar analysis for actions to restore a system to normal operation;

(iv) times required to take the different actions;

(v) summaries of data telemetered, alarms provided and basic acquisition of telemetered data;

(vi) predictive studies implemented;

(vii) methods of decision making and means of implementation for restoration.

"Remedial measures to reduce the incidence and effect of major disturbances on power systems", (2).

This paper reported on the results of an international survey of actions taken by utilities to reduce the incidence and effect of major disturbances and introduced directly as a result of such disturbances. The information was obtained in reply to a questionnaire circulated to members of Study Committee 32 in December 1976. It requested information on each disturbance such as its initial cause and any relevant system abnormalities at the time, the ensuing events in the development of the disturbance highlighting significant factors in this and in restoration, recommendations made to reduce the future incidence of such disturbances and their effectiveness if implemented, observations on the adequacy of telemetry and instrumentation during the disturbance and finally notes on techniques of special interest used in subsequent analysis of the disturbance.

Replies were received from 16 countries describing 50 disturbances in 26 utilities over the period 1961 - 1976 (all but 9 of the disturbances were from 1970 onwards). The tabular summaries provided in the paper included for each disturbance:

(i) weather and prior system conditions;

(ii) initial cause and subsequent sequence of events;

(iii) duration of spread of disturbance, frequency variation during this time and demand disconnected;

(iv) an expansion on significant factors in the initiation, spread and restoration.

The recommendations and actions implemented by the various utilities were summarised including comparisons between the utilities highlighting common problems.

"Aids for the emergency control of power systems", (3).

This paper published at the request of the Chairman of Study Committee 32 was a more general study of emergency control. One of its main purposes was to provide guidance on aids which should be considered by utilities wishing to develop their facilities for control in emergencies.

A wide range of topics was considered including definition and objectives of emergency control, typical patterns in the evolution and containment of disturbances, a review of the present state of the application of aids for emergency control and a proposal for selected aids and procedures, the role of emergency control in the future and the evolution of aids for emergency control. Perhaps the most important features of this paper were the suggestion of typical ways in which a disturbance evolves and representing this in graphical form, the role of emergency control in the future and the discussion on costs and benefits.

"A report on a further survey of major disturbances" (4).

Following the publication of the 1978 paper a new questionnaire seeking information on disturbances was circulated to all member countries of Cigre in 1981. The resulting paper reported on 15 incidents over the period 1978-1981. Although the presentation was similar to the earlier paper, two significant new features were introduced - the concept of classifying the severity of a disturbance in terms of system minutes [5] and the inclusion of diagrams to show first the evolution of a disturbance and then the restoration process.

"The implementation of emergency control", (6).

The motivation of this paper was to consider the application of computers and aspects of centralisation in emergency control. Following a definition of emergency control which necessarily considered possible system states, a framework for existing and future types of automatic control was put forward. This included the concept of "adaptive" emergency control in which ideal containment and restorative actions would be determined based on observations of pre- and post-fault states of the system. The scope for improvement in emergency control facilities was assessed, leading into the impact of system structure on emergency control and the best indications by which to detect an emergency situation. A logical flow diagram for simple applications of adaptive control was included, one of a number put forward in the full paper presented to the Study Committee. The paper concluded with comments on technical developments in the field.

"A review of emergency control of power systems", (7).

This paper reviewed the (then) current status of control of power systems during emergency conditions dealing broadly with the steps that can be taken to minimise the risk of a major disturbance occurring and, if it should occur, its containment and the restoration of normal conditions. There was some discussion on operator training and on restoration, including black start.

"System restoration following a major disturbance", (8).

This paper collated information from 16 utilities in 13 countries on restoration strategies, provided in response to a questionnaire circulated to members of WG 01. The paper included information on automatic disturbance limiting mechanisms such as generation rejection and islanding, load rejection and black start capability of generation, automatic switching of transmission for restoration, security of auxiliary supplies, training of control operators and priority of actions in the restoration process.

"Third survey of major disturbances", (9).

The paper summarised information on 24 disturbances provided in response to the questionnaire mentioned earlier. The majority of these occurred over the period 1980-1985. In addition to commenting on these disturbances, a brief comparison was made with the two earlier surveys to see for instance if there is any trend in types of disturbances. The relationships between extent and severity of disturbances and restoration time were also considered.

"A note on strategy of restoration", (11).

Dr. Berntsen of Norway suggested at a meeting of WG 01 that there might be a relationship between a preferred strategy of restoration following a major disturbance and system structure [10]. This hypothesis was discussed at length in Working Groups meetings and, following Dr. Berntsen's move to other work, summarised in this note. The conclusion reached was that it was not possible to establish any correlation between strategies of restoration and characteristics of systems. Both from this and other studies however, there is much commonality between the restoration practices of utilities.

The papers listed above have been those prepared with the support of first Study Committee 32 and then 39 of Cigre. Other sources of information in this area are a series of annual reports from the North American Electricity Reliability Council (12), a brochure from UCPTE (13) and some papers in its annual reports, and a number of reports by IEEE Task Forces (14, 15, 16). Study Committee 32 (later 39) also set up a Working Group 05 to study the related field of reliability of bulk electricity systems and several papers have been published (5, 17, 18). Individual utilities sometimes publish reports on their own disturbances (e.g. 19, 20, 21, 22, 23). The Study Committee also supported studies by its Working Group 04 on the performance of generating plant during disturbed conditions (24, 25, 26).

CHAPTER 2

SOME GENERAL ASPECTS OF CONTROL AND CONTROL FACILITIES DURING DISTURBED CONDITIONS

INTRODUCTION

As noted in Chapter 1, it has become common practice to refer to system control during disturbed conditions as "emergency control". It is proposed in this chapter to consider the more general aspects of emergency control such as its definition and relationship to system state, objectives, the impact of system structure on methods used, and a conceptual framework for techniques of emergency control (this will be taken up again in chapter 7.)

2.1 DEFINITIONS OF EMERGENCY CONTROL AND RELATIONSHIP TO SYSTEM STATES

Control in emergency can be defined as "the special facilities and procedures provided by a utility to enable it to maintain and restore viable operation following an incident which disturbs the system operating conditions to a point where the available system capacity is no longer sufficient to meet demand in all or parts of the system or where abnormal splits exist within the network."

The term "credible contingency" is often used in these definitions. This is a contingency or fault which has been specifically foreseen in the planning and operation of the system and against which specific measures have been taken to ensure that no serious consequences would follow its occurrence. It has sometimes been called a "defined contingency". A "non-credible contingency" is one, usually more severe and not specifically defined, for which only general preventive measures are taken. As might be expected, a non-credible contingency is much less likely to occur than a credible contingency. Typically the set of credible contingencies will include the loss on fault or otherwise of any circuit or transformer, the largest generator, any busbar. Three phase faults will usually be assumed for stability assessments, occasionally 2 phase to earth for systems with weaker interconnections. Two coincident fault outages are sometimes assumed on well developed systems, perhaps subject to bad weather conditions existing (otherwise a single outage).

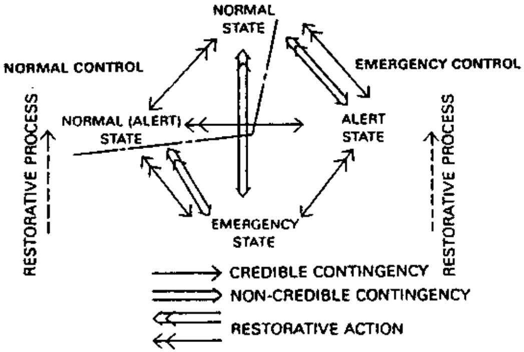

Fig.1 Relationship between System States Contingencies and Types of Control

System states and contingencies can be related as shown in Fig. 1. This gives a second, and in some ways more useful definition of emergency control, as control during the time when the system is in an alert or emergency state or in process of being returned from these states to normal. Normal control is control during the time when the system is in a normal or normal (alert) state.

2.2 THE OBJECTIVES OF EMERGENCY CONTROL

The objectives of emergency control are to prevent a system degenerating into the alert or emergency states but if this does occur, to minimise disruption and restore normal conditions as quickly as possible, without exposing the plant to non-sustainable overloads or abnormal values of frequency and voltage. It will be seen that this introduces the element of time (e.g. "non-sustainable overloads"), and this in turn means introducing time into the descriptions of system states. These then differ in this respect from the definitions put forward by Dy Liacco and widely used in North America, or the Carlsen-Fink ones which have been used Scandinavia. With time specifically incorporated, the system state definitions suggested are:-

<u>Normal</u> - All loadings are within the continuous capabilities of plant, with voltages and frequency within agreed operational limits. System conditions following any credible contingency are acceptable.

<u>Normal (alert)</u> - If a credible contingency occurs, action can be taken within the time scales allowed by plant capability to restore the system to a normal state. Very rapid or immediate action is not necessary.

<u>Alert</u> - This state requires very rapid or immediate action. If a credible contingency occurs the system will enter the emergency state. Alternatively, the existing conditions are such that action must be taken rapidly to prevent unacceptable overloading, voltage conditions, frequency changes, or plant trippings caused by protective gear operation.

<u>Emergency</u> - Unacceptable loading, voltage or frequency conditions already exist on the system, or demand has been lost, or the system is split. Action must be taken immediately to bring the system to an acceptable state.

The term "restorative action" will be used to denote return of the system from one of the alert or emergency states to the normal state. In such action the system is progressed as rapidly as possible from its most abnormal state to a normal state, possibly through a sequence of alert states - refer again to Fig. 1 for the relationship between system states, level of contingency and actions.

Techniques and facilities used for such emergency control can also be used to supplement primary system capacity. Expanding on this, emergency control type facilities may be installed for two broad reasons:-

A - To preserve system integrity following a "non-credible" contingency:-

(1) To maintain as much as possible of the system in a viable operating state following a disturbance, as a result of which the demand cannot be met by the remaining generation and/or transmission capacity without exposing the plant to non-sustainable overloads or operation at abnormal values of frequency or voltage (The combinations of initial system state and disturbance will together in general be more severe than the set of defined contingencies taken for the planning and operation of the system);

and (2) following this to restore a viable operating state, with all demand supplied, as quickly as possible.

B - As an alternative to system capacity:-

(1) In planning, to reduce installed generation or transmission capacity by transiently equalising demand and system capacity remaining after a defined incident, thereby providing the short time necessary to institute measures to restore a viable operating state with all demand supplied. It seems unlikely that any appreciable reduction in generation capacity would be achieved, although the plant mix might be affected.

(2) In operation, to overcome limitations in transmission capacity, in particular caused by delays in consents and construction. The mechanism is as in B(1).

(3) In operation, to reduce immediately available operating reserves, particularly of generation. The mechanism is as in B(1).

Although the procedures and aids to meet these objectives may be similar, or identical, the design problems of the two applications are different. In the first, any combination of equipment faults, outages or human errors may occur affecting the whole or part of the system. Neither the resulting system states nor the necessary remedial actions can be determined except in broad terms. Where the distinction is necessary, this is referred to as "true emergency control" in the remainder of this brochure.

In the second, the abnormal states of the system, and hence the necessary remedial actions are well defined as those resulting from one of a number of defined incidents.

2.3 THE EFFECT OF POWER SYSTEM STRUCTURE ON EMERGENCY CONTROL REQUIREMENTS

Two aspects of this subject are considered below -the effect of system structure on the need for emergency control and the impact the structure may have on the facilities used. In doing this, a classification of structure was introduced as follows (6),

U1 - A utility which is part of a very much larger interconnection and occupies a central position in that interconnection.

U2 - A utility which is part of a very much larger interconnection but is on the periphery of that interconnection.

U3 - A utility which is not interconnected with neighbours or is much the biggest part in any interconnection.

Further classification will indicate broadly whether the utility has a multiply meshed transmission network with thermal rather than stability or voltage limits (sub-classification (a)) or has a lightly meshed transmission network with stability or perhaps voltage rather than thermal limits (sub-classification (b).

2.3.1 Effect of System Structure on the Need for Emergency Control

There appears to be little correlation between the need for true emergency control and system structure. Some general observations are:

U1(a) - This is potentially a very secure system but with some risk posed by undefined cross-system flows caused by external changes. Experience suggests that such risks are not negligible.

U1(b) - There is an obviously greater risk than in U1(a) of external changes causing problems from cross-system power flows. Such systems are also likely to be less secure than U1(a) against the internal non-credible contingency.

U2(a) - These systems may be susceptible to loss of external interconnectors and if this risk is to be minimised there is a need for emergency control of generation and demand which is not dependent on frequency deviations for actuation.

U2(b) - Much as U2(a), but with greater risks from internal non-credible faults.

U3(a) - The security of such a system will depend very much on its own planning, operational planning and control policies.

U3(b) - This system will be similar to the U3(a) system, but probably less secure than against the non-credible contingency.

These general comments assume that the transmission between utilities includes capacity for uncertainty as well as planned power transfers. This reservation, and the level of uncertainty considered, inhibits any general argument that the larger an interconnection the more secure it is likely to be because of the probability that the initiating cause and phenomena during a disturbance will not increase proportionally to the size of the interconnection.

Systems of type (a) are felt to be more secure against the non-credible contingency than those of type (b) because the loading tolerances of thermally limited circuits will be greater in magnitude and duration of overload than those of stability limited systems.

It is possible, and sometimes necessary, to consider an interconnected system of several utilities as one utility from the emergency point of view. Conversely different parts of a single utility can be considered as separate "utilities" within an "interconnection" in which case the comments above would apply to those parts.

A quantitative assessment sponsored by WG 05 (17) indicated that interconnection with neighbouring utilities is an important factor in lowering the frequency of the smaller disturbances (classified as degree 1, up to 10 system minutes*) particularly for large systems. Stability limited (type b) systems experienced significantly more disturbances, at all levels of severity, than thermally limited (type a) systems. Systems above 1000 MW in size have similar numbers of disturbances, greater than the number for systems below 1000 MW. No very large disturbances (above 100 system minutes) were reported for these small systems.

One might conclude that increasing system size if anything increases the need for emergency control facilities (surely an argument for some form of sectioning very large systems during major disturbances) and that the need is more likely to be evident with stability limited than with thermally limited systems.

2.3.2 Effect of System Structure on the Form of Emergency Control

In contrast, the system structure and size can significantly alter the form of implementation of emergency control. Most obvious is the use of under-frequency disconnection of demand. This will not protect a small part, even a whole utility within a large interconnection, against transmission overloads, excessive voltage changes or instability caused by generation loss; in comparison to the total connected capacity, an important local loss of generation is unlikely to influence the system frequency to the extent required to operate under-frequency relays.

An important general question is to what extent system sectioning should be employed. It can be used to isolate utilities from each other, for instance on detection of very low frequencies or oscillatory conditions, and/or within large utilities to isolate disturbed from healthy sections.

The form of transmission constraints are likely to have an important influence. Response times of several seconds to minutes will usually be acceptable for remedial actions to reduce thermal overloads whilst action to prevent transient instability will need to be taken in milliseconds. Actions to rectify unacceptable voltage conditions should probably be taken in the order tens of seconds to minutes.

2.4 A CONCEPTUAL FRAMEWORK FOR FORMS OF IMPLEMENTATION OF EMERGENCY CONTROL

As noted earlier the main differences between the use of emergency control techniques to contain the effect of non-credible contingencies on the one hand and to compensate for deliberate or fortuitous underprovision (by usual standards) of primary equipment on the other hand are in the degree of uncertainty on contingencies, system states to be met and actions. However even when emergency control techniques are employed to contain the effects of non-credible contingencies, normally only very few system variables, not normally correlated with other variables, are used to determine very specific actions.

An "adaptive" emergency control approach can be conceived in which ideal containment and restorative actions are selected based on the observed state of the system. The operator could provide this adaptive feature in an interactive approach, the computer indicating alternative and numerical solutions and the operator making the final choice.

The three basic forms of implementation as shown in Fig 2. The adaptive approach just suggested is shown in Fig 2a, the usual present day form of application in Fig 2b (called "pre-defined logic" emergency control) and the application to reduce capital or operating costs, or to compensate for delays in commissioning in Fig 2c, (see also Chapter 7).

2.5 DESIGN CRITERIA FOR EMERGENCY CONTROL FACILITIES

A number of almost self evident criteria will establish the basic form of an emergency control scheme:

(a) The most appropriate system variable/s should be chosen to initiate emergency action;

(b) the actions taken should in general be the minimum necessary to contain the disturbance, particularly where adjustment of generation output or disconnection of demand are concerned;

(c) the actions should be implemented at the geographical locations on the system where they are most effective to contain the disturbance and run least risk of precipitating further problems.

It may be noted that these points are mainly concerned with making the emergency control adaptive to the actual system state.

Other suggested design criteria are:

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* As defined in (5), the severity of a disturbance in system minutes is the number of minutes of energy at peak load equivalent to the energy not supplied during the disturbance, i.e.

$$\text{System minutes} = \frac{\text{energy not supplied due to disturbance (MWh)}}{\text{maximum system demand met to date (MW)}} \times 60$$

(d) the emergency control system should have a functional reliability such that the probability of avoiding demand disconnection as a result of its successful operation is several times greater than the probability of demand disconnection as a result of its possible maloperation. An alternative, simpler approach would be to seek a reliability from the emergency control system no worse than that obtained from first line protective systems;

(e) the actions taken and the reasons for these should be indicated to the operator;

(f) alarms should be given when the emergency system is not functioning or its correct operation is doubtful (e.g. suspect data);

(g) it should be possible for the operator to override incoming telemetry known to be incorrect and, where pre-defined logic is used, to select alternatives in line with actual power system conditions;

(h) the system must be robust, that is it must meet the criteria and objectives whatever the state of the power system;

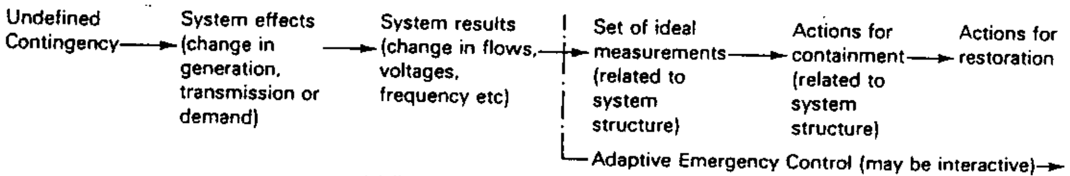
(i) decision and action times must be less than the time at which a further step degradation of the system would occur.

