RESTORATION SERVICE ECONOMIC SCHEMES IN POWER SYSTEMS

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Abstract- A restorative framework that promotes an economically and technically feasibly solution for system restoration is presented. Within this, two alternative restoration schemes whose selection depends upon several system characteristics at the time of restoration, are shown. A sequential approach is given through a series of connecting events, alternatively a parallel restoration scheme is given through the simultaneous manipulation of isolated parts of the network. Results show that the framework can be generalized and become a useful tool for operators during restoration procedures.

I. INTRODUCTION

It is well recognized that power system security has been historically provided through comfortable margins of generating capacities, transmission lines capabilities and reactive power compensation. It is also known that not all possible system configurations and systems demands can be taken into account during the planning of such overall margins, thus secure and reliable operation will not always be so under random and unpredicted conditions. On top of this, nowadays, the new organizational structure to which the electric industry is been drawn into, exploiting the potential economic benefits of competition, is pushing these traditional security margins to their very limit. Overall this means that even well designed, planned and operated systems, are indeed vulnerable to potential contingencies leading to cascading events which could end with a very low or nil system security level; in practice a blackout or brownout condition [1]. Under these circumstances it is prudent to be prepared for such an event by developing a well behaved, readily accessible and easily understood power system restoration plan, in order to allow a timely and orderly transition to a normal operating condition[2,3,4].

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However the meaning of the words timely and orderly has a profound impact on the particular scheme, all of which can be traced down to the economical and technical characteristics of the system. The complex ways which link the latter features, both dynamically and in a steady-state mode, together with the urgency of the actions themselves, make restorative schemes difficult to develop, and hard to generalized [5,6].

This study presents a steady-state restoration scheme which gives an initial priority to the economical restrictions of the system, and follows on with the technical feasibility of the scheme [7,8]. It is clear that both of these features play an important role under the industry newly defined decentralized structure.

II. RESTORATIVE SCHEMES FEATURES

A. Theoretical aspects

The restorative state denotes a halt to the system degradation and the beginning of the necessary control actions in order to restore supply to the level of required system service quality. Stated mathematically, although inequality constraints associated with system restrictions are satisfied, some (or all) of the equality constraints are completely or partially violated [1]. This means that load service to some (or all) customers is not been accomplished, hence comes the restorative plan or scheme in order to fully satisfy the needs of these customers. It is clear that there are many 'ways' to carry out this mission, depending on the elements available and the sequence to which they are put into operation.

Under this scope, the problem of developing power system restorative schemes is a very much ad-hoc task, in fact, there seems to be no single solution to the problem. Experience in most power systems, has shown that most utilities have developed their own restorative schemes to meet the needs of their particular system Although it is difficult to generalized these schemes, most bulk power system have some characteristics in common and behave in a similar manner during the restoration process [2,6,9]. In general all of them enhance the technical features of the system, however as it is now discussed, economical considerations are also important..

B. Technical and Economical aspects

Technically the major portion of the initial effort in restoring power system supply, lies within restart and reintegration procedures for generation and transmission systems, during which load pick-up is necessary in order to bring generators to stable operating conditions. Aside from dynamically related considerations, during steady-state restoration procedures a great deal of attention is given to the balancing of active and reactive power. Hence the need to check line flows, voltage levels and phase angles in order to carry out a well designed plan.

From another point of view, many restorative actions have an impact on the economies of the system (most in the short term). To mention but the most important are the start-up cost of thermal units, the cost of ancillary equipment for this purposes, the operating costs of all generators and the loss of load value or failure cost [10]. Thus, a particular combination of elements during the restoring scheme, can lead to a higher overall cost than another one, hence it seems that the restorative action must not only be carried out in a minimum time but with due consideration to the economical impact of the actions themselves. In practice economical considerations are often neglected in restorative schemes, so that although technically feasible, these plans may not be so from an economical point of view. This fact becomes more clear under the electricity industry new regime, whereby market oriented decisions more or less define the operative behavior of each actor during the restorative scheme although on the other hand regulation defines all their responsibilities towards the interconnected power system. The following restoration proposal considers a mixture of important economical and technical features within a common operative framework. As it is shown, restorative solutions before been technically feasible are filtered to be economically feasible.