Working Group 05 has recently completed a survey of the performance of emergency control aids (27) which shows an effectiveness, defined as (number of successful operations) divided by (number of successful + unsuccessful + failure operations), of between 90 and 100% for various forms of emergency control.

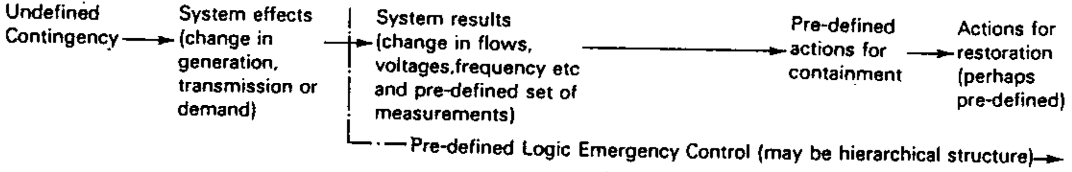
2.5.1 The Relationship between Contingency, Effect on System and Remedial Actions

In order to implement criteria (a) to (i) above, it is necessary to consider the effects on the system of both contingency and remedial actions. These interactions are shown in Tables 1-4. Table 1 shows the effect on the system of four of the major classes of contingency - loss of generation (or import), loss of demand (or export), loss of transmission and loss of transmission causing a system split. The table also includes possible remedial actions, the time to implement these, and methods and system data required to determine the remedial actions, both the essential minimum and a more optimal solution. Table 2 suggests the outcomes if adequate and timely preventative action is not taken.

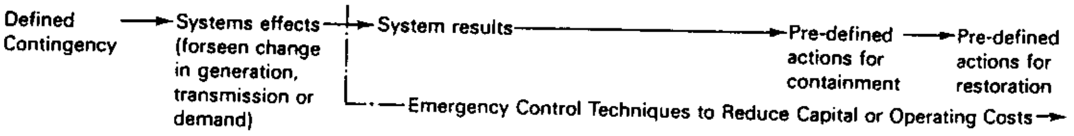
Table 3 correlates the possible remedial actions with the objective sought and is effectively an amplification of column 3 of Table 1. The relative values of various system variables to detect an emergency and locate its position and cause are shown in Table 4 for the basic system structures.



(a) "ADAPTIVE" EMERGENCY CONTROL



(b) "PRE-DEFINED LOGIC" EMERGENCY CONTROL



(c) EMERGENCY CONTROL TECHNIQUES USED TO REDUCE CAPITAL OR OPERATING COSTS OR TO COMPENSATE FOR DELAYS IN COMMISSIONING

Fig.2 A Conceptual Framework for the Development of Emergency Control Techniques

TABLE 1

THE EFFECTS OF DIFFERENT TYPES OF CONTINGENCY AND METHODS TO CONTAIN THESE EFFECTS

System Effect of Contingency	Possible Results (see note)	Containment Method (in order of preference)	Time Available	Logic Used in Containment Method		Data Requirements for Containment	
				Essential	Optimal	Essential	For "Optimal Logic"
A. Sudden loss of generation (or import from other part of system)	System frequency fall (1)	Increase generation	1/10's secs to secs	Freq./power loop on generators	Load flow	Frequency	Network configuration and flows/ voltages
		Reduce demand	1/10's secs to secs	Detect frequency fall and reduce demand	Equate demand reduction to gen. loss; load flow	Frequency	Generation lost; network configuration and flows/ voltages
	Transmission overloads (2)	Increase generation Reconfigure network Reduce demand	secs to minutes	Detect overload and heuristic or decision table	Load flow	Circuit flows or overload indications	Generation lost; network configuration and flows/ voltages
	Transient Instability (3)	Increase generation Reconfigure network Reduce demand	millisecs	Decision table or heuristic logic	-	Generation lost or circuit flows	-
	System Oscillations (4)	Increase generation Reconfigure Reduce demand	secs to minutes	Decision table or heuristic logic	Load flow	Generation lost or circuit flows	Network configuration and flows/ voltages
	System voltage drop (5)	Increase generation Q and/or P Reconfigure Reduce demand	millisecs/ secs to mins (if progressive change)	AVR loop on local reactive sources; decision table or heuristic logic	Load flow	Voltages	Network configuration and flows/ voltages
B. Sudden loss of demand (or export to other part of system)	System frequency rise (1)	Reduce generation	1/10's secs to secs	Frequency-power loop on generators	Load flow	Frequency	Network configuration and flows/ voltages
	System voltage rise (2)	Reduce Q on reactive sources Reduce generation P	1/10's secs to secs to minutes (if progressive change)	AVR loop on reactive sources	Load flow	Voltages	Network configuration and flows/ voltages
	Transmission overload (3)	Reduce generation Reconfigure network	secs to minutes	Decision table or heuristic	Load flow	Circuit overload indication or flows and states	Network configuration and flows/ voltages
	Transient instability (4)	Reduce generation Reconfigure work	millisecs	Decision table or heuristics		Circuit states and flows	
	System Oscillations (5)	Reduce generation	secs to minutes	Decision table or heuristics	Load flow	Demand lost or line flows	Network configuration and flows/ voltages
C. Sudden loss of transmission (no system split)	Transmission overload (1)	Reconfigure Adjust gen Adjust gen and demand	secs to minutes	Decision table or heuristics	Load flow	Circuit overload indications or flows and states	Network configuration and flows/ voltages
	Transient instability (2)	Reconfigure network Adjust generation Adjust generation and demand	millisecs	Decision table		Circuit states and flows	
	System Oscillations (3)	Reconfigure network Adjust generation P and Q Adjust generation and demand	secs to minutes	Decision table or heuristic		Circuit states and flows	Range of change of flows; network configuration & flows/voltages
	Voltage fall (4)	Reconfigure network Adjust generation Q and/or P Adjust generation and demand	secs to minutes (if progressive change)	AVR loop on local reactive sources; decision table or heuristic	Load flow	Voltages and circuit states	Network configuration and flows/ voltages
D. Sudden loss of transmission causing system split	One section may suffer generation deficiency (see A) and the other demand deficiency (see B), requiring the appropriate action in each section.						

Note: The numbers identify cases in Table 2.

TABLE 2

THE RESULTS OF INADEQUATE ACTION TO CONTAIN THE EFFECTS OF CONTINGENCIES

System Effect/ Result Combination	Most Likely Second Stage Effects if Initial Contingency not Contained	
A.1	Frequency fall not halted	- Cumulative loss of generation and system collapse
	Excessive disconnection of demand/poor damping of turbine governors	- Oscillation of frequency/cumulative loss of generation/ system collapse
A.2, B3, C1	Sequential tripping of over loaded circuits	- Uncontrolled system split with necessary consequence of generation/demand imbalances (possibly severe) in separate sections
A.3, B4, C2	Tripping of circuits on e.g. instability	- As A.2
A.4, B5, C3	Build up of oscillations/ circuit trippings	- Uncontrolled system split with consequential generation/ demand imbalances in separate sections
A.5, C4	Cumulative voltage fall as tap changers operate/ transmission capability decreases	- Cumulative loss of generation, circuit trippings-system collapse
B.1	Too responsive governors lead to oscillation of frequency	- Cumulative loss of generation and demand resulting in possible system collapse.
B.2	Voltage rise not halted	- If very severe, extensive faults/ tripping of circuits-possibly resulting in system collapse

TABLE 4

DETECTION AND LOCATION OF EMERGENCY CONDITIONS

TYPE OF POWER SYSTEM	SYSTEM DATA	VALUE		COMMENT
		AS DETECTOR OF EMERGENCY CONDITIONS	AS LOCATOR OF SOURCE OF EMERGENCY	
U1 and U2	Circuit breaker state change	Depends on circumstances	Good	Except for particular case of system split, likely to be used as confirmatory or initiating rather than primary data.
	Frequency	Unreliable, doubtful	Poor. May be valuable to detect system split	
	Total utility transfer	Good	Good in broad terms	
	Circuit flows	Good	Good	
	Voltages	Good for type b systems	Good for type b systems	
	Low frequency oscillations in current and voltages	Valuable, particularly as warning		
U3	Circuit breaker state change	As U1 and U2	As U1 and U2	As U1 and U2
	Frequency	Good (for system up to say 60 GW or so)	Poor	May be useful to detect system split
	Total utility transfer	May be useful		Only relevant to sections of utility, treat them as U1 and U2
	Circuit flows) Voltages) Low frequency) Oscillations)	As U1 and U2	As U1 and U2	As U1 and U2

TABLE 3

ACTIONS AND OBJECTIVES IN CONTAINMENT OF DISTURBANCES

Possible Actions	Objectives									
	Equalise Generation Demand Balance in Whole or Part of System	Restore Frequency	Restore Voltage	Prevent Thermal Overload in Network	Prevent Instability				Isolate Healthy System and Maintain its Integrity	Improve Capability for Restoration
					Steady State	Aperiodic	Oscillatory	Voltage		
Reduce Demand										
i) by distrib. voltage reduction	x	x	x	x						
ii) by disconnection	x	x	x	x	x	x	x	x		
On Generation										
i) reduce or increase (1)	x	x(2)	x(3)	x	x	x	x			
ii) trip	x	x(2)		x		x	x			
iii) isolate onto auxiliaries									x	x
iv) governor feed back					x	x	x			
v) dynamic braking						x				
vi) fast valving						x				
vii) fast excitation					x	x	x	x		
viii) by-pass valving										x
ix) pumped storage operating mode	x	x	x	x	x		x			
x) load station aux. gas turbines	x	x	x						x	x
xi) load hydro & main gas turbines	x	x	x	x	x					x
On Network										
i) auto-reclose (high speed)			x	x		x				x
ii) auto-reclose (slow speed)			x	x						x
iii) series capacitor insertion					x	x				
iv) section network									x	x
v) adjust shunt compensation (including SVC's)			x			x	x	x		

Note: (1) - the appropriate action will depend on the circumstances.
(2) - for example, reduce or trip generation if the frequency is high.
(3) - for example, increase generation if the system voltage is low because of excessive power flows.

CHAPTER 3

REVIEW OF TYPICAL MAJOR DISTURBANCE SITUATIONS

INTRODUCTION

It is proposed in this chapter to review the results of the surveys on major disturbances. As noted in the list of papers, there have been three of these reporting on some 90 disturbances classified as major by the utilities involved. Most occurred in the period 1970-1985. This does not exhaust the published information. The North American Reliability Council publishes annual reports of the most interesting disturbances which have occurred in its area (USA and eastern Canada) whilst information on most of the really major disturbances is published on an ad hoc basis by the utility concerned (see e.g. Refs. 12, 19-23).

Following an outline of the questionnaires some collated statistics for the disturbances are provided. This is followed by descriptions of the typical ways in which disturbances may evolve. The chapter concludes with comments on the changing pattern of disturbances over the years.

3.1 THE QUESTIONNAIRES

The first questionnaire was circulated to members of the Study Committee in December 1976. A second questionnaire was circulated in 1981 to all Cigre member countries and was reissued in 1983. The principal changes were that the second questionnaire requested the severity of the disturbance, in terms of system minutes, and included diagrams on which the progress of the disturbance and the sequence of restoration could be indicated.

The main information requested was as follows:

(i) country and utility, utility statistics including control structure;

(ii) weather and system conditions at the time of the disturbance and any significant abnormalities in power system or control;

(iii) quantitative data on disturbance (time duration; demand, generation and reactive power disconnected; frequency variation; restoration times for transmission, generation and demand);

(iv) sequence of events in disturbance, including completion of diagram (figs. 3, 3a);

(v) sequence of restoration, including completion of diagram (fig. 4);

(vi) significant factors in causing the disturbance, its spread and in the restoration;

(vii) analysis or system instrumentation which helped materially to determine the cause of the incident or the sequence of events.

Amplifying the disturbance sequence diagrams, a sequence is shown in Fig. 5a in which a switching error (box 6) caused a simple fault (box 1) with maloperation of protective gear (box 7). This led to a further circuit tripping, overload on remaining circuit/s (box 9) and system sectioning (box 10). The sequence is continued for each of the islands separately, a possible sequence being shown in fig. 5b. In island A (fig. 5b), the situation is shown as stabilising as a result of a correct level of demand disconnection (box 25). On formation of island B box 22), there is a significant overgeneration (box 24), too much rejection of load by the generation (box 28) and island collapse (box 31). Comparison of Fig. 5 with Fig. 3 shows where information defining the particular incident has been added.

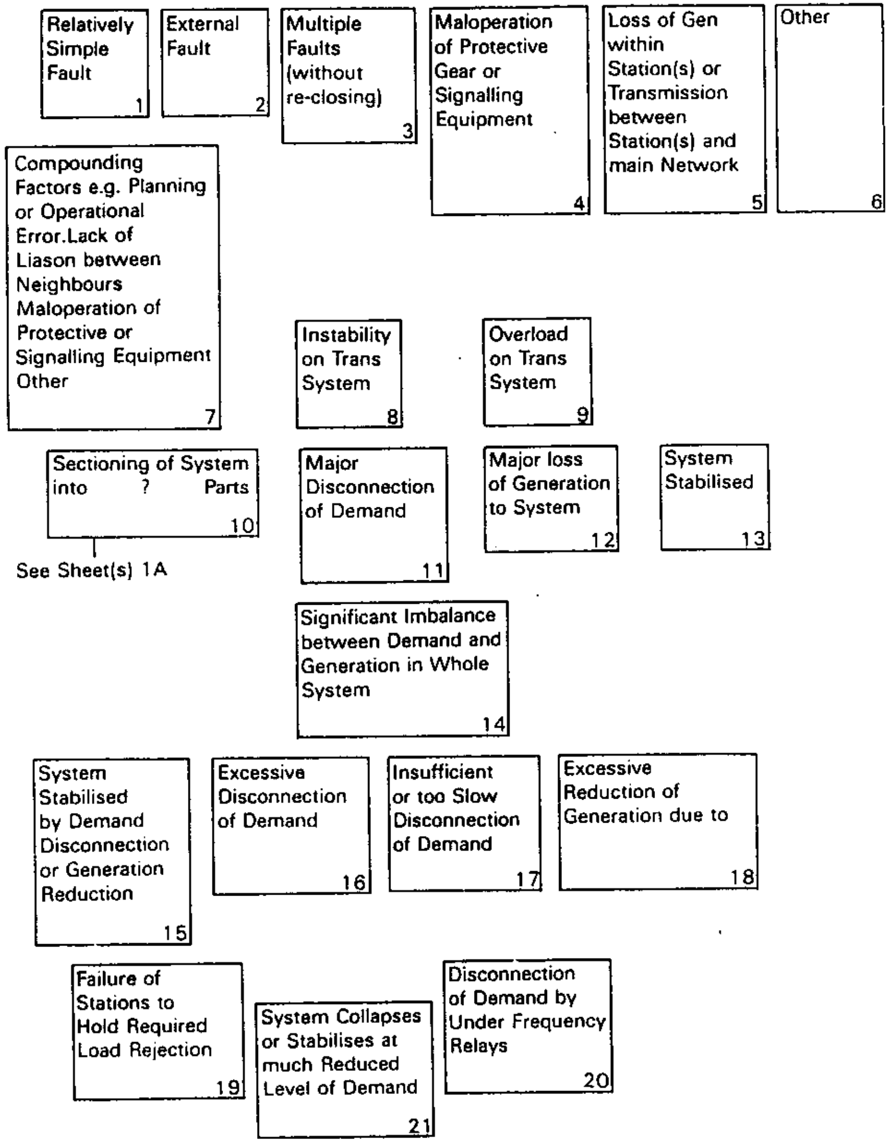
3.2 AN ANALYSIS OF INFORMATION AVAILABLE FROM THE REPORTS ON THE DISTURBANCES

Although as discussed in the next section it is easy to detect general patterns in the evolution of disturbances it is difficult to analyse factors in detail because of difficulty in interpretation of the available information and the wide range of detailed events. However, as far as possible, the direct causes and significant factors in the initiation and spread of the disturbances are analysed below. Inevitably there is some subjectivity in the statistics presented. The severity of the disturbances is also considered.