III. SCHEME PROPOSAL

A. Generalities

The information needs as well as the main decision analysis which the restoration scheme makes, are depicted in Fig. 1. This 'upper-level' flow diagram, actually describes the basic idea of the framework. As shown initial information concerning the meaning of a normal state (load and generation pattern, grid configuration, etc.) for a specific power system is needed. To complement this, information related to the way the system is operated both technically and economically is required. This type of data actually represents the target system of the restorative actions. Finally, information related to the conditions from which restoration procedures must begin (i.e. the restorative state), are made available. It can be assumed that a sort of state estimator fully describes the restorative state (operating generators, loads been satisfied, lines out of operation, etc.), that is, the status of all elements of the power system under restoration.

Once all of this information is available and ready to be processed, a decision has to be made regarding the restoration solution to follow, that is whether a sequential or a parallel scheme is followed. The proposal here made is to solve this through a "restoration factor" or Fr as it will now be referred to. This factor has the role of sensing how good or bad are system conditions prior to restoration. As such, restoration factor should be based on many inherent characteristics of the system like the size of the system, the blackstart capacity and location, the amount and location of unserved power and of course, as its the basis of this paper, economical considerations like generator operational cost and loss of load value.

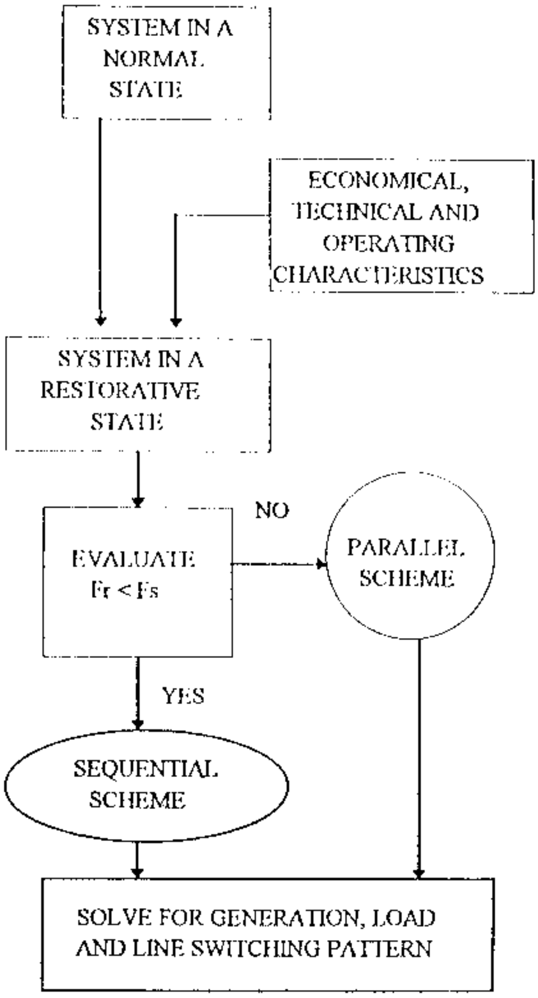

Fig. 1. Restoration scheme -upper level- decision analysis

However the difficulty of simultaneously considering all of them is formidable. As a simple way to approach this problem, the following definition has been given to the restoration factor Fr = f(% of high voltage energized lines, % of unserved power, operating cost, loss of load value). In particular it has been assumed that $Fr = \alpha^*(\%\text{ of high voltage energized lines}) + \beta^*(\%\text{ of served power})/(\alpha + \beta)$, with $\alpha + \beta = 1$. Generally speaking α and β depend on empirical knowledge of the system (i.e. importance of one against the other). As it is shown this restorative factor oscillates between 1 (normal state) and 0 (blackout start). Although simple, Fr leads the way to automate decisions during restoration schemes.

B. An algorithm

Based on the conceptual design of Fig. 1, a middle decision analysis flow, whether for a sequential approach or a parallel scheme, is presented in Fig 2. Within this analysis and generally speaking, a sequence of steady-state balancing events take place, in such a way that they are economically and technically consistent through a closed loop solution.

As for this and from Fig. 2, initially a simple economically-based objective function is used to guide the sequence of events, it is from this latter pattern that a more comprehensive technical criteria follows. Overall a closed loop algorithm makes sure that operating cost and unserved energy cost are minimized but also operative restrictions are satisfied. To carry out this an approximate optimal DC load flow, which minimizes the operating cost and that of unserved energy is used. The output of this stage serves as input to a full AC load flow, capable of handling islanded portions of the power system. The control variables within this algorithm, are the generation/load program and the sequence of line switching. The decision process which this algorithm carries considers not only generation pick-up limits, but also voltage difference limits, phase angle limits and lines flow limits. On the other hand there are some features which are not here considered, but which can incorporated as operating characteristics (i.e. time to carry out a particular maneuver or other dynamic restrictions).

Finally it is stressed that this loop is carried out whether the criteria considers a sequential or a parallel scheme.

C. Sequential scheme - lower level decision analysis -

Once it has been decided that a serial approach will be followed (i.e. Fr < Fs with Fs given, by the user, typically 0.3), the main steps which the algorithm carries out are:

- begin restoration in the island (if any) with highest generation availability, otherwise begin with highest available generation

- connect potential generators

- proceed with high voltage lines

- pick up load

- employ economical (DC load flow) and technical (AC load flow) criteria to connect lines, loads, and generators

- continue until a normal or target power system has been reached

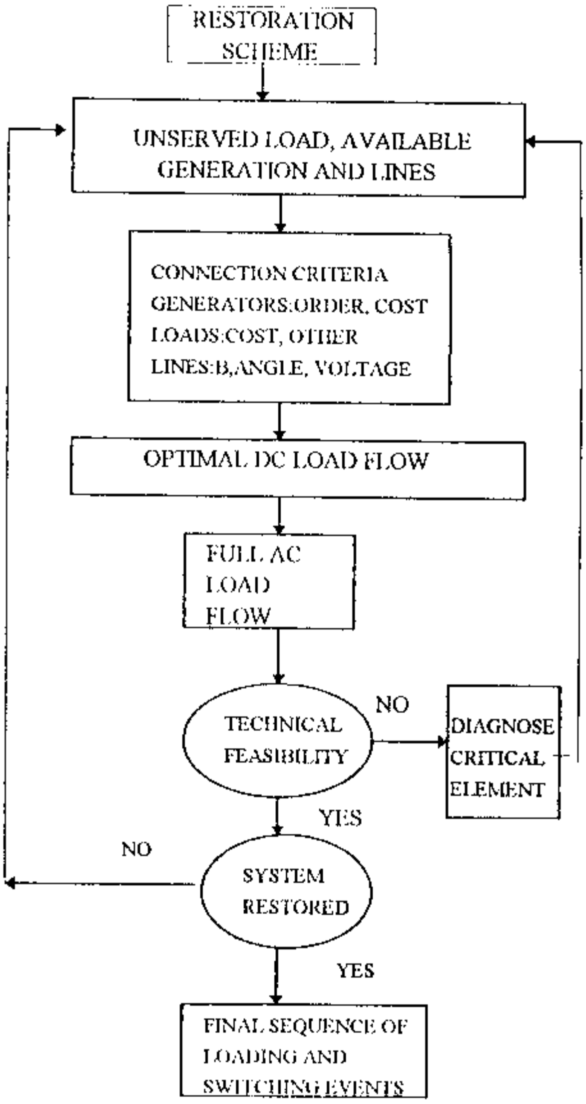

Fig. 2. Restoration scheme -middle level- decision analysis

D. Parallel scheme - lower level decision analysis

The steps which the algorithm follows once the decision has been made as to the use of a parallel approach are:

- identify and individualize all islands and their elements

- begin a sequential scheme in the island with the highest failure cost, if not possible search for the next highest value, continue until no further load or generation is available

- employ economical (DC) and technical (AC) criteria to connect lines, loads, and generators within island

-proceed with next island

- connect islands according to maximum failure cost and maximum generation, that is the island with the highest failure cost with that of highest generation availability

- continue until a normal or target power system has been reached

IV. SIMULATION AND RESULTS

An algorithm which incorporates the decision analysis previously described was developed using FORTRAN language. The application of the methodology was performed on the test system shown in Fig. 3. The main point to stress here are not the data numbers themselves, but rather the decision making process (i.e. relative rather than absolute). Information regarding normal operating conditions is shown in Table 1.