3.2.1 Direct Causes of the Disturbances

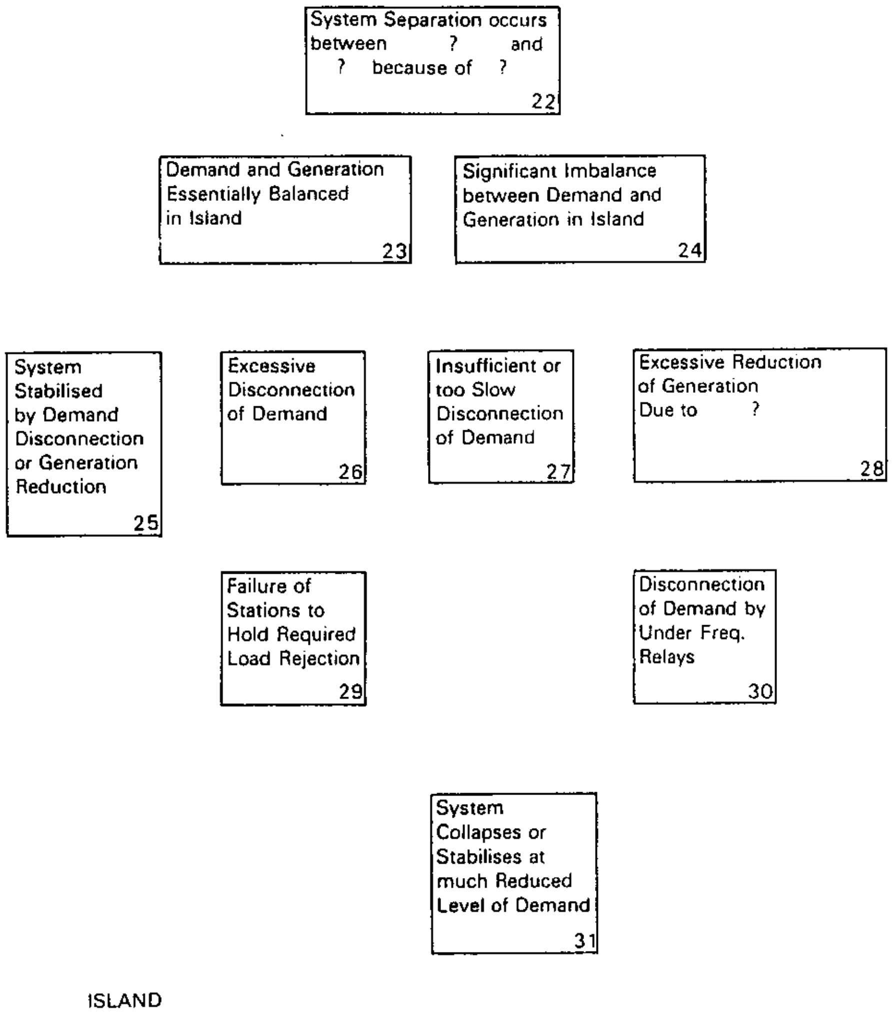
The direct causes of the disturbances are analysed in Table 5. The classification is into primary equipment failure (subdivided into secondary factors such as weather, environmental, etc.) and other failures such as overload, secondary equipment failure, etc. Failure by type of equipment is shown in Table 6.

It can be seen that faults on primary equipment account for some 70% of the disturbances, with bad weather a causative factor in $^1/3$ of these. Protection problems caused about 30% of the failures not caused directly by primary equipment failure.



(1) SEQUENCE OF EVENTS IN DISTURBANCE

Fig.3 Diagram to Show Evolution of Disturbance Prior to any System Split



(1A) SEQUENCE OF EVENTS IN ISLAND FORMED FROM PART OF SYSTEM
(Please complete for each Island)

Fig.3A Diagram to show Evolution of Disturbance Following any System Split

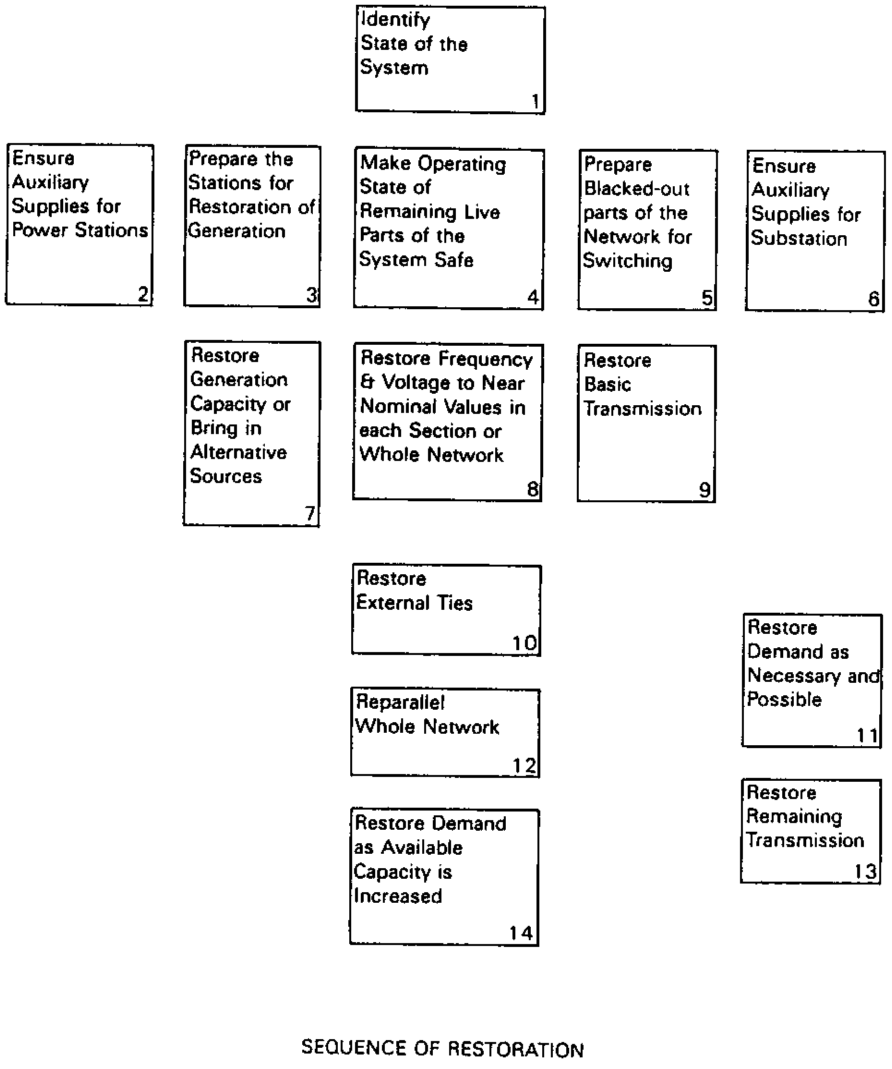


Fig.4 Diagram to Show Process of Restoration

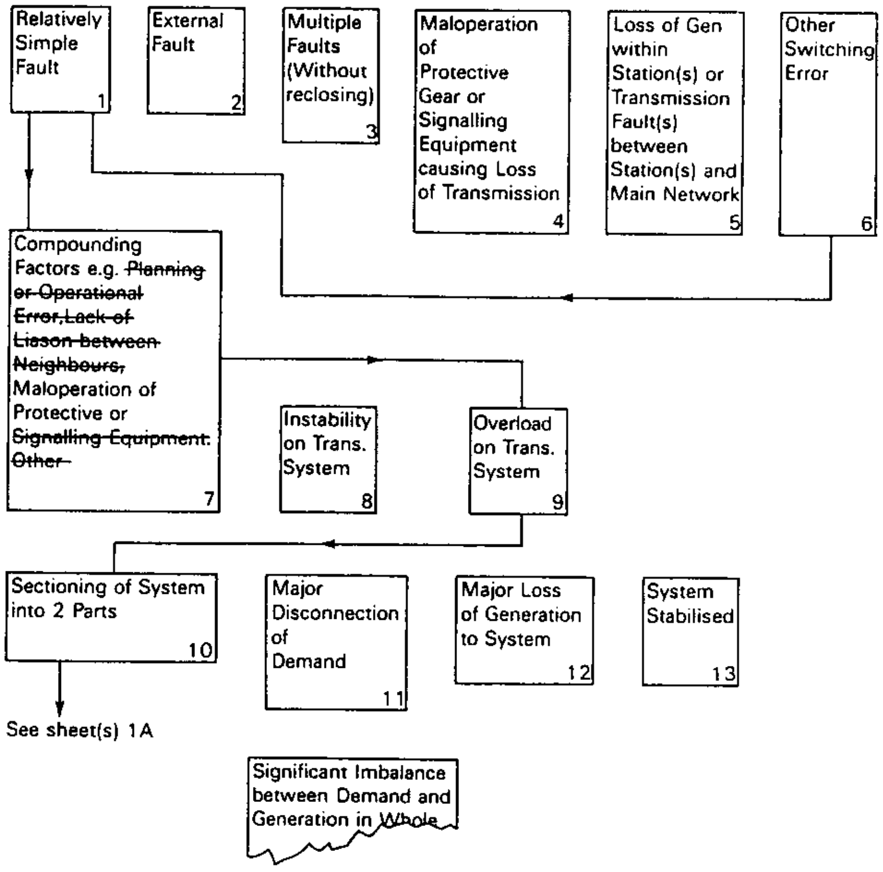


Fig.5 Example of Completed Return
(a) Initial Disturbance & Events
(Prior to Sectioning of System)

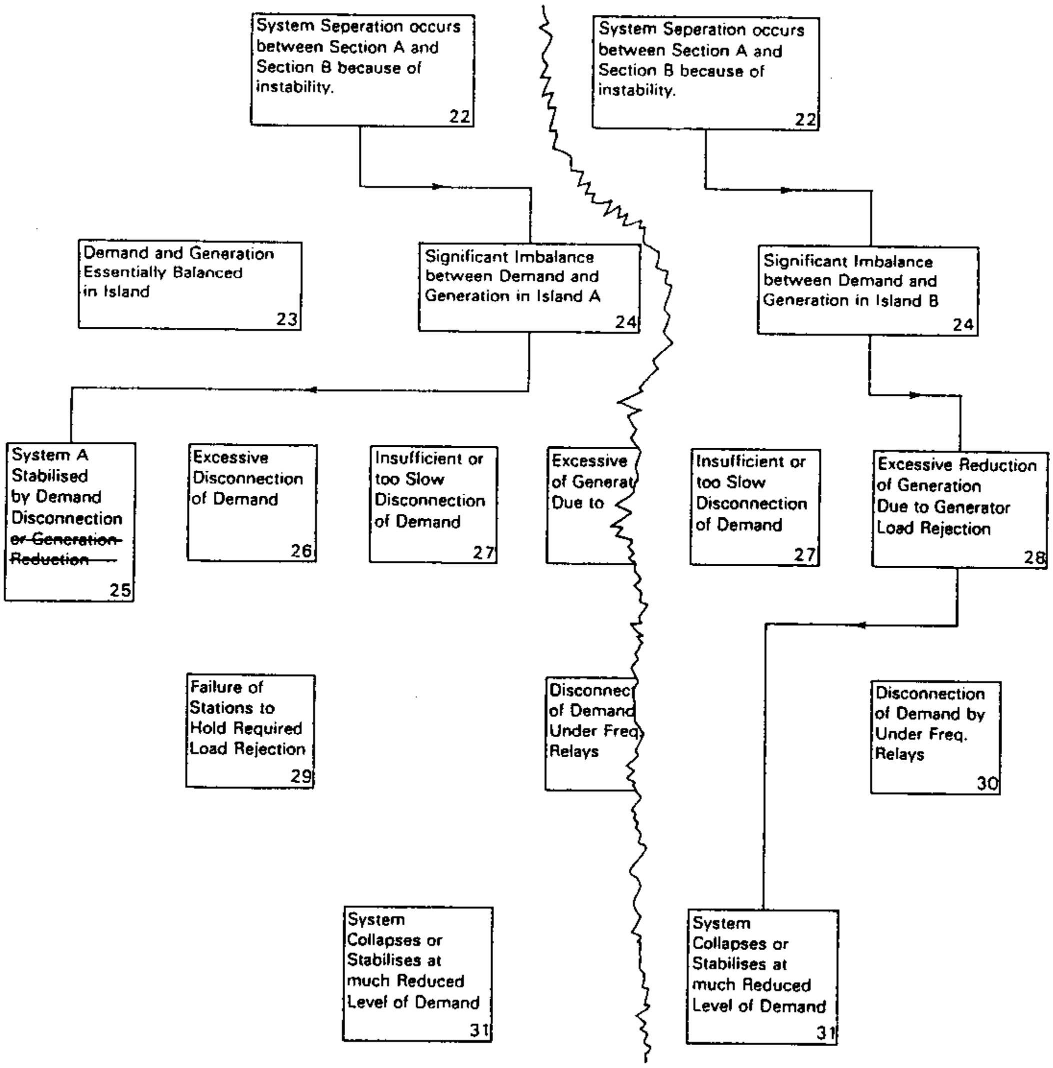


Fig.5 Example of Completed Return
(b) Events Following Sectioning of System

TABLE 5 - DIRECT CAUSES OF DISTURBANCE

SURVEY	EQUIPMENT FAULT					OTHER REASONS					
	Contributory Factor					VOLTAGE	OVERLOAD	INSTAB-ILITY	PROTEC-TION	HUMAN ERROR	TOTAL
	NONE/ NOT KNOWN	WEATHER	ENVIRON-MENT	HUMAN ERROR	OTHER						
FIRST	13	12	6	-	2	2	2	4	3	7	51
SECOND	3	4	1	3	-	-	-	-	3	1	15
THIRD	8	6	2	1	1	-	1	1	2	2	24
TOTAL	24	22	9	4	3	2	3	5	8	10	90
% OF OVERALL	26.7	24.4	10	4.4	3.3	2.2	3.3	5.7	8.9	11.1	100

TABLE 6 - FAILURE BY TYPE OF PRIMARY EQUIPMENT
(equipment fault or other reason)

SURVEY	BREAKER	BUSBAR	LINE	GENERATOR	SYSTEM	OTHER	TOTAL
FIRST	2	8	22	10	7	3	52
SECOND	1	4	6	1	2	1	15
THIRD	2	4	14	3	-	1	24
TOTAL	5	16	42	14	9	5	91
% OF OVERALL	5.5	17.6	46.1	15.4	9.9	5.5	100

The surveys suggested that only one in three of disturbances has been caused by what might be called an abnormal fault condition, that is something exceeding the credible contingency criteria typically adopted. About half of the faults so classified as abnormal have been caused by busbar faults or breaker failures. This distribution of causes is not surprising in that mal-functioning equipment or deficient operational planning provisions for example could represent a continuing contingency hazard which on the occurrence of the appropriate fault would precipitate a multiple outage of primary plant.

3.2.2 Significant Factors in the Initiation and Spread of Disturbances

These factors are analysed in Table 7. The plus and minus signs indicate cases in which factors helpful or detrimental respectively to controlling the spread of the disturbances are noted. One or more significant factors contributed to the spread of some 75% of the incidents. The commonest detrimental factors are problems with protection/automatic switching, stability, generation control and load shedding. The most helpful factor is load shedding. Earlier actions or faults were detrimental in some 10% of the cases. The influence of external systems was usually helpful.

TABLE 7 - SIGNIFICANT FACTORS IN THE SPREAD OF DISTURBANCES

SURVEY	Other e.g. Weather Config.	Protection/ Auto Switching	Human (real time)	Oper. Plan	Overload	Stability	Voltage/ Reac. power	System Control Facilities	Load Shed	Gen. Control	Communications	Earlier Fault/ Action	Equipment	External System
FIRST	-2	-8 +1	-2 +3	-2	-3	-9	-6	-1 +1	-7 +9	-10 +1	-2	-9	-4	
SECOND	-1	-3		-1				-2	-2 +3	-2 +2	-2	-1		+2
THIRD	-4	-8 +1	-3	-1	-4	-6	-3	-5 +4	-5 +4	-3 +1		-1	-1	-1 +3
TOTAL	-5 +3	-19 +2	-5 +3	-4	-7	-15	-9	-8 +5	-14 +16	-15 +4	-4	-11	-5	-1 +5

3.2.3 Magnitude of the Disturbances

The severities of the disturbances in terms of percentage of demand lost are shown in fig. 6. Restoration times for demand and generation are plotted against percentages of generation and demand lost in figs. 7 and 8 and against disturbance severity in figs. 9 and 10. It is difficult to see any real correlation between restoration times and severity of disturbance. Noting that by definition the disturbance severity is a function of the demand restoration time and with the assumption that this time is proportional to the percentage of demand lost, as suggested by Fig. 7, it will be roughly proportional to the square root of system minutes. This restoration time - disturbance severity curve, normalised to pass through the 100 system minutes/5 hours restoration time point is added in Fig. 9. The application of the relationship is probably no more than that given a value of system minutes, one can derive a rough estimate of the duration of outage.

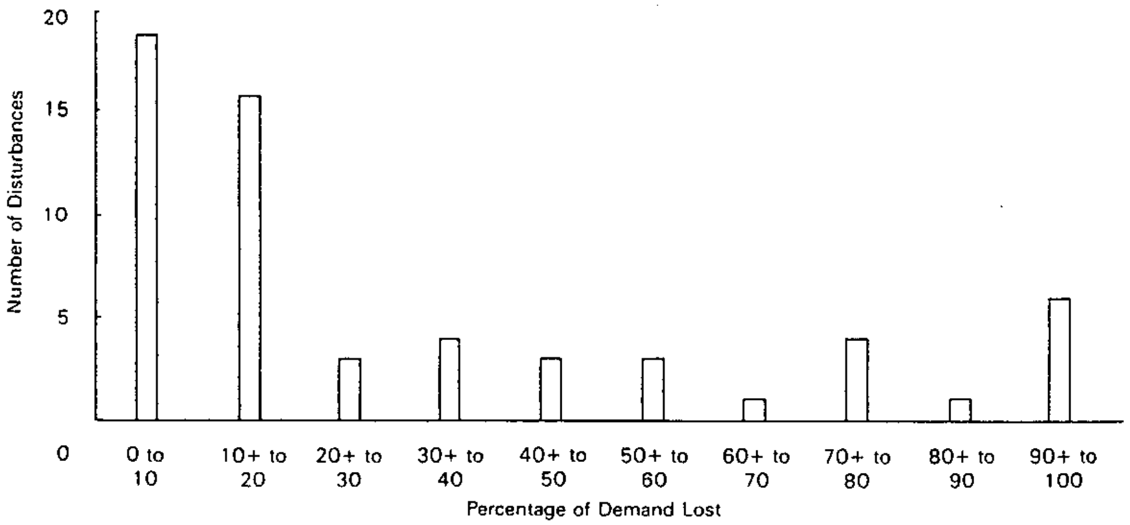


Fig.6 Severity of Disturbance

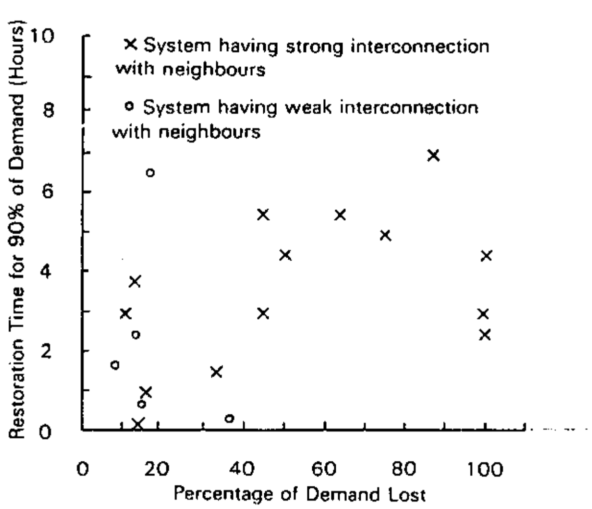


Fig.7 Relationship Between Demand Lost and Restoration Time

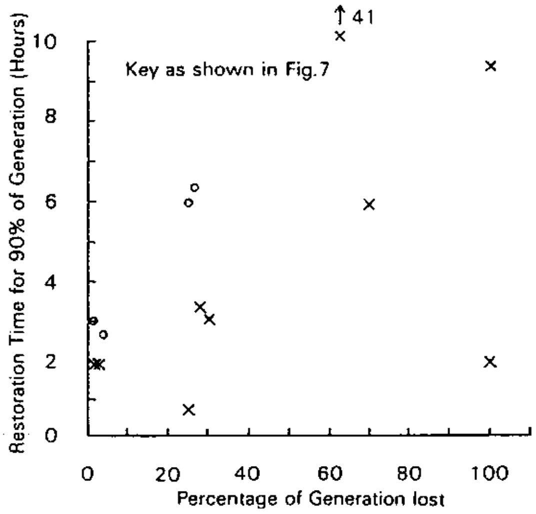


Fig.8 Relationship Between Generation Lost and Restoration Time

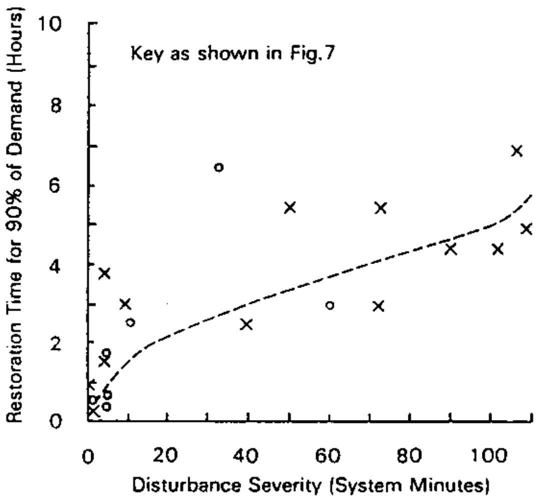


Fig.9 Relationship Between Disturbance Severity and Demand Restoration Time

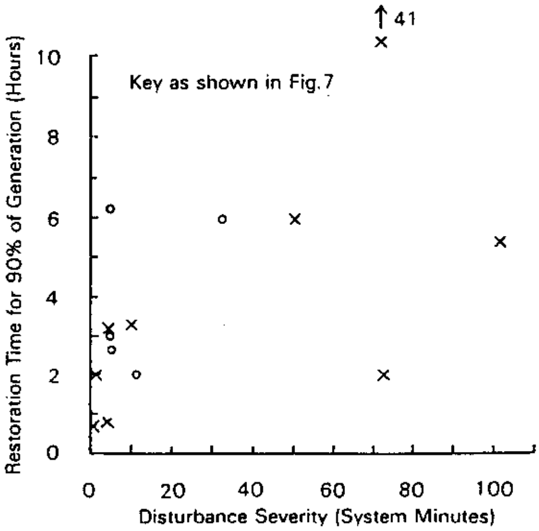


Fig.10 Relationship Between Generation Severity and Generation Restoration Time

3.3 Typical Patterns of Evolution and Restoration of a Disturbance

It is possible to identify a pattern to the way in which many of the large scale disturbances of the past have developed. This is shown in Fig. 11.

Some sequence of events (e.g. a simple fault with a compounding factor or multiple/complex fault with or without compounding factor -upper part of fig. 11) leads to a significant imbalance between demand and generation in all or parts of the system. There can be a wide range of compounding factors - inadequate liaison between neighbours, errors in operational planning or control, maloperation of protective gear, signalling failure, etc. The system or its separate parts should stabilise at points (S1 or S2) through the action of governors and load frequency control, disconnection of demand or less frequently disconnection of generation - all actions intended to eliminate the imbalance between demand and generation and to restore the frequency to its nominal value. If however these control actions are not sufficiently matched to the imbalance, further adjustments of generation will be called for and if these are outside the capability of the plant or its control loops, further disconnection of demand or loss of generation may occur; these possible cases, all of which have occurred in practice, are shown in the lower part of Figure 11.

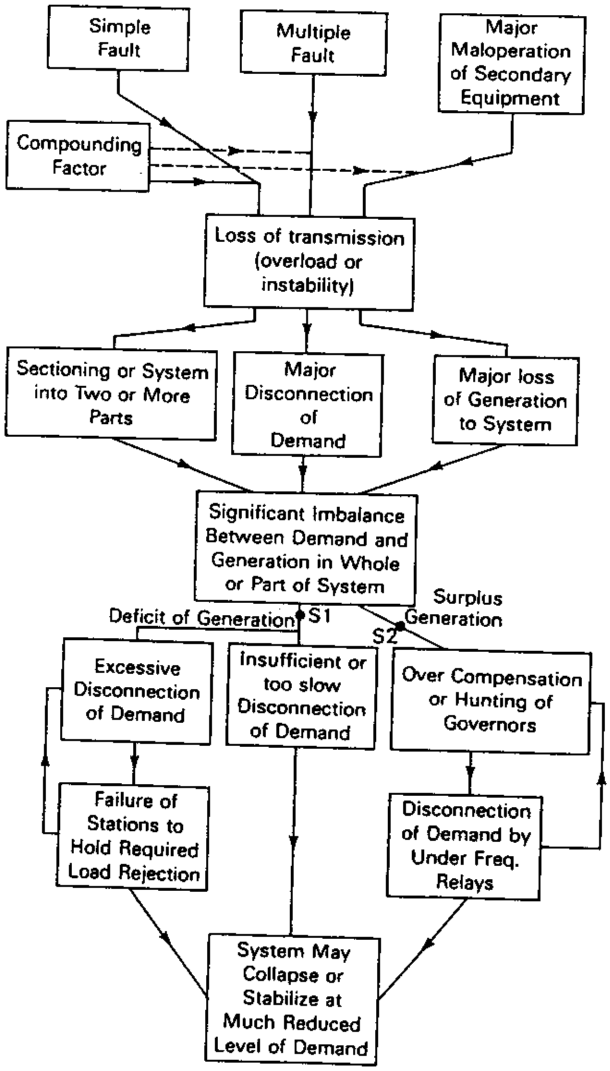
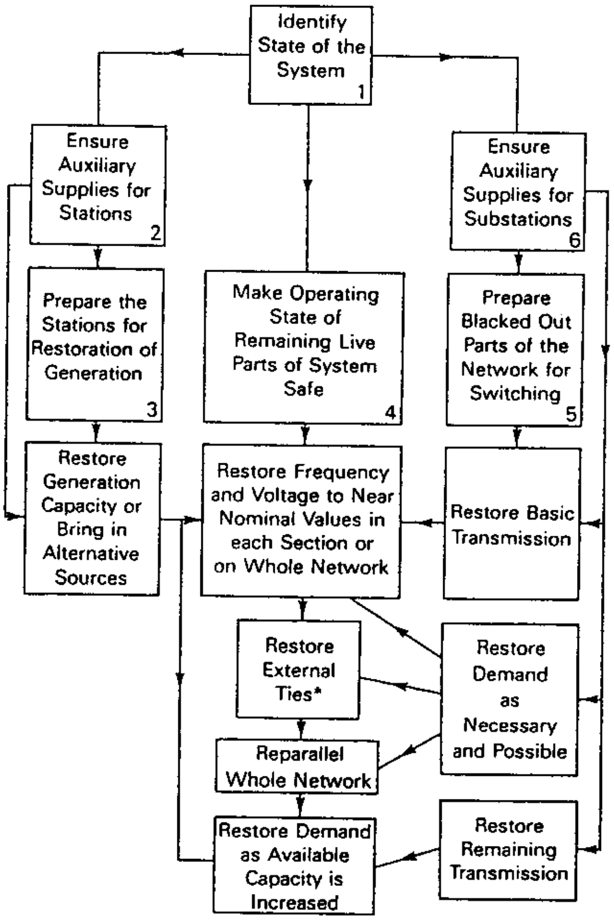


Fig.11 Typical Mechanisms of Large Scale system Disturbance

Essentially, the containment of a major disturbance requires that the events shown in Figure 11 be halted as early in the sequence as possible. The ideal way to achieve this is to adjust the controlling actions as closely as possible to the magnitude of the disturbance. The time scale of the events will frequently be so short that control actions must be automatic.

Restoration generally follows the basic pattern shown in Figure 12 namely restore the remaining parts of the network to a reasonably secure operating condition, prepare blacked-out generation and transmission for live operation, reparallel any isolated sections and finally restore the full transmission network and remaining disconnected demand.

Restoration of demand may well be proceeding throughout this process, not least to load the transmission network and re-energised generation and hence assist control of voltage and frequency. Early restoration of external ties is also helpful in that the external system provides a reservoir for short term surpluses and deficits of power as generation and demand is reconnected as well as helping to stabilise frequency and voltage conditions in the affected area. A basic requirement is an appreciation by the Control Centre(s) of the state of the system when it has attained a steady, although depleted, state and preferably a knowledge of the cause of the disturbance. Good communications and reliable auxiliary supplies for control rooms and for telemetry and instrumentation in power stations and substations are essential.



*These can serve as a sink for imbalances between generation and demand as blocks of generation are synchronized, in addition to increasing the power available to the system

Fig.12 Typical Sequence of Restoration

CHAPTER 4

AIDS USED TO PREVENT AND CONTAIN DISTURBANCES

INTRODUCTION

One of the difficulties in making a survey of the aids used by utilities to control emergencies is to distinguish between aids for normal operation and for emergency control. A common sense approach is necessary, otherwise one could list all the control and auxiliary mechanisms of a power system as being aids to emergency control.

Proceeding from section 3.3, following the removal of the first cause of the disturbance aids for the containment of emergencies have the objective of either removing an imbalance between generation and demand over the whole or isolated section(s) of the system or of reducing the transfers over the transmission network to values sustainable for periods long enough to implement such other actions as are possible or desirable. It is possible to categorise these aids either in terms of the action, or of the mechanism through which the objective of maintaining or restoring a viable system state is achieved. The former is done in this chapter but Table 3 has cross-referenced these actions and mechanisms/objectives. As a general comment some of these actions, for instance reduction of demand, will be applicable to all systems whilst the value of others, for example system sectioning or the type of auto-reclose, will depend on the structure of the system. References 28, 29 and 30 provide a review of practice in three countries of UCPTE. Another survey has recently been published by SC 39 (31).

4.1 ACTION ON DEMAND

Demand disconnection by under-frequency relays is one of the most effective and widely used methods of protecting a system against a major loss of generation. Its main limitations are lack of sensitivity in protecting small parts of large interconnections and difficulties may be experienced in equating the demand disconnected to the generation lost. It is also not possible to vary the location of disconnectable demand from that determined by the siting and settings of the under-frequency relays.

Demand disconnection by frequency-trend relays is used in conjunction with under-frequency relays by some utilities. A typical criterion is that both a given fall and rate of fall of frequency should be exceeded. The value of the rate of change is used to determine the level of demand shedding. It is argued (32) that such a combination, compared to the more usual under-frequency relay, will result in a smaller frequency drop and shorter periods of under-frequency running for a given power deficit, and is also less likely to produce unnecessary tripping of demand for a slow asymptotic frequency fall to a value below the under-frequency threshold value. However it seems that rate of change of frequency is not widely used to initiate disconnection of demand.

It is commonly accepted that all possible measures should be taken to prevent system frequency falling to below some 95% of nominal value, that is falling below 57 Hz on a 60 Hz system or 47.5 Hz on a 50 Hz system. Within the 5% band however, the range of frequency threshold values used and amounts of demand shed vary quite widely ((33), (34) and (35)). Some of the differences will be caused by the need to allow thresholds for other actions, for example on gas turbine and pumped storage plant.

Loss of generation within a section of a large interconnected system or of transmission connections into a section may pose special problems in that whilst overload of remaining circuits or low voltages may result, the system frequency will not necessarily indicate any abnormal conditions. The most effective immediate action may well be to reduce demand, and some utilities have provided schemes to disconnect demand on detection of overloads on transmission circuits or of low system voltages.

In one scheme (36) demand can be disconnected in order to keep transmission flows within transient stability limits. The magnitude of demand "armed" for disconnection can be varied and the data acquisition system monitors the security of the network by checking whether actual flows satisfy simple inequalities.

A number of utilities have provided facilities for reduction of demand from control centres by voltage reduction or by disconnection. Typically, some 40-60% of demand will be disconnectable in stages of 10-20%. The frequencies between which the various stages are disconnected will probably be some 98% and 96% of nominal frequency in a utility forming part of a much larger interconnected system with a substantial part of the total generation under automatic load-frequency control.

A utility without external connections is likely to use a somewhat wider range, say down to 97-96%. Frequency deviations will tend to be larger for a given loss of plant on the smaller system and hence probably also on the single utility system. The lower frequency limit will be determined by the lowest frequency at which it is considered safe to allow plant to operate, even for a short time, before incurring risks of progressive loss of output or of damage. Intentional time delays will usually be small or zero, although time delays may be used instead of frequency levels to discriminate stages of disconnection. The geographical distribution of the relays should take account of the importance of the demand supplied and of the power flows and voltages which might occur following disconnection of demand. Other worthwhile precautions are to assess the load rejection capability which may be required from generation should the relays just operate (i.e. the frequency falls to just below a setting level) and of the voltage that could occur following the demand disconnection. Attendance of staff at substations to reconnect the demand will be required unless relays are installed for this purpose or telecommand is provided from manned points. The cost of fitting an under-frequency relay will be some 2% of the cost of the associated circuit breaker at subtransmission voltages.

4.2 ACTION ON GENERATION

Governors and secondary regulation are the main and universally applied mechanisms for adjustment of generation to restore first frequency and then, on interconnected systems, tie line flows, to nominal values following an imbalance between demand and generation. Problems may be experienced with the governor control, for instance non-linearity or incorrect damping, and in the case of thermal plant with the overall capability of the boiler to follow the power output demanded from the generator.

Schemes to reduce or disconnect generation automatically (often called generation rejection) have been installed when it is necessary to reduce generation rapidly following loss of transmission capacity from an exporting station(s).

The extent to which these schemes are used is surprising. One of the best known is that installed by Ontario Hydro (36) to overcome limited transmission capacity (due to delays in consents for new lines) to a nuclear station; a better then 90% success rate was achieved when tripping nuclear generation to its own auxiliaries followed by reconnection when system conditions were suitable. In another utility station operators have standing instructions to reduce the output of their plant to a given figure within say 3-5 minutes of the loss of an exporting circuit, thereby taking advantage of short term overload capacity of the transmission network. Generation rejection schemes are sometimes installed (e.g. in CEGB) to eliminate the need to reduce generation at high merit stations when transmission circuits are being maintained whilst still accepting a double circuit outage risk.

Many utilities practice automatic or manual isolation of plant on to its own auxiliaries (24), or to its auxiliaries plus some local load, when system frequency and/or voltage are low. This will be done to protect the plant (the permitted operating times at shaft resonance frequencies, often only a few percent below nominal speed, are small) or to ensure that the system generation is as far as possible ready to pick up load following a major shutdown. Bypass valving has been proposed as one way to reduce the load rejection duty on the boiler in such circumstances (25, 26).

Several additional alternatives exist to increase the capability of circuit(s) limited by stability, e.g. dynamic braking, fast valving, excitation control, series capacitor line compensation, and static var compensators (SVC's). The first two of these are, as the ones just described, devices for rapid control of energy input, whilst the others are mechanisms to increase the power transfer capability of the network.

Because of the increases in transfer reactance at the machine terminals and effective decrease in any local demand due to the depressed voltage, there will be a power surplus during the fault period which will accelerate the rotors of machines. Shunt resistors switched into circuit at the machine terminals during the period of the fault can be used to absorb this surplus power and hence improve the network stability limit. Alternatively, rapid closing and partial or total reopening of turbine steam valves can be provided, actuated on detection of the critical fault condition or power imbalance, to reduce the energy input to the prime mover during the fault (37).

Rapid response excitation with high ceiling voltage and use of series capacitors or mid-line SVC's in long transmission circuits are ways to reduce the effective transmission phase angle for a given power transfer and hence to improve the transient stability characteristics of the system.

The incidence of low frequency oscillations (of the order of 0.5 -2 Hz) on power systems has increased and power system stabilisers are widely used. These have been used in the USA since the 1960's. Other well known applications are those in several parts of Brazil (38), between Yugoslavia and Italy and in the Nordel system. A small number of stabilisers have been installed even on the highly interconnected system in Great Britain. Pending a permanent cure, the oscillations can often be stopped by decreasing power transfers. Occasionally the oscillatory power flows have caused circuits to trip.

Action to increase generation rapidly is more costly and difficult to implement, generally requiring specific provision of the appropriate type of plant at the planning stage. Gas turbines will often by capable of running up to full load in 5-10 minutes from start up. Pumped storage plant is often designed to reach full load in well under 1 minute, 30 seconds being quite typical and occasionally as short as 10 seconds (e.g. the 1800 MW Dinorwig pumped storage plant in Great Britain). Hydro plant can have similar performance, for example 20 seconds from no load to full load.