TABLE I
NORMAL STATE OPERATING CONDITIONS

Bus #	Pg MW	Operating Cost U.S.$/KWh	Pl MW	Failure Cost U.S.$/KW h	Ql MVAR
1	6x100	0.08	1	0.14	0.5
2	2x100	0.1	240	0.15	136
3	2x180	0.09	40	0.15	19
4	-	-	160	0.17	82
5	-	-	240	0.18	113
6	1x150	0.06	80	0.16	45
7	-	-	100	0.20	55
8	1x100	0.1	15	.0.16	7
9	-	-	100	0.19	54

Simulation was carried out both for a parallel scheme and for a sequential restoration scheme. Tables 2 and 3 present an example of possible restoration information in relation to the parallel and sequential schemes respectively. Additional operational criteria not included in those tables relates to priority loading of generators, an empirical way to take into account start-up costs. Clearly the pseudo-optimal solution sequence of switching events to be obtained, is dependent on this restorative initial data.

Following the diagram depicted in Fig. 2 and for the parallel scheme, the resulting sequence of switching lines, generation output and busbar load pick-up shown in Table 4.

The events presented in Table 4 have followed the decision analysis previously described. It is interesting to note that three potential isolated portions of the network (these are detected by the algorithm), are been handled simultaneously in relation to restoration events which follow.

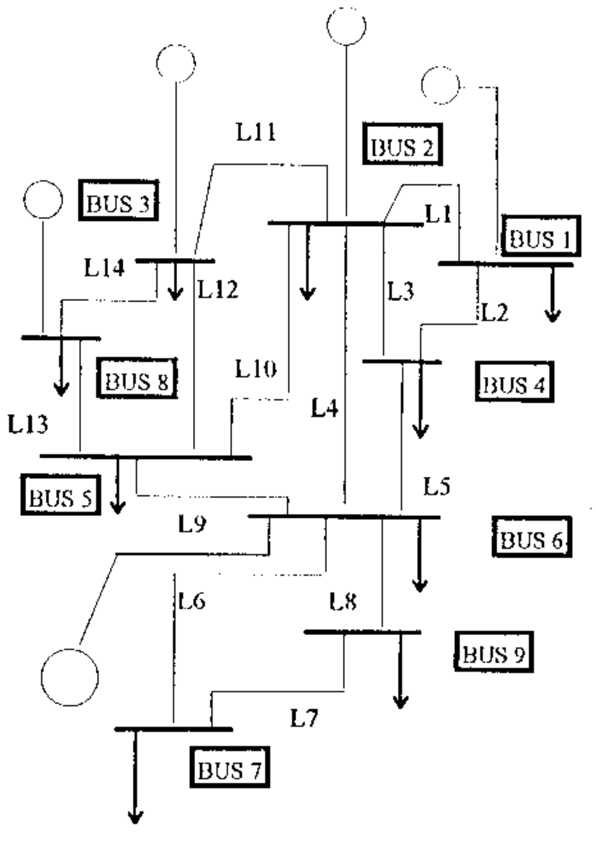

Fig. 3 Power System under Restoration

As for simulation results related to the sequential scheme, from Table 5 it can be seen that a mixture of economical and technical events take place. In any case these results are clearly dependent not only on the initial conditions given but most importantly on the economical and technical data of the system. Although this research represents a particular approach to a closed loop, consistent economical and technical solution, it is believe that it can easily be modified to cope with further refinements.

TABLE 2
RESTORATIVE STATE OPERATING CONDITIONS
FOR PARALLEL SCHEME

Bus #	Pg (MW) available	Pl MW	Ql MVAR	Energized lines
IS-1				
1	3x100	1	0.5	L1, L3 ON
2	2x100	240	136	L2 OFF
4	-	0	0	
IS-2				
3	1x180	40	19	L12, L14 ON
5	-	180	55	L13 OFF
8	1x100	15	7	
IS-3				
6	1x150	50	20	L6, L7 and
7	-	15	7	L8 ON
9	-	30	10	

TABLE 3
RESTORATIVE STATE OPERATING CONDITIONS
FOR SEQUENTIAL SCHEME

Bus #	Pg (MW) available	Pl MW	Ql MVAR	Energized lines
1	4x100	1	0.5	
2	1x100	40	18	L1, L2 ON
4	-	60	22	L7, L8 ON
6	1x150	20	5	all other
7	-	100	55	lines OFF
8	1x100	15	7	
9	-	0	0	

V. SUMMARY

When compared with traditional power system studies which deal with normal, alert or emergency states, little has been said regarding restorative schemes. Maybe because most work has concentrated in efforts to avoid the reaching of this state.