As would be expected plant having these rapid response characteristics is used as system spare to meet losses of generation or increases in demand. It can also be used for reactive compensation, gas turbine units in this case being fitted with a clutch between the gas turbine and the generator.

In practice whereas disconnection of demand will mainly be used as a "last ditch" measure to maintain the basic integrity of a power system, generation rejection is more likely to be applied to overcome the effects of delays in association transmission works. There will be economic and security incentives to make full use of new generation. It will probably have low operating costs and its full availability will help to ensure the desired plant margin.

In such circumstances, generation rejection schemes will be well justified. However, the consequences of rejection of generation on the system over-all generation-demand balance must be considered and if necessary, demand disconnection also provided. Other applications could be where the probability of transmission being overloaded does not justify reinforcement but it is nevertheless worthwhile on security or economic grounds to be able to use all available generation on occasions.

The initiating signal for the rejection of generation will be related to network conditions (e.g. tripping of circuit breaker, excessive flow or change of flow on circuit). An essential prerequisite, as with demand disconnection, will be to make sure that the generation rejection does not precipitate untenable system conditions.

Any control mechanisms installed should be matched by the performance of the generating plant. In practice, one of the more onerous requirements is likely to be the ability to reject suddenly a substantial proportion of output (in the limit to reject from full load down to the auxiliary load), to continue operation at the reduced output for say at least one hour, and to be able to pick up load rapidly and, again in the limit, operate satisfactorily as an isolated unit (24, 25, 26).

As noted earlier, the ability to increase generation in an emergency situation, i.e. beyond that called for to follow the demand changes and to meet small to modest losses of generation, will be determined by the plant mix adopted in planning the system.

4.3 ACTION ON THE NETWORK

Automatic reclosing of circuits is used very widely. In delayed auto reclosing, the tripped circuit is reclosed between say 2 and 30 seconds after the initial opening. With high speed auto reclosing, the tripped circuit is reclosed within say 2 seconds of the initial opening. Perhaps a general distinction in the applications of high speed and delayed auto-reclose is that high speed will be used in less interconnected networks in which rapid circuit restoration is necessary to maintain the connectivity of the network and its stability. High speed single phase reclosing is used successfully in many countries, up to very high voltages. Its main benefit is that a high proportion (60-90%) of line faults can be cleared with minimal disturbance to the network. Some countries use high speed reclosing (1 second or under) for single phase faults and slow speed or manual reclosing for two and three phase faults. The manual reclosing may be by telecommand from the Control Centre.

Auto reclosing provides four main benefits: it enables a network to withstand a sequence of faults, essentially converting the potentially serious condition of a number of overlapping outages into a sequence of single (and almost certainly credible) outages; it may permit the capability of the network to be increased by allowing the use of short term overload ratings of circuits or higher transient stability limits; it reduces the workload of routine switching and gives much decreased times for circuit restoration. This means that for the same security of supply the provision of auto-reclosing may enable the amount of switchgear to be reduced. If improvement in stability limits is an overriding consideration, single pole operation of circuit breakers may be allied with automatic reclosing.

In practice some form of automatic reclosing will almost certainly be justified. The limited information available showed a bias towards delayed auto-reclosing. In general, the facility should include a check synchronism feature (e.g. checks on reclosure angle, rate of change of angle, voltage difference within limits). It may well be worth-while to consider its application in conjunction with schemes to reduce numbers of circuit breakers such as the 4-switch mesh used by the CEGB. The cost of fitting auto-reclose will probably be up to 1% of the cost of the associated breaker at transmission voltages.

Static VAR compensators have been proposed to improve steady state and transient stability limits particularly when installed in conjunction with micro-processor based controllers (39).

System separation, that is the controlled opening of circuits to isolate a predetermined part or parts of the system, has been applied between utilities and within utilities with the objective of preventing a disturbance from spreading through the whole system. Like demand disconnection it is a "last ditch" measure. The separation may be done in more than one stage, being initiated by detection of low frequencies or severe oscillatory conditions or perhaps high power flows (29, 31). In another case (40), a section of the network isolated on fault may be further split (using under-frequency monitored reverse power relays) to separate generation with its auxiliaries and matching demand from the remaining demand in that section. This remaining block of demand is then reconnected within 3 to 4 seconds to the main network, (more quickly than would have been possible if the demand had been disconnected by under-frequency relays) followed by the isolated generation section. The under-frequency relays installed on this remaining block of demand are such that they will not operate at voltages below 60% nominal.

4.4 PROTECTION

The choice of protection will affect both the risks of a major disturbance occurring and of it spreading. Maloperations or inadequacies in the designed application of protective gear are two of the more frequent causes of major disturbances. The questions to ask in selecting the protection scheme are:

(a) Will the protection operate reliably, discriminatively and at adequate speed over the whole range of switching, load and fault conditions?

(b) What will happen if any signalling required for the protection fails and is this likely to occur at the same time as a power system fault?

(c) Is every part of the system within the zone of a main protective system?

(d) What will happen if the main protection system fails? Should a second main system be installed? If the fault has to be cleared by backup protection, what discrimination can be achieved and will this be acceptable in terms of any resulting loss of plant?

(e) Can the protection be operated incorrectly by load currents in the steady state or with oscillatory conditions following fault clearance? Are the operating levels satisfactory for both system and plant protection?

(f) What procedures are required for initial setting of the relays and subsequent changes?

(g) Is there adequate provision to pass the necessary information on relay operations back to the Control Centre? Has the control engineer been provided with sufficient information on protection settings and performance to enable him to interpret reported relay operations?

4.5 ACTION FROM THE CONTROL CENTRE

Much of the preceding material in this chapter has referred to equipment provided in the field to initiate automatic actions to prevent or contain disturbances. The control engineer, with back-up from his operational planning colleagues, will play an important role in helping to prevent disturbances and if these occur, in minimising their spread and duration. However, to perform these tasks he will need comprehensive and timely information on the system plus rapid two-way communication with field staff and with the control centres of interconnected systems. He should be supported by computer aids.

4.5.1 Control Room Facilities and Communications

Essential control room facilities are a clear display of the configuration of the system, preferably including "splits"* at substations and flows on at least strategic circuits, displays of detailed substation switching arrangements for restorative switching and in case of faults within substations; displays of system state changes with time of occurrence and audible and visual alarms; displays of voltages from most substations and frequencies from selected substations; displays of generation, demand and transfer conditions for strategic groups of substations and power stations and for the whole utility; effective and rapid means of ensuring control actions on transmission and generating plant ("urgent message"); communications with all substations and power stations; effective and rapid communications with the control centres of neighbouring utilities (including distribution utilities); standardised nomenclature for equipment and actions within the utility and with neighbouring utilities; up-to-date records of the operational status of all generation and transmission plant with capacities and any limitations on method of use; up-to-date records of protective gear characteristics and settings; up-to-date manuals of operational procedures and standing instructions.

There has been considerable discussion on the value of overview diagrams in the era of comprehensive VDU displays. It has been found in some severe disturbances that the system wide overview diagram enabled control staff to keep up with the evolution of the disturbance better than from the VDU displays. The author's view is that overview diagrams are generally justified for generation/transmission systems where there will be interaction between plant states and loads across the whole system, in contrast to the situation on distribution networks.

4.5.2 Computer Aids

At present the main functions of computer aids in the control of emergencies are in the preventive and detection areas, namely for the determination of viable operating conditions (i.e. predictive studies in operational planning and on-line load flow and contingency analysis in the control phase) and for the absolutely essential functions of data acquisition and display. Reference has already been made to the need for clear displays of system conditions and prominent indication of changes of state and alarms.

Operational planning studies on expected operating conditions should be available to control engineers. These should have explored the transmission capability of the system and interaction with interconnected neighbours.

On-line flow and contingency analysis are clearly desirable but almost by definition one may query their efficiency in detecting those major disturbances which would be caused by the non-credible contingency. Equally however, they should continue analysis of the system whatever its current state (e.g. after the first contingency) and if sufficiently rapid and robust, will be useful in planning the restoration of normal conditions after a major disturbance. Such aids will require state estimation.

4.5.3 Telecommand

It is judged that telecommand of transmission plant from Control Centres has been increasingly applied over the period of these studies. This may well include facilities for disconnection and reconnection of demand. Some utilities incorporate logic for sequence switching within the telecommand facility (i.e. an ability to initiate a sequence of isolator/circuit breaker operations from a single instruction). It seems however that such sequence switching facilities may not be used during major disturbances, some operators wishing to telecommand each switching operation separately at such times.

4.5.4 Integrity of Services

The onset of disturbed conditions may bring together simultaneously the following adverse conditions:

(a) higher than normal information flow, both automatic and manual, from the system to the control centre;

(b) more requests for information and a greater number and more urgent instructions (manual and automatic) from the control centre to the system;

(c) system conditions outside normal operating limits;

(d) the control engineer's experience being a less reliable guide than usual;

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* a "split" substation is one at which one or more live busbar sections are not electrically connected, within the substation, to other live section/s.

(e) auxiliary supplies for instrumentation, communications, processing and control being unavailable from the system within acceptable voltage and frequency limits at power stations, substations, and control centres;

(f) station auxiliary supplies being unavailable from the system within acceptable voltage and frequency limits;

(g) data transmission being corrupted by primary system conditions.

Unless these hazards are recognised in design work by providing margins in the capacity of communications and telemetry, adequate scaling of transducers and instruments, and provision of auxiliary power supplies at strategic points independent of the main system, there is a risk of the containment and restoration of a disturbance being delayed by failure of one or more of the services.

In more general terms, the requirements for integrity of ancillary services can be stated as:

(a) the risk of malfunction of these services causing a loss of supply should be significantly less than a similar risk on the primary plant;

(b) their availability should be such as to not detract except very marginally from the quality of supply afforded by the primary plant;

(c) there should be no known common cause failure with primary plant;

(d) the range of system conditions over which they should continue to operate, with acceptable accuracy, should exceed any system conditions for which their continued operation is required.

4.6 DEFENCE PLANS

The term "defence plan" has been adopted to describe the totality of measures provided by a utility in the control phase to contain the effects of credible and non-credible contingencies. Descriptions of such plans often concentrate on action on main plant.

The summarised findings of a recent survey (31) were that defence plans against credible contingencies were commonly based on centralised monitoring and manual remote control facilities. The strategies most commonly adopted were to reconfigure generation, accepting economic penalties, and to operate within short time emergency ratings of transmission plant with manual (sometimes automatic) control action after a contingency to contain potential overloads.

Defence plans to cover non-credible contingencies were mostly based on decentralised automatic schemes. These have been extended beyond the traditional under frequency demand shedding. The range of actions is:

shed demand to contain collapse of frequency or voltage,

open interconnections to limit the spread of disturbances,

island generation and demand areas,

disconnect generating plant to prevent damage.

The larger systems (the survey included systems from below 1 GW to nearly 50 GW) adopted a wider range of plans for non-credible contingencies, perhaps because of the greater variety of system configuration possible.

CHAPTER 5

PRACTICE IN THE RESTORATION OF NORMAL CONDITIONS

INTRODUCTION

This subject has been referred to in several of the Cigre papers but was considered in some depth in the papers on system restoration published in 1986 and in 1987.

There will be two levels of problems. In the less severe the disturbance or shutdown will be relatively localised and with luck the remaining healthy system should provide a stable source of frequency and power for start-up to the disturbed area.* In the more severe case, most or all of the system will be shutdown, the so-called black-start situation.

Topics considered in this chapter will be typical patterns of restoration, strategies adopted by utilities, dependence of strategies on structure of the system and facilities to aid restoration.

5.1 RECOVERY FROM AN ABNORMAL OPERATING SITUATION, LOCAL ISLANDING OR LOCALISED LOSS OF DEMAND

The strategic questions concern such issues as the priority of actions - should the remaining system be made secure or should demand, or transmission or external ties etc be restored. The tactical questions will deal with how the individual components of the strategy should be implemented - generation adjustment, configuration change or even further restriction of demand.

In general, achievement of a sustainable operating state is given very high priority. This implies a close to normal frequency (by adjustment of demand, generation and if available transfer from external sources), reduction of overloads to values sustainable for the periods necessary to achieve a long term solution (by adjustment of demand, generation or configuration) and acceptable voltages, that is within very few percentage points of nominal (by adjustment of power transfer, reactive sources or possibly configuration). Whether the "sustainable operating state" should be capable of withstanding a further contingency is more debatable, depending on weather conditions, the risk of further faults and their potential impact. Control of the generation demand balance is likely to be more difficult in islanded parts of the system. For instance, units which have perhaps tripped to houseload during the disturbance and have to be brought up to a significant output within minutes may in a small island have to be found load from another station/s. Demand restoration will have to proceed in small steps to match the governing and load pick-up capability of the islanded generation.

Preparation of generation and transmission facilities for return to service and assessment of the cause of the disturbance are both given high priority. The former is essential for restoration of the system and demand, the latter not least to ensure that the circumstances leading to the disturbance are not unwittingly caused again. Frequently utilities specify that a substantial proportion of generation shall be capable of isolation for a limited period of time on to house load or this plus local demand (24, 25, 26). Particular aspects of the restoration of transmission will be the resynchronising of islands and closure of external ties. As might be expected, the importance attached to restoring external ties depends very much on circumstances, for instance the strength of the external system and of the ties and the locations at which these are connected within the utility; they can be very valuable as a means to provide power for black start and to assist matching generation and demand during restoration. Varying importance is also given to the reconnection of islands.

If an island is a significant part of a utility (say 20% or more) then both the island and the main part of the system will benefit from the sharing of resources provided by reconnection. Otherwise the advantages of reconnection and hence its priority will depend on the relative generation/demand positions in the island and main system. It can be noted that a small island isolated by transmission outages is likely to be on the periphery of a system.

Restoration of disconnected demand has not been mentioned. It is the objective to which all the actions just discussed are leading but a common approach of utilities is to safeguard the system, and thereby minimise risk of further disruption and loss of supply by too precipitate reconnection. One well known phenomenon is that a block of demand increases steadily in magnitude for some time after being reconnected and may then decrease slightly once the energy not supplied during the outage is made up.

5.2 TYPICAL PATTERN OF RESTORATION IN BLACK START SITUATIONS

Black start conditions receive considerable attention from utilities either suffering or observing the large scale blackouts which have occurred in recent years. The general approach is to nominate stations with plant such as gas turbines which can be quickly started, as focal points of the restoration process and from which electrical connections and black start supplies can be provided to remaining stations. Reconnection of demand is an essential part of this process to provide load for the generators and help to keep voltages below acceptable (upper) limits. Electrical islands are thereby formed which will be progressively synchronised to each other; in

*This however is not always the case. Some 30% of the running generation in the CEGB was lost during the exceptionally severe wind storm in England in October 1987. Although in total some 70% of the generation remained in operation, black-start conditions existed in the affected areas because of problems on the transmission network and it was necessary to start-up stations in this area from emergency diesels and then gas turbines.

general the bigger the island, the more stable is its frequency likely to be. The problems of charging long e.h.v. circuits (with the effect on voltages) may be a limiting feature during the phase of parallelling islands. If the system has a hierarchical control structure (e.g. System and Regional Centres) it is likely that the early stages of this process will be directed by the Regional Centre/s, with the System Centre supervising first parallelling across Regional boundaries and between major islands and later the full restoration of demand.

In addition to, and sometimes consequent upon the high voltage problems, other difficulties which may be experienced are transformer overfluxing, fault currents too low to operate some types of protection, switching overvoltages, stability of governors when units are lightly loaded onto a very small system, phase unbalance in transmission circuits and possible effect on protection, and control of islands. The normal control centre may not have frequency indications from all islands and for such, control may be delegated to nominated power station/s within the island/s.

One major issue is the security of generation and transmission to be provided during the restoration; the question is simply-should the emerging system be loaded to its total capability in order to expedite restoration of demand (i.e. assuming there there will be no further faults or trips), or should a margin be kept so that if there is more trouble, the risk of a further large shutdown is reduced? Practices seem to differ but one can note that in several blackouts there have been further losses of supply during the restoration process.

It is not easy to detect a precise pattern of restoration, since several actions will often be taking place simultaneously, (in Fig. 12 for example, the preparatory actions-boxes 1 to 6). Apart from the extra emphasis on the need to provide supplies for start-up to numerous stations and the wider extent of islanded operation, there are considerable similarities between the situation considered in the last section and this one.

5.3 STRATEGIES OF RESTORATION USED BY UTILITIES

A number of questions were addressed to utilities on the facilities and precautionary measures used in restoration and also the sequence of actions if faced with a black-start situation. 14 countries, (16 utilities) responded and a summary of some the information is given below.

5.3.1 Facilities for Restoration

Generation - proportion designed to isolate to auxiliary or auxiliary plus local load.

All the utilities made some provision for this, but the proportion varied from 100% to nuclear only. Over 50% of the utilities required this on 80% or more of their plant.

Generation - proportion designed for black-start

It seems that some 40% provided on site black start facilities for 80% or more plant. The others provided it on lower proportions and/or relied on outside sources. Several countries mentioned the nomination of quick start units to provide existing power to neighbouring stations and the predetermination of "electrical corridors" through the transmission network to transmit power from such stations to the major stations. Nuclear stations are given high priority both in restoring power for auxiliaries and in restoring load (to avoid "poisoning out").

Transmission - proportion using automatic opening of circuit breakers in preparation for restoration

Only some 25% of the utilities reported doing this although others mentioned manual opening, (presumably done by most or all utilities, at least selectively).

Transmission - other aids in network restoration

Most countries have prepared plans for switching, often quite detailed. These may start with lists of breakers, which if they have not already opened as a consequence of the disturbance, should be opened manually. Sometimes such opening is done automatically, for example if a zero voltage condition is detected for 3 seconds. In another case, the opening is selective so to minimise the switching required to restore the system.