However, no system will ever be absolutely secure and will eventually, due to unforeseen events reach a blackout or at least a brownout operating condition. The huge damage which a lack of electrical energy can cause, can be minimized or rationalized through a proper restorative scheme. The proposal which this research has given to the problem, seems to be a logical step in order to provide a sound economical and technical solution to the combinatorial nature of restorative schemes.

TABLE 4
SEQUENCE ON RESTORING EVENTS
FOR THE PARALLEL SCHEME

Sequence #	Description of events within the sequence
1	IS-1: close L2 IS-2: close L13, Pg3=142
2	IS-1: 1X100 available, Pg1=148, Pl4=100 (28) IS-2: Pl5=200 (85), Pg3=165 IS-3: Pl6=70 (35), Pg6=142
3	IS-1 and IS-3 (now IS-13) are connected via L4, Pg1=140, Pg6=150
4	IS13: Pl4=130 (66), Pl6=80 (45), Pl7=60 (25), Pl9=50 (27), Pg1=233, Pg2=200, Pg6=150 IS-2: Pl5=210 (95), Pg3=176
5	IS-13: 1X100 available, close L5, Pg1=234, Pg2=200, Pg6=150 IS-2: 1X180 available
6	IS-13: Pl4=160 (82), Pl7=100 (55), Pl9=100 (54), Pg1=413, Pg2=200, Pg6=150
7	IS-2 and IS-13 are joined through L10, Pg8=100, Pg1=320, Pg2=200, Pg3=260, Pg6=150
8	Pl5=240 (113), Pg1=355, Pg2=200, Pg3=260, Pg6=150, Pg8=100
9	L11 is closed, Pg1=348, Pg2=200, Pg3=260, Pg6=150, Pg8=100
10	L9 is closed, Pg1=339, Pg2=200, Pg3=260, Pg6=150, Pg8=100

The algorithm presented assumes that a reliable information system is available, which in turn will provide a reliable idea of the system state variables and the status (availability, quantity, speed, priorities) of most elements in it.

Although some important features, notably dynamical ones, have not been considered here, it is thought they can be incorporated within the algorithm. Aside from this, the developed scheme can be used as a simulation tool to the system operator, providing him a checkout on his own decisions particularly from an economical point of view when cost of generation and unserved power can be relevant.

Finally this algorithm is been refined at the moment to incorporate more experience (from the system operator) logic, such that complex operational restrictions (whether economically based or technically based) can be handled in a consistent manner.

TABLE 5
SEQUENCE ON RESTORING EVENTS
FOR THE SEQUENTIAL SCHEME

Sequence #	**Description of events within the sequence**
1	1x100 (available for Pg2), close L10, Pl5=80 (38), Pg1=37, Pg2=150, Pg6=131
2	1x100 (available for Pg1), close L3, Pg6=131, Pl5=120 (56), Pg1=50, Pg2=100, Pg8=100,
3	2x180 (available for Pg3), close L11, Pl2=140 (79), Pl3=40 (19), Pg1=87, Pg2=150, Pg3=50, Pg8=100, Pg6=131
4	1x100 (available for Pg1), close L4, Pl2=240 (136), Pl6=80 (45), Pg1=134, Pg2=200, Pg3=100, Pg6=150, Pg8=100
5	close L14, close L3, Pl4=100 (52), Pg1=121, Pg2=180, Pg3=180, Pg6=150, Pg8=100
6	close L12, close L9, Pl5=240 (113), Pl9=25 (6), Pg1=215, Pg2=200, Pg3=220, Pg6=150, Pg8=100
7	close L5, close L6, Pl9=100 (54), Pg1=339, Pg2=200, Pg3=260, Pg6=150, Pg8=100

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