To assist restoration a few utilities have installed equipment which on detection of voltage on an incoming circuit closes the breaker/s on selected ongoing circuit/s, establishing a live path through the network. Precautions include blocking of the closing action to prevent repeated reconnection onto a permanent fault, non-closure of a breaker open before the disturbance, and manual inhibition of automatic switching from the control centre. Automatic switching of reactive power sources is included.

Some countries (Sweden, Great Britain) have reported two level restoration strategies in which a general national strategy sets targets for local Areas or Regions, such as establishment of islands of generation for progressive interconnection. The Areas/Regions will have detailed plans for the establishment of such islands, providing auxiliary supplies to stations without internal black start facilities, demand points to be used at this stage, etc.

Transmission - auxiliary supplies

It is important that emergency power supplies should be available at substations so that switching and communications are not affected.

System control centres will also need their in-house emergency supply (usually diesel). A utility may need to check that communication centres, including those of other relevant services, have adequate back-up supplies.

5.3.2 Priorities in Restoration

The utilities responding to the enquiry were asked to list their priority of actions in restoration. A summary of the replies is given in Table 8.

Table 8

PRIORITIES IN RESTORATION OF SYSTEM

	Priority(1)			
Action	1	2	3	4
Avoid damage to utility plant	14	-	-	-
Secure generation	2	5	5	2
Secure transmission	2	1	10	8
Restore external interconnections	1	6	1	-
Reparallel islands	1	3	-	3
Restore demand (2)	1	1	2	5

Notes: (1) Some utilities list more than one action with a given priority. In that case, each action is shown with that priority.

(2) Several utilities show restoration of demand as part of other actions.

It will be seen that the highest priority is given to preventing damage to plant. The second is to improve the availability and flexibility of power supply (generation, interconnection and parallelling islands) whilst the third is to improve the transmission situation. High priority is always given to restoring auxiliary supplies and providing demand at nuclear stations.

5.4 PROBLEMS IN RESTORATION

A number of problems recur in the reports on disturbances referenced earlier. An IEEE Task Force on Restoration has also listed some of these (15, 16). The information below is taken from both these sources.

(i) keeping voltages within limits (usually upper limits) particularly during the early stages. This is done by energising as few lines, as possible, switching out shunt capacitors and switching in shunt reactors, operating generators at minimum excitation and picking up low power factor demands as far as possible.

(ii) balancing demand and generation whilst maintaining reasonable frequency and sufficient control of generators. The merits in terms of generator control of picking up small increments of demand (but taking longer) have to be balanced against picking up larger increments, thereby reducing the restoration period but at the risk of precipitating an uncontrollable drop in frequency. A percentage of the demand restored should always have under-frequency relays fitted.

(iii) overloading of communication facilities.

(iv) equipment operating problems due for instance to inadequate auxiliary supplies, and control and protection interlocks.

(v) lack of information at control centres caused for example by delays in data acquisition and display, or insufficient telemetry (the first of these has generally been overcome in modern SCADA systems).

(vi) lack of appreciation by the control operators of the state of the system. This may include inability to determine the cause of the disturbance or inability to formulate decisions for restoration. It may be caused by lack of information at the centre/s or failure to assess the available information adequately.

(vii) only insufficient or out of date guidance available to control operators. It has be remembered for instance that the operators' normal understanding of the behaviour of the system may not be applicable to the conditions during restoration. An operator is unlikely to experience a major disturbance more than once or twice in his career and hence his pertinent experience, apart from any obtained in training, may be very limited.

5.5 THE DEPENDENCE OF RESTORATION STRATEGY ON SYSTEM STRUCTURE

It has been suggested (10) that an organisation will respond to a blackout situation with a "natural" restoration strategy that will as far as feasible fulfil the objectives and responsibilities of the organisation. For the local distribution utility, the objective will be the rapid restoration of local load perhaps by establishing a local island at a lower voltage, whereas the organisation responsible for the main grid would have as its objective the most rapid restoration of the entire system. The merits of "natural restoration pattern" should be evaluated as part of the work on determining the restoration plan.

In spite of considerable effort it was not possible to establish a correlation between strategies of restoration and characteristics of systems (11). The debates on this subject confirmed the general pattern of restoration outlined in section 5.3, plus the suggestion that a utility, whatever its size, would seek to establish a main backbone to provide black-start supplies to stations. For a small system, this backbone could be at what are normally regarded in larger systems as subtransmission or distribution voltages.

5.6 COMMUNICATIONS

Several utilities have experienced problems caused by the media and public seeking information from the utility during a blackout. There can be two effects -

(i) the public telephone system is overloaded, in particular lines servicing the utility. This can cause difficulties in contacting off-duty staff and may impact on the system operation communications system, depending on its degree of independence from the public communications network.

(ii) operational staff are distracted from their work in handling the disturbance situation to provide information to the media and civil authorities.

A number of utilities have set up "system incident centres" to reduce these problems. These would be activated if a severe disturbance had occurred, or was anticipated (e.g. forecast of extreme weather), their function being to act on as a focal point for reception and dissemination of information inside and outside the industry. Typically these would be associated with the Headquarters/National or System Control Centre and possibly at Regional Centres. They would be manned by system operation managers and staff (not control staff) and public relations staff. Their task would be to collect information concerning the disturbances and to collate this for senior utility staff and for release to the civil authorities and to the media. They would also handle queries from these groups.

In some utilities, selected operational staff are expected to report for duty of their own accord when very critical supply conditions arise.

CHAPTER 6

TRAINING OF SYSTEM CONTROL OPERATORS FOR EMERGENCY SITUATIONS

INTRODUCTION

Interest in the training of system control operators has increased considerably in recent years, spurred by the several large disturbances which have occurred, the continuing updating of energy management systems and the increasing facilities available from these, and finally the increasing size, interconnection and complexity of power systems.

This chapter will concentrate on training for handling emergencies, in particular the use of training simulators.

6.1 THE NEED FOR AND FORMS OF TRAINING

It has already been said that a shift operator may only experience a major disturbance once during his career. Taking this together with the expectation that the operating conditions will be abnormal and his everyday experience correspondingly less relevant, that he will be under stress particularly if the situation is deteriorating or consumers are disconnected and that containment of the situation may require him to disconnect demand (an action which is against his whole outlook) it is clear that the provision of training to operators in handling major disturbances needs serious consideration. The objectives of such training will be to increase his knowledge of the technical characteristics of the system under dynamic or degraded conditions, of the procedures and facilities available to him, and not least to increase his confidence in his ability to make and implement the right decision without delay at such times.

The training can take several complementary forms:

(a) lectures or video training packages on technical aspects such as voltage and power flow control, forms of instability, operation of islands, protective gear performance, etc (e.g. the Plato system, see also (41)).

(b) self tuition and training on procedures in emergency including demand disconnection, restoration, black-start, communications.

(c) talk through and group discussions on incidents internal and external to the utility.

(d) exercises, including handling of disturbances, on a training simulator.

Of these, the real time dynamic simulator will be the most effective mechanism to train control engineers in the handling of severe disturbances.

The broad objective of the training will be:

to increase confidence in ability under stress to weigh up situations and to make and implement timely, correct decisions.

to improve knowledge of the technical characteristics of the system under dynamic or degraded operating conditions.

to improve knowledge of procedures and facilities for handling emergency situations.

An important question is whether the objective should be to train the individual control engineer, the control team (say 2 or 3 engineers simultaneously) or even two control teams, representing say the National (or System) Control Centre and one of the Regional (or Area) Control Centres in a multi-tier control hierarchy. Certainly some major incidents have been worsened by inadequate understanding between individuals or between centres. There is undoubtedly value in training a team and even extending this to simultaneous training of teams from two centres. The penalties are increased cost and complexity (for instance in the MMI, including the cost and difficulty of providing mimic diagrams), probably increased size of power system to be modelled with attendant implications on computation requirements, and difficulties of simultaneous release of several operational staff.

6.2 REAL TIME TRAINING SIMULATORS

There are two broad types of training simulators:-

(i) generic, in which performance of the operational system is modelled but there is no attempt to replicate the actual system or the man-machine interface.

(ii) replica, in which the performance of the actual systems is modelled and an actual or close approximation to the operational man-machine interface is provided.

The general view is that replica simulators are better for training operational staff and it will be taken in the remainder of this chapter that only this type is being discussed.

Ideally, it should be possible to model the following types of incidents on the simulator:

multiple, coincident or sequential faults,

protection operation (overcurrent, impedance, demand shedding and other automatic switching schemes),

oscillatory conditions, including non-uniform oscillations of different machines,

system splitting and islanding.

It is not difficult to do the relevant computations in the turn around times of many seconds, minutes and even hours acceptable for operational planning work. The essence of a training simulator is however that the the system information should be presented in SCADA timescales, e.g. updated every few seconds. This adds substantially to the technical problems, in particular of approximating the dynamic and transient performance.

Ideally the man-machine interface should be a close replica, if not identical, to that provided for an operator position in the control room. It may be acceptable for some training purposes to use spare operator positions in the control room driven from the operational standby processors or a training computer suite, although the author doubts whether this approach should be extended to include emergency training. Accepting then a separate interface one difficulty is the configuration diagram, particularly if more than one power system is to be modelled. Noting that experience has shown that the configuration diagram has an important role in enabling the operator to keep track of major disturbances and that operators prefer strongly to be trained on their own power system, the necessary flexibility might be obtained, with some sacrifice on replication, by using large screen projection forms of display. However, the arguments for training on a model of the operators' own system probably apply most strongly at the main generation-transmission level for which there will be one control centre anyway. This would permit one "representative system" to be modelled for the other (e.g. Regional) systems and centres without serious impact on the training.

Managerial issues appear to have received less attention in the literature than the technical areas. Amongst those which have been considered in the author's company are the merits of individual, team or multiple centre training. Such questions having implications on cost and staffing of the training establishment, require to be considered in the context of the utility/s for which the training facility is to be provided. In the author's view and if a choice has to be made, it would be more important to take account of the division of responsibility and work between operators in a control room than between control rooms.

As regards system size, the situation seems to be that whereas only a few years ago it was not at all sure that system dynamics could be modelled in real time except for very small systems, this problem seems to be reasonably solved if one accepts that, to include the effect of any transient instabilities, the model may need approximations and perhaps calibration tuning of these by off line studies. There is clearly much to be said for modelling all of that part of the system for which the trainee has responsibilities in his normal work, together with sufficient of the remainder to allow its effect to be included meaningfully. Various references give in some detail the present state of the art; one quotes for example the solution of a 500 node network in 4 seconds.

Each trainee position should be provided with the telecommand (probably working straight into the system model) and telegraph/telephone facilities to other Centres and power substations which the trainee would have available in the operational control room (only in the simulator these would go to the instructor's console). Access should be available to off-line computer aids, as provided in the operational control room.

The requirement from the power system and telemetry models are that these should produce information on the state of the power system of the same type, quantity and quality as that provided by the operational data acquisition system. If the operational data acquisition cycle for measurements is, say, 5 seconds, the evolution between the 5 second intervals may not need to be computed at all (say for flows/voltages) or in detail (say for machine oscillations in stability modelling) provided that the 5 second end points are assessed. (This could be important in the approach to feasibility of modelling stability). Modelling of protection and automatic switching may require finer time discrimination. In particular, it is important that frequency changes are determined at small time intervals if under frequency relay operations are simulated. In terms of system phenomena, an objective would be to model single and multiple faults, instabilities (effects if not detailed mechanism), islanding, load shedding, protective gear operations, etc. Detailed calculation of some of these could well be impossible and, hence, look up tables or scenarios based, for example, on earlier off-line calculations might be used.

The model should include the normal control mechanisms (governor, boiler, automatic voltage regulator) and the control applications implemented operationally, e.g. tie line frequency control, economic dispatch, contingency analysis, operator load flow, etc. Facilities to freeze the simulator or to operate in slow motion (say ½ or ¼ real time) would seem valuable.

In the author's view, a realistic rather than exact simulation (in design terms) of the system is required from the model. It is unlikely that a training scenario will ever be exactly duplicated in real life. On the other hand the objective should be to show all electrotechnical phenomena which could occur in the time scales of interest. These objectives in conjunction with the earlier comments on dynamic modelling suggest that one approach could be, for example, to calculate high speed transient phenomena off line and on detection of similar conditions feed the end results into the model from a scenario tape (see above). In the EDF training simulator (42), probably the most advanced available to date, the immediate reaction of the system to a major disturbance which might cause instability is assessed by calculating the first few iterations of a transient stability analysis and from this deducing its final status based on simplified criteria.

The instructor console/s will have four roles:

(i) To introduce power system or other faults and incidents (this task could be made easier and done more precisely by the use of scenario tapes).

(ii) To act as the external world to the trainee/s (i.e. to receive and implement as station, substation or other control centre operator all instructions to such personnel from the trainee/s and to provide verbally such information as requested.

(iii) To monitor the progress of the training run.

(iv) To monitor the trainees' performance.

Although simulators for training in specific tasks such as switching and to a lesser extent loading have been in use for years, ones for training on overall system tasks including the handling of emergencies are quite new. The requirement is to produce a realistic simulation of how a system would behave. It seems that digital computers typically used in system control applications have the capability to do this. However if part of the on-line system, the training function would be located on a stand-by suite and discontinued whilst that suite was needed in the on-line role.

6.2.1 The Present Status of Training Simulators

A recent survey (43) including at the time of writing 29 replies showed that 14 of the utilities had simulators in operation or on order. A further 7 planned simulators. 11 of the 14 operational simulators were fully integrated into the EMS, the remaining 3 being stand-alone.

6.2.2 Other Applications of Training Simulators

A training simulator has some of the characteristics needed for predictive and other study work. It may exceed the requirements in some areas, be less in others. The potential benefits suggested in using it for study work have been the availability of the real time MMI, ready availability of operational data and possibly reduced costs.

The simulator can also be used as a "test bed" for assessing the technical and economic performance of new applications software or real time facilities under realistic conditions.

An assessment of modelling requirements for various functions is given in Table 9. The conflict between the applications needed for the different functions is highlighted by comparing columns 4, 5, 6 and 12 with columns 7, 10 and 11.

Combining the applications introduces conflicting design requirements -high accuracy at the same time as real time computing speeds - and may cause conflict for access to the simulator. If however a utility is prepared to forego the more complex requirements in the two areas, a viable compromise can be achieved (44). Some, generally smaller, utilities are following this path.

6.3 TRAINING IN PRACTICE

Training in various aspects of emergency control provided in practice in the early 1980's was summarised in (8). For the 16 utilities replying, the situation was as follows:

TABLE 10

TRAINING PROVIDED

	Form of Training			
	Group Discussion & Inputs	Formal Education Lessons	Practical	
			On System	Simulator
No. of utilities providing	9	5	2	7

Reference is made in one or other of the replies to voltage reduction tests, simulated demand shedding and black start simulation (by supplying false data from a substation into a control centre), use of video tape and group discussion on previous faults and on fault scenarios.

A new amplified review will be presented at the 1989 Cigre symposium in Bangkok (45).

TABLE 9 - A COMPARISON OF MODELLING REQUIREMENTS

	System Line Diagrams (1)	Detailed Substation Diagrams (2)	Steady State Network Applications (e.g. load flow) (3)	Energy Balance (4)	Simple Fault & Protection (5)	Approx. Transient & Protection (6)	Detailed Transient & Protection (7)	Detailed Unit Commitment + AGC (8)	Contingency Analysis & Real Time Load Flow (9)	Approx. Unit Commitment + AGC (10)	Simulation Models - Including Probability (11)	Need to Operate Real Time (12)
Training Simulator												
A "Steady State" system (e.g. load following, monitoring, frequency control, simple fault).	x		x	x	x			x	x			x
B "A" plus severe disturbance modelling	x		x	x	x	x		x	x			x
C "A" plus switching instruction	x	x	x	x	x			x	x			x
D Extended Real Time	x		x		x		x	x	x			
E Operational Planning	x		x				x			x	x	
F Extension Planning	x		x				x			x	x	

Note:- (1) Detailed post event incident analysis will require network analysis facilities as D and E.

(2) Training simulator as A, B, C, could, subject to availability, also be used to extend appreciation of system behaviour in non-control staffs.

CHAPTER 7

THE EVOLUTION OF EMERGENCY CONTROL

INTRODUCTION

It is proposed in this chapter to review some of the possible developments in the emergency control of power systems. This will be done in two parts - improvements likely in the short term as an evolution of present practice and more fundamental developments such as increased adaptivity of the emergency control facilities to the actual state of the system and the use of artificial intelligence.

7.1 DEVELOPMENTS IN THE SHORT TERM

It has been anticipated (6) that the technical development of aids to control in emergency will be concentrated in four areas - improved operational planning, improved recognition of potentially dangerous situations, improved identification of system conditions during and after a disturbance and improved actions to contain the fault conditions and return to normal. Training aspects are dealt with in the previous chapter.

7.1.1 Improvements in Operational Planning

Operational planning is an integral part of normal system operation. There is little doubt that present hardware is technically adequate, providing as it does access at points of work to large mainframe computers with the opportunity of co-ordinated studies and transfer of data between centre(s) (46, 47, 48). Frequently energy management systems, many with considerable computing power also include facilities for operational planning studies.

One does, of course, meet the problem raised by contingency analysis -how to predict the fortuitous combinations of events which are most likely to result in severe disturbances. This is not possible and hence the role of operational planning is to ensure that the credible contingencies are properly evaluated, including interactions between neighbouring systems. This last point is quite important, several disturbances having been caused by failure to co-ordinate transmission outages near the boundaries of neighbouring utilities.

Another important aspect is to ensure that the outcome of operational planning studies is readily available to and understood by the control engineers on shift.

7.1.2 Improved Recognition of Potentially Dangerous Situations

Again, because of the difficulty of predicting hazardous combinations of events, the most that can be done is to make sure that potentially dangerous operating states, either of the system as existing or following any defined contingency, are recognised. The major developments needed are improved and more rapid evaluation of transient (aperiodic and oscillatory) stability limits extending ultimately to on-line evaluation, and of dangerous voltage conditions. Developments are taking place in all these fields (49, 50) spurred in part by recent disturbances.

It is quite common now for energy management systems to include a facility for power flow, possibly contingency analysis studies, to be done on predictive as well as real time date. This will help to overcome reported situations in which switching during severe loading conditions has actually worsened the system security or remedial switching has been deferred because of uncertainty of its effect.

Reference has already been made to the increasing use of automatic system switching to improve effective transmission capacity. As far as is known, utilities do not generally ask for such schemes to be modelled in contingency analysis programs which seems a mistake in that unnecessary warnings will be given resulting, if followed, in too conservative operation. All the system manipulation facilities needed (circuit add/delete, generation and or demand change, etc.) will be available in a contingency analysis program. The additional software needed would be to model the logic of the automatic system switching scheme - recognition of the conditions for switching, determination and modelling of the switching.

7.1.3 Improved Identification of System Conditions During and After a Disturbance

Modern data acquisition and display systems are adequate to present to the control engineer the status of the power system at all times. State estimation adds a desirable refinement, but essential if any form of on-line load flow is to be done. One utility with practical experience of on-line estimation considers that security and economy are improved because of the closer limits to which it is possible to work with state estimated data. It may also be noted, however, that conditions during a severe disturbance, with the system in an abnormal state, quite possibly split, and a rapid succession of changes in configuration, may place heavy demands on a state estimator. However, if for instance contingency analysis is to be any use during a disturbance, it must keep up with the changes in network configuration, as experience in the 1977 New York blackout demonstrated.

Based on experience during major disturbances, developments are justified to aid rapid appreciation of the cause of a disturbance, of the system capability that is immediately available and that can be made available over the period following attainment of steady conditions and of the demand trend including indication of the demands lost at each location and recoverable on switching.

As for appreciation of the cause of a disturbance, it is possible to telemeter into the control room relay flag indications, the status of protective systems and of auxiliary plant, etc. Acknowledging that some maloperation of secondary equipment may have contributed to a large disturbance, one need is to develop criteria by which the reasonable set of information necessary to determine or infer the sequence and causes of equipment outages can be determined and techniques by which such information can be analysed on-line and presented at the Control Centre to highlight the probably cause and sequence of the disturbance. One potential danger is lack of discrimination in the choice of alarms presented, leading to the risk of the control engineer being flooded with unnecessary information, thereby delaying his decisions. Time tagging of alarms will be valuable or failing this, an indication of the order in which alarms occurred.

Progress has been made in this area through the application of expert systems techniques (51, 52). One objective is to identify from the relay and switchgear indications, and preferably other system information, the location and type of fault that caused these indications. The detailed indications and alarms would not normally be shown, perhaps only those not consistent with the main inference.

7.1.4 Improved Actions to Contain Fault Conditions and Return to Normal

One of the most important general objectives in the further development of control aids in emergency is to ensure that actions on demand and plant do not "overkill", that is do not provide a compensating action which so exceeds the effect of the disturbance itself as to precipitate further significant disturbances to individual items of plant if not to the system itself. Essentially, the effect of the disturbance and the containing actions should be balanced. It has, for instance, been suggested that a "closed loop" form of demand disconnection should be used more widely; this would overcome problems caused by the magnitude of potential generation loss being largely independent of the time of day whereas the demand disconnection at a particular under-frequency setting and perhaps the amount of running plant will depend on the demand level at the time. A second general objective is to develop techniques by which restorative actions are ideally located, i.e. disconnection of demand effected at points which most helps transmission conditions, any system sectioning effected at points which isolates the disturbed part of the network optimally with respect to conditions in the remaining healthy parts. A third general objective should be to determine and apply those system operating variables singly or together which provide the best warning of the onset of critical conditions.

Such generalised objectives tend to argue for integration of the different types of emergency action and for some form of co-ordination of local controllers, or even central determination of emergency control actions (see section 7.2).

7.1.5 Analysis of Disturbances and Simulation

These topics have been put together since they tend to converge on one main requirement, that is an ability to simulate the dynamics of a power system over a period from say a second or so up to 20 minutes. The simulation would include the action of the plant and main control mechanisms in the stations and on the network. With such a model available, analysis of a disturbance or simulation of any postulated condition should present no technical difficulty, although earlier reported experience suggested the problems of preparing the data are large and the model needs fitting to the individual system.

Another main requirement for analysis is to ensure that sufficient data exists from which to reconstruct disturbances. This is no longer a technical problem; some utilities, for example ENEL and CEGB, have installed multi-channel recorders to log voltages, currents, discrete events, etc. either on detection of some abnormality or continuously. A review of such equipment is also given in (53).

7.1.6 Improved Tactics for Restoration

The developments already considered will assist restoration by limiting the spread of a disturbance or by improving the control operator's knowledge of the status of the system. However these will not specifically address two problems quite often reported - overloading of the system during the early stages of restoration and control of high voltage.

Simple analysis could help in both. The first difficulty is caused in part by the demand at a point tending to increase for a short time after reconnection. It should be possible to obtain from telemetry continuous values of the demands at individual or groups of supply points so that a geographical breakdown of the demand at the instant/s of disconnection during a disturbance would be known. These figures could be further broken down if needed into estimates for individual supply points from historic distribution data, if necessary adjusted for the passage of time since disconnection, have empirical factors applied for the usual ratios of on-reconnection/normal levels and for increase following reconnection, and hence used to provide an estimate of what demand wuld be picked up on restoring supply points.

The second difficulty could be reduced, and perhaps already is, by making it very easy for the control operator to estimate simple incremental power flows using the on-line telemetered data, so that the effect of switching in a circuit could be estimated very quickly. It should also be possible to prepare tables indicating the rise in voltage to be expected on switching in each circuit.

7.2 LONGER TERM OR MORE FUNDAMENTAL DEVELOPMENTS

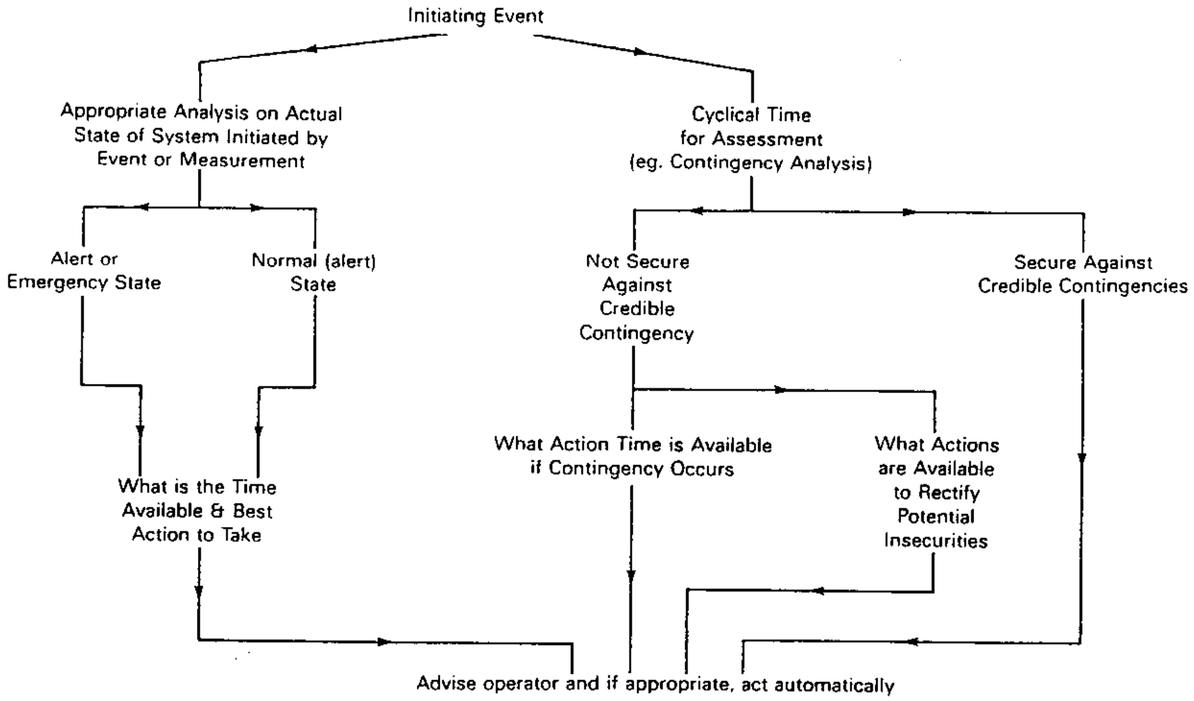
The topics considered below will be the development of adaptive emergency control and the use of expert systems.

7.2.1 Adaptive Emergency Control

A basic approach to adaptive emergency control is suggested in Fig. 2 (see also Ref. 6). A general flow chart is given in Fig. 13 and includes the following steps:-

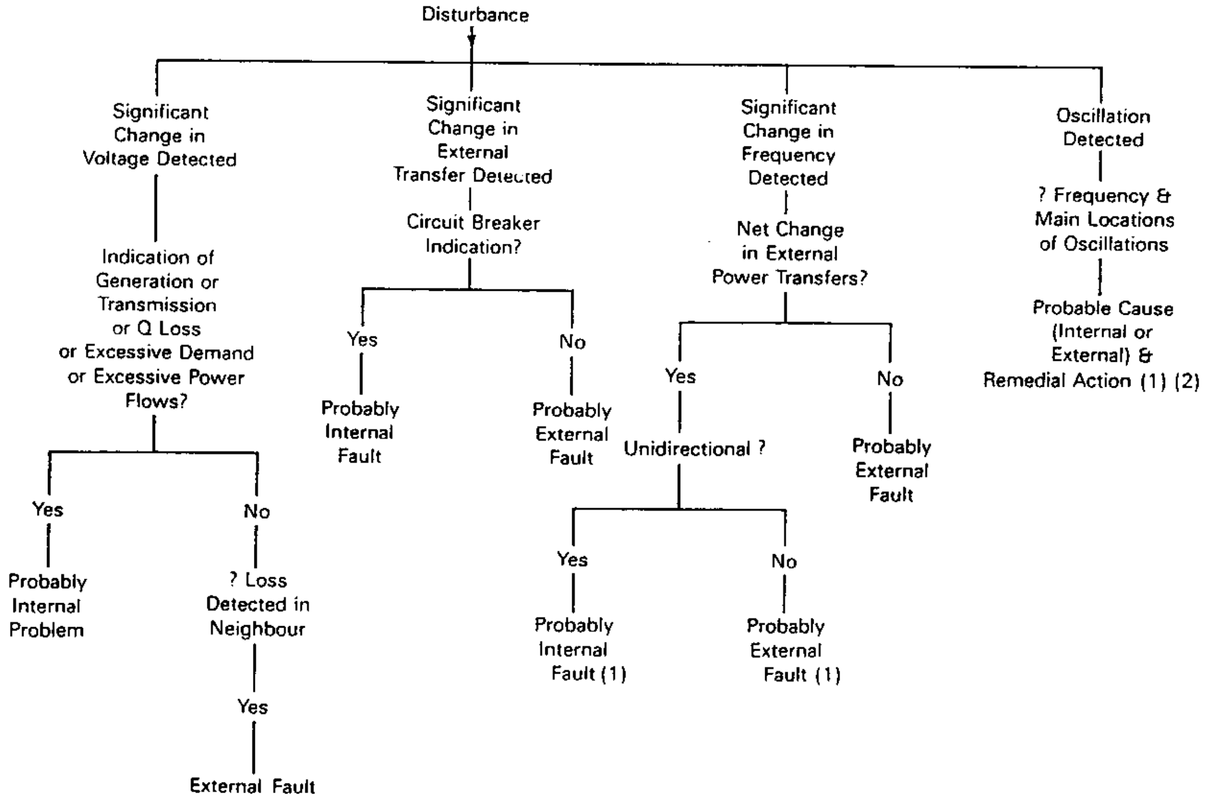
(i) Continually scan telemetered values to determine if there is need for action.

(ii) If a problem is identified use all the appropriate telemetered data to identify the cause and location of the problem. The relative value of various system



Notes: (1) Depending on time available & complexity of phenomena, actions could be determined by analysis or from pre-calculated decision table.
(2) If time permitted, it seems likely that better solutions would result from taking actions incrementally

Fig.13 Outline of Analysis & Decisions for Emergency Control



Notes: (1) Circuit breaker operations could provide contirmatory evidence of internal fault.
(2) Magnitudes of critical power flows could provide contirmatory evidence.

Fig. 14 Sub-Routine to Determine Broad Location of Disturbance variables for this task have been indicated in Table 3. Logic to determine the broad location of a disturbance is suggested in Fig. 14

(iii) Determine the priority of actions and times available for actions (Fig. 15) to contain the results of the disturbance. Much of the decision making here could be from decision tables incorporating pre-calculated levels for action. If the system is in one of the alert states, from very few to many minutes would be available. If the system is already in an emergency state, the action would have to be taken in from milliseconds to, at most, a few minutes. Those actions for which seconds to minutes are available could be met by some form of centralised logic as is already done in some applications using predetermined logic. Actions which have to be taken in milliseconds can at present only be accomplished by local logic and action; when one remembers the time required for data transmission and the action itself, this may always be the case. However, the advantages of centralised logic could be obtained in part by determining parameters for local logic, if necessary predictively, from a central installation.

(iv) Determine the optimum action to contain the results of the disturbance which can be taken in the time available; if necessary operator assistance would be provided, e.g. for a configuration change.

(v) Implement action and check for system viability.

(vi) Repeat as necessary.

Flow charts were prepared to handle several types of contingencies (elimination of overloads, elimination of abnormal voltages, containment of sudden and gradual frequency changes, etc.). As examples, Fig. 16a suggests a sub-routine for the elimination of an actual (as distinct from potential) overload whilst Fig. 16b suggests one for the containment of a gradually falling frequency on a type U3 system.

The analytical requirements needed to cater for a full range of disturbances would be extensive, including contingency analysis, optimum load flow, permissible transfers to groups of substations, frequency trend/time for action, permissible duration of overload, linear program, comparison of variables against limits, generation dispatch, economic dispatch, voltage/reactive power analysis, optimum demand adjustment.

In some ways, the ideas for adaptive emergency control put forward are quite subjective - they emerge as the end product of the assumptions that the best, i.e. potentially least objectionable, emergency actions will be determined by applying power system analysis techniques in an analytical or synthetic manner and probably semi-predictively, to a system whose state is defined by the latest telemetered sample plus an observed change. The available actions, in order of minimum, overall further disturbance to the system (and almost certainly time to determine/implement) are:-

(1) subject to check on viability, adjust configuration (this probably requires manual decision making at present)
(2) adjust generation
(3) adjust demand.

However, action (1) may only be possible on a well meshed network, already for instance adopting specific switching configurations to control power flows or fault levels. Other systems, e.g. those with localised generation/ demand centres and a relatively weak transmission network might find it necessary to adjust generation and/or demand first. This priority is intended first to minimise the disturbance to consumers and second to minimise the risk of overcompensating for the initial cause and hence precipitating further problems.

The analytical models required would seem to be a mixture of ones for dynamic analysis, network analysis and tie-line frequency and economic dispatch including network constraints. There would be scope for optimisation techniques, e.g. linear programming to provide a "minimum cost" combination of ideally located generation adjustment and demand reduction. The mechanisms would in practice have to include exhaustive checks for initiation and completion of the various emergency control actions; these have not been included.

Such developments as these would certainly require centralisation of the decision making function introducing problems of speed of data acquisition and transfer, as well as of computation. Perhaps the boundary between containment and restoration will blur in the future - containment will consist of very rapid, and perhaps non-optimum, actions to bring the system to a state which although abnormal (e.g. with line overloads) can be sustained long enough for optimum final containment actions to be determined and implemented prior to restoration.

Another, and probably technically easier solution, would be a form of hierarchial control, as touched on above. In this a central emergency control facility would provide parameters such as set points and perhaps alternative strategies to local emergency controllers. This could be done predictively and would adapt or tune local emergency control mechanisms throughout the system to the present, pre-contingency system state. It is effectively used in applications in which the operator arms and sets the action to be taken (e.g. generator disconnection) in accordance with the present state of the system. A simple outline of what such a hierarchical emergency control system might comprise is given in Fig. 17.

7.2.2 The Application of Expert Systems

In the author's view, expert systems offer an exciting prospect to engineers responsible for the operation and control of process systems/and for the development of facilities for these purposes. An assessment of possible applications is given in (54). Two of these will be outlined briefly below.

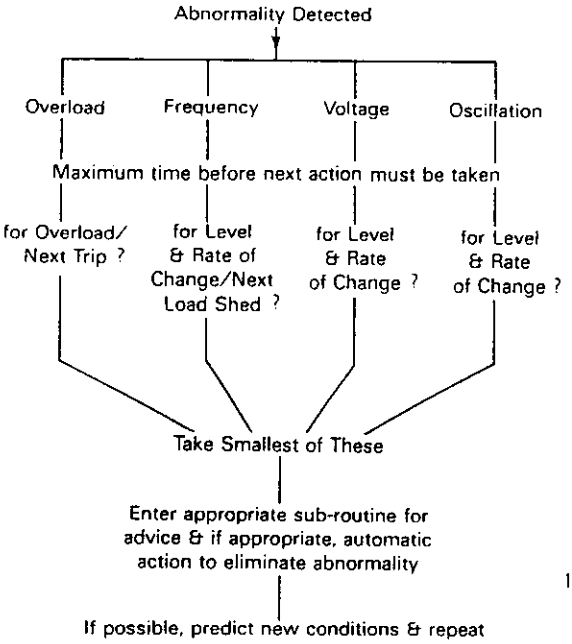
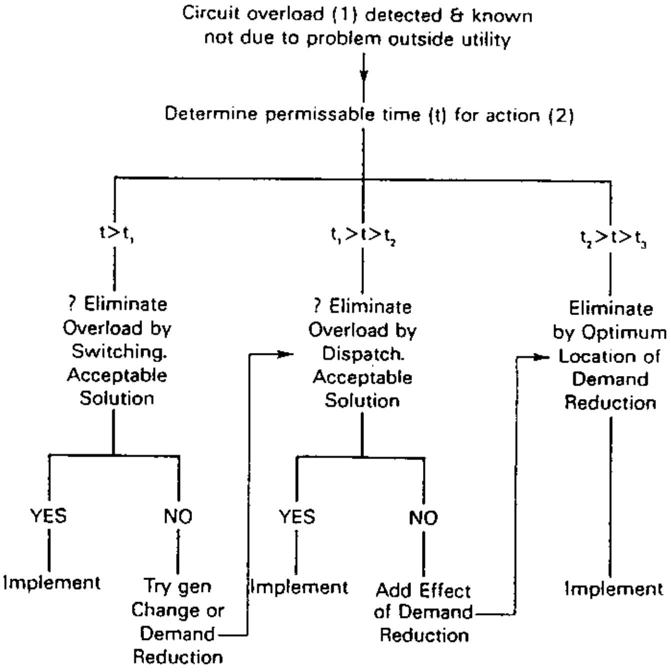


Fig. 15 **Sub-Routine to Assess Priority of Actions**



Note: (1) Overload includes any excessive flow or slemmated flows, whether thermal or stability

(2) t_1 = time reqd. to study & implement switching change (probably manual assessment)

t_2 = time reqd. to compute & implement gen. change

t_3 = time reqd. to compute & implement demand change.

Fig. 16a **Adaptive Sub-routine for Elimination of Actual Overload**

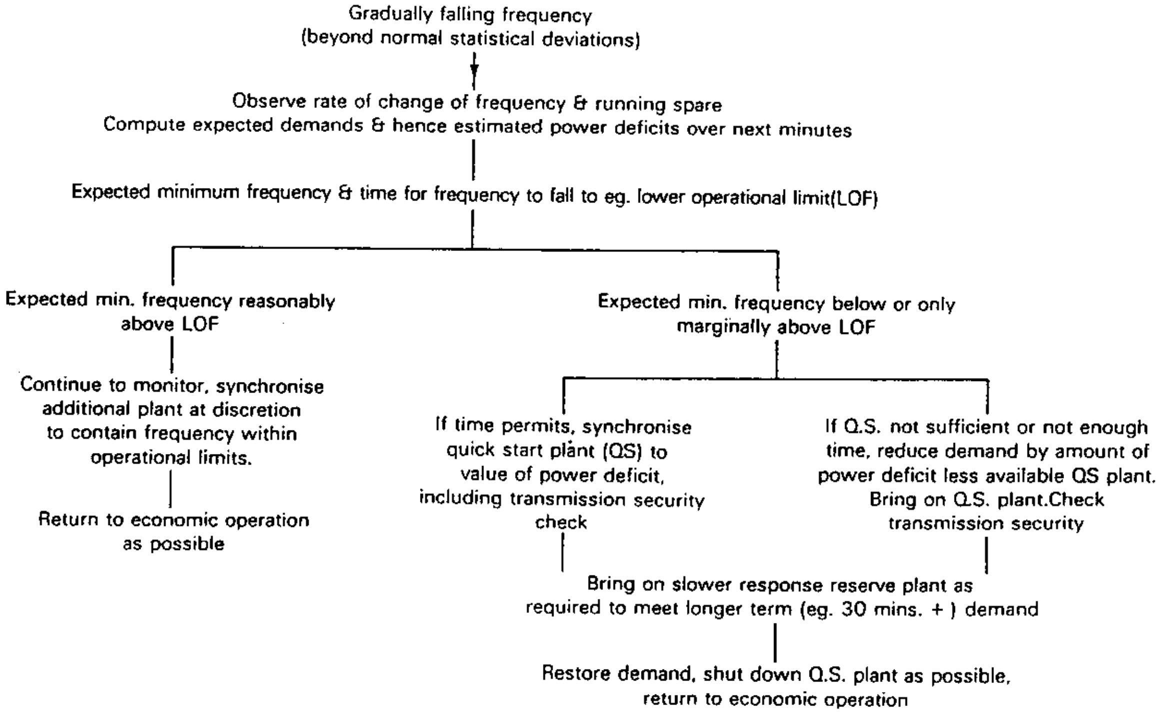


Fig. 16b **Adaptive Sub-routine for Containment of Gradually Falling Frequency on a Type U3 Utility**

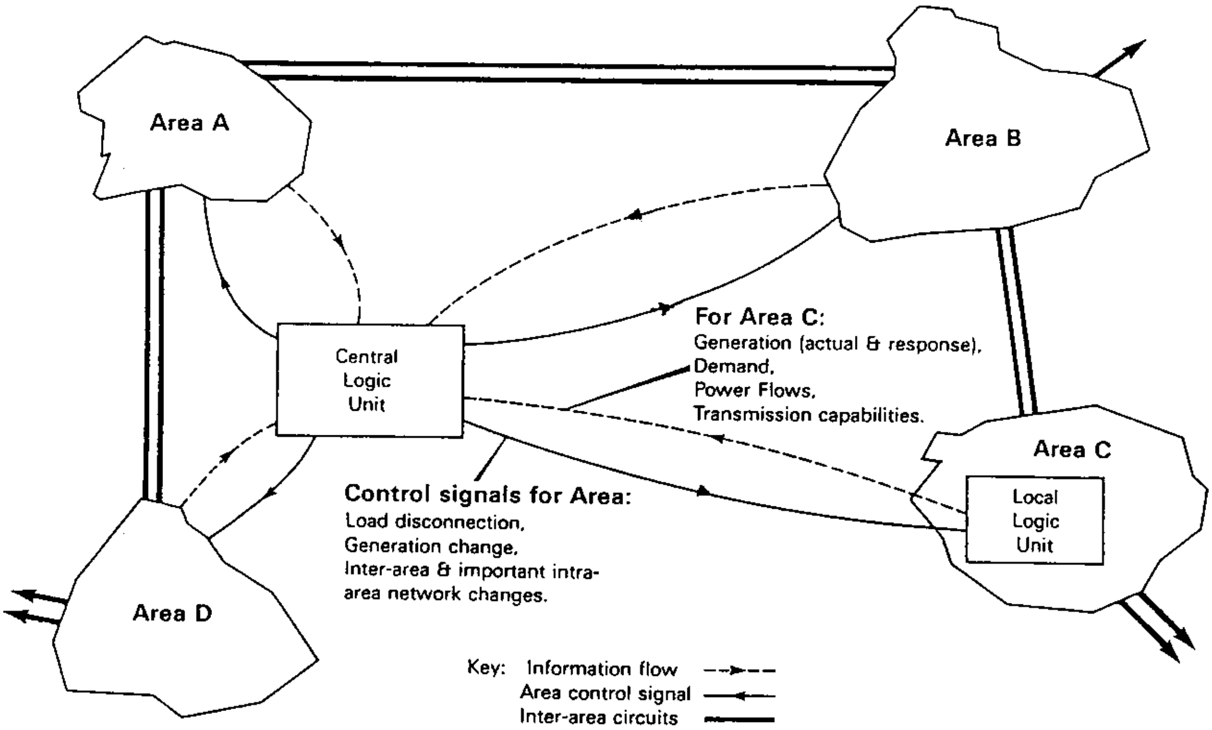


Fig. 17 An Example of a Hierarchical Control System

A frequent problem in a severe emergency is a surfeit of information leading to tens or hundreds of alarms, many of which may be unnecessary for a basic understanding of the situation. The problems may be compounded by incorrect or missing information. The need is to identify what has probably happened, its cause and the present state of the system. The penultimate item is included because there have been cases in which disturbances have been repeated during the restoration process when conditions similar to those causing the initial event have been unwittingly reproduced.

Important factors in determining the present system state and in formulating plans for restoration will be:-

(i) the broad topology of the system (split, isolated from neighbours, etc.).

(ii) the generation - demand situation overall and in separate islands, this including:-

  (a) any unused generation immediately available, would further generation loss precipitate major disruption?

  (b) any loss of demand?

  (c) any significant demand or generation changes in the immediate future?

  (d) the short term availability of isolated or tripped generation

  (e) the status of low frequency relays

(iii) the security of the transmission network; including:-

  (a) is the present state sustainable, how long before switching must be done to relieve overloads assuming no further faults?

  (b) what would be the effect of further circuit outages?

(iv) environmental conditions:-

  (a) the weather

  (b) any special circumstances (e.g. flooding)?

(v) functioning of the transmission network:-

  (a) is normal operation possible or is this adversely affected by e.g. extreme weather conditions, availability of staff, the state of auxiliary services at substations?

(vi) potential support from external systems.

These questions pose a complex, imprecise problem to the control engineer. Existing aids will, if sufficiently fast, provide the answer to some specific questions but will not take account of the uncertainties or interactions.

Turning to restoration, priorities will depend on the type of system and be influenced by organisation and management. Although the strategy and perhaps detail of restoration will have been set down, these will have to be adapted to circumstances at the time (for example the situation following a system collapse caused by loss or overload of some critical circuits would be quite different from that resulting from an ice storm). There will be a considerable element of judgement and uncertainty in plant and demand conditions. Conventional analysis, if the turn round is fast enough, will be adequate to test the viability of specific system states but the postulation of these states will be up to the control staff.

These three tasks - containment of the disturbances, system identification and restoration of normal conditions - would provide very worth while, albeit ambitious, applications for expert systems (ES). A piecemeal approach could be used. In fact the interpretation of alarms was one of the early applications (52). One could look to the ES including analogue (as in some pre state estimation topology checks) and fault recording information to cross check with protection and state alarms. There have already been numerous papers on the use of expert systems to aid system restoration.

Another application could be the monitoring of normal operation. This is at the boundary of emergency control, but the more effectively it is done, the less is the likelihood of a severe disturbance developing. It would seem that the "breadth first" type of expert system could with advantage be developed to scan the telemetered data coming into a control centre and the results of the data processing (contingency analysis, tie line frequency and economic dispatch instructions etc) used to isolate and alarm any developing abnormalities. Such a plant monitoring application has already been reported in the chemical industry.

CHAPTER 8

COSTS AND BENEFITS OF EMERGENCY CONTROL

Generalised cost-benefit analysis of aids to control in emergency is largely unexplored. The difficulties are to assess the costs properly attributable to control in emergencies, as distinct from those for normal control, as well as expected savings which in money terms will mainly accrue to society rather than the utility.

At the control centre most requirements for manually directed control in emergency will be met by the facilities provided for normal operation. Additional ones which may have been partially justified by their role in emergency control can be listed as follows:

contingency analysis,

increased number of alarms from power and substations,

overview diagram of system.

It is not so difficult to distinguish facilities in the field specially provided for emergency control, as follows:

demand disconnection,

generation rejection,

defence plans in general, particularly those for non-credible situations.

Auto-reclose, although playing a vital role in emergency control, has a significant role in more normal operation. In addition there will be the equipment including power supplies, required to ensure the integrity of the communications, telemetry and control systems during disturbed conditions, as outlined in the section on integrity of services.

Information was obtained from a few utilities on the cost of control facilities. In very round terms, the cost of equipment and buildings for modern system control (excluding controls within stations) are of the order of 1% or less of the net generation and transmission assets of an undertaking. Excluding emergency auxiliary supplies it seems that the cost of facilities for emergency control may be of the order of 10% or less of the cost of the total system control facilities, i.e., say 0.1% of the net generation and transmission assets of an undertaking.

In contrast, the social and economic costs of large scale blackouts, which successful applications of emergency control should prevent, can be large. The total cost of the blackout of New York on July 13-14, 1977 for instance, was put at some $310M, roughly $4 per kWh not supplied (this is somewhat higher than often quoted figures for the cost of an unsupplied kWh in terms of its normal cost of supply). Alternatively, and for this assessment more usefully, it is say some 20% of the net generation and transmission assets.

Summarising these very rough figures, it seems that the cost of equipping a power system with emergency control devices (but excluding standby auxiliary power supplies whose costs could be significant and any additional manning) may be of the order of 1/2% of the cost to the community of a more or less complete and lengthy shutdown. The risk of such a shutdown occurring is of course very small and there can be no absolute guarantee that an emergency control system will prevent a major shutdown.

The cost of the disturbance in Sweden in December 1983 was estimated at 200-300 m Swedish kroner - of which 100 m was cost to industry, 100-200 m cost to other consumers and 20 m cost for more expensive generation. About 65% of all supplies were affected, with the majority of the demand restored within 5 hours.

Such assessments do not apply to the other applications of emergency control techniques, that is the applications of these to overcome the effects of delays in the commissioning of transmission or generation or as a means of reducing planned transmission or generation capacity. Taking the case of delays to transmission, the most frequent applications are to reduce the risk of uncontrolled shutdown of demand because of inadequate transmission capacity and to avoid limitations on output from new generation caused by insufficient transmission capacity from that plant. The first, and relatively less frequent case, could well be met by rapid reduction of demand, with costs and benefits as outlined above. The second case would probably require the application of a generation rejection scheme. Again in very round terms, one could probably say that the elimination of a restriction of 100 MW from new plant could cover the cost of the generation rejection control equipment in a few days at most. There would be benefits to system security because of the increase in total system generation availability.

Another possibility might be that the techniques could be used to reduce the dynamic duty on plant by adjusting generation and demand transiently so as to minimise the sudden output changes required.

Turning to the use of emergency control techniques as a means of reducing investment in transmission or operating costs of generation, the relative costs (capital for transmission, operating for generation) of main plant will be so large compared to the costs of emergency control equipment that the issue will never be a simple one of cost against savings. Rather it will be whether the degradation in quality of supply, probably marginal, is acceptable or whether other factors such as availability of capital, or wayleaves, or fuel dictate adoption of the policy of using emergency control techniques to reduce primary plant requirements. Not unimportant points are that if emergency control techniques are used to reduce the capacity of main plant, they cannot be relied on also as a buffer against delays in commissioning plant or as a means of containing major, non-credible disturbances.

Overall it seems that all forms of resources (except perhaps human beings!) will have to be spread more thinly in the future. As far as the electricity supply industry is concerned, there will be less land available for generation and transmission works, more concern about the effect of development and of operation on the environment, less money because of competition from other areas of investment with bigger returns, and greater resistance to paying an economic price for electricity because of competition from other less basic but more appealing products. The effect will be to drive designer and operator to minimise resource requirements and maximise efficiency of operation. This will lead to tighter margins in planning and operations, bigger incentives to pool facilities between utilities, and hence a greater chance of big and small disturbances. The need for emergency control facilities and training is likely to increase rather than decrease in the future.

CHAPTER 9

CONCLUSIONS

The outcome of some 12 years work done under the auspices of Cigre Study Committee 32 and then 39 has been reviewed in this brochure. Before and during that time the value of the more basic forms of emergency control such as demand disconnection, auto-reclosing and in the later years generation rejection have become fully accepted. Schemes to overcome local or short term difficulties in transmission are widely employed and some countries and utilities have developed anti-disturbance and power system stabilising schemes.

In spite of the apparent diversity in the mechanisms of large scale losses of supply, there is a common pattern to the way in which these evolve. In addition, the basic cause of a disturbance is often not so much a complicated multiple event as a simpler immediate cause plus compounding factors.

It is thought that development will continue towards making emergency control installations better suited to the task to be done, that is imposing minimum change on plant operating conditions and minimum impact on demand. Steps in achieving this will be to ensure that the most appropriate signals are used to initiate optimum actions at optimum locations. In the long term this could lead to the adaptive emergency control suggested in Chapter 7. A continuing and possibly increasing problem however will be to ensure that the logical designs of schemes are correct, that operation occurs when needed and not otherwise and not least that there are no unexpected interactions between schemes.

Turning to restoration most utilities appear to follow the same broad pattern. Although the strategy and perhaps detail of restoration will have been set down, these will have to be adapted to circumstances at the time (for example the situation following a system collapse caused by loss or overload of some critical circuits would be quite different from that resulting from an ice storm). There will be a considerable element of judgement and uncertainty in assessing plant and demand conditions. Conventional analysis, if the turn round is fast enough, will be adequate to test the viability of specific system states but the postulation of these states will be up to the control staff.

Expert systems may provide a mechanism for harmonious blending of the human judgemental and intuitive approach with the very strong analytical and optimisation techniques already available to the power system engineer. It would effectively become another variant of interactive computing but with the expert system posing questions and trial solutions for analysis rather than the engineer.

Containment of the disturbance, system identification and restoration of normal conditions would provide very worth while, albeit ambitious, applications for expert systems. A piecemeal approach might be used. One could look to the expert system including analogue and fault recording information to cross check with protection and state alarms. There have already been numerous papers on the use of expert systems to aid system restoration, although admittedly only applied to simple situations.

Another application could be the monitoring of normal operation. This is at the boundary of emergency control, but the more effectively it is done, the less is the likelihood of a severe disturbance developing. It would seem that the "breadth first" type of expert system could with advantage be developed to scan the telemetered data coming into a control centre and together with the results of the data processing (contingency analysis, tie-line frequency and economic dispatch instructions etc.) used to indicate and alarm any developing abnormalities.

Will there be another area of development in which emergency control techniques are used more to increase system capability and to minimise the dynamic duty on plant? If this does occur it must be remembered that if a scheme is provided both to increase system capability and the system's resilience against non-credible contingencies, then on occasion both functions will be needed simultaneously and one or other objective may suffer.

In conclusion, it is judged that the need for emergency control facilities to minimise the risk and severity of major disturbances is likely to increase in the future. This will follow from proportionally less financial and physical resources being available for the supply of electricity, resulting in higher utilisation of plant and more complicated systems. The same will be true of the use of such facilities to minimise the effects of inadequate transmission, and to a lesser extent generation, capacity on normal operation.

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