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Proposing a Market Based Approach for Restoration of Power Systems

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Abstract – *Power system restoration is an important task for system operators. Therefore, much research has been carried out to optimize restoration process, among which, recognition and access to the network skeleton during restoration has been considered as a dominant approach. If the main skeleton-network is recognized appropriately, then reconfiguration and restoring major parts of the network can be performed at the shortest possible time.*

Restructuring in power industry has introduced new challenges to power system. While, restructuring has affected power system operation seriously, little attention has been paid to restoration process as an extra ordinary mode of system operation in a market based environment. One approach for restoration problem is based on performance indices introduced to rank nodes of the network. In this paper, a new method based on a comprehensive ranking index for electrification of network buses during restoration process is proposed which results in reduction of both the interruption cost and restoration cost. In our ranking approach, both the network configuration and the value of lost load at different buses of the network have been considered in a market based operated system. In the method, the dominant network skeleton for restoration is distinguished such that the restoration time for the rest of network from this skeleton network will be reduced. Our simulation results confirm the validity and efficacy of our proposed approach in different situations, especially in a market-based environment. We have used the Genetic Algorithm (GA) to solve the optimization problem. The method has been tested on IEEE 30-bus network. Results show that this method in compare with similar methods has a better performance.

***Keywords**: Power System Restoration, Skeleton-Network Reconfiguration, Restructured Power Industry, Genetic Algorithm*

Nomenclature

i	Node number
$\beta(i)$	Betweenness of *i*th node
$\gamma(i)$	Closeness of *i*th node
$\delta(i)$	Inverse of interruption cost of *i*th node
n_{jk}	The number of shortest path between *j* and *k*
$n_{jk}(i)$	The number of shortest path between *j* and *k*, which pass through *i*
$d(i,j)$	Distance between *i* and *j*
$IC(i)$	Interruption Cost of node *i*
N	The set consisting of all nodes in skeleton network
L	The set consisting of all lines in skeleton network
$l(j)$	The line number *j*th
n	Number of network's nodes
t	Number of skeleton network's nodes
$n_{\Delta U}$	The number of nodes that their voltage is over the limited area
L_c	The number of lines in skeleton network
MP_i	The maximum capacity of ith line
CP_i	The current capacity of ith transmission line

I. Introduction

Modern societies are dependent on electrical energy. On the other hand, while, the demand for electric energy as a reliable energy is increasing, the power system and its operation becomes more and more complicated. Exposure of power systems to serious blackouts during the past decade has been a consequence of heavy loading of these systems together with uncertainties introduced to the system due to serious structural changes of power industry [1]-[3].

Serious blackouts have occurred all over the world during the past decade. Some examples are two blackouts in 1999 in Taiwan [4], in Brazil (2002) [5], in Sweden and Denmark (2003) [6], in big parts of North America (2003), in java-bali in Indonesia (2005) and in a big part of the Europe connected network (2006) [7].

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Long time blackouts may have serious economical effects on both the society and power industry itself. On the other hand, a fast and suitable restoration plan can alleviate the affects and losses associated with duration of blackouts [8]. As a result, attention has been paid to fast restoration techniques after the blackout during the past decade, especially in market-oriented environment [9]-[11].

The restoration of power system after a partial or complete blackout has always been considered as a challenging problem for system operators. Various research works have been carried out in the field. Essentially, two different strategies for restoration can be distinguished known as restoration by zone and restoration by path [12].

Restoration by zone: In this strategy (also known as island restoration method), after a blackout occurs, first the power system status is assessed. Then, the network is divided into separated subsystems (islands) each having a black-start plant. Finally, after restoration of each area and before complete load pick-up, they are synchronized with each other. Using this method, the restoration of different zones can be done in parallel and simultaneously. Therefore, the restoration time decreases to the less possible amount for subscribers. The step, which usually causes some problems, is to synchronize these islands and restore the network to its former integrated state. It should be note that in this method many black-start plants are needed.

Restoration by path: In this strategy, first, the main part of the network is energized. Then, the rest of network buses and loads are energized in parallel. Because of the stability of the premier network and step by step energizing of the power network, this method, as compared with restoration by zone method, is more reliable. However, the main problem with this strategy is the time needed for energizing the whole network, which is longer than that of restoration by zone [13].

As restoration time is one of the most important factors in energizing the network after a blackout, most researches on restoration problem have been focused on the island restoration method. In this method, because of the parallel restoration of several islands, it is possible to energize more subscribers at the premier steps of restoration. However, in this method synchronizing the islands is a complicated problem and may result in network collapse again. This may cause serious damages to electrical devices.

In this paper, we have focused on reduction of restoration time needed when restoration by path method is used which is the only method for restoration in cases where only few black-start power plants are available. In addition, our method can be used in restoration by zone method for finding the best skeleton network of each island. If the best skeleton network is used in each island, the time needed for the process will be reduced. Therefore, this method can lessen the time needed for restoring power networks in both by zone and by path methods.

Almost all restoration techniques relying on path method, utilize a performance index for ranking the network buses. While the performance of these techniques mainly depends on the indices associated with them, less attention has been paid to their comprehensiveness. Furthermore, they may not necessarily have an appropriate performance for some networks.

In this article, a combined performance index for recognition of network skeleton is proposed. Using this index, both the time and cost of restoration are reduced. The method has been test on IEEE 30-bus network. The optimization problem has been solved by genetic algorithm. Simulation results confirm the priority and efficacy of the proposed algorithm.

Coming up, in part II, the new method is explained. Section III explains the flowchart of the main program. Simulation results are analytically discussed in section IV. Finally, concluding remarks appear in section V.

II. Description of New Network Reconfiguration Method

Generally, the restoration process for power systems, which relies on path method, includes two separated stages: first; assigning the skeleton network and second; performing practical actions in order to energize the whole network from skeleton network [14]. In this paper, attention has been paid to the first stage, recognizing a subsystem of the network as the skeleton network. This subsystem is assigned such that it includes most of important buses necessary for restoration process.

To determine the skeleton network, normally, an index is defined for ranking network buses. This index assigns a value to each bus of the network, which is a measure for the importance of network buses.

Traditionally, the total number of buses directly connected to a bus in the network (the degree of bus) has been considered as a good measure for ranking network buses. This means that according to network topology, the nodes directly connected to more buses are ranked as buses that are more important. Although this index is valid for most of the networks, the most important nodes in compare to other network nodes do not necessarily have the highest degree in some exceptions. Some examples for such exceptions are illustrated in Fig. 1 [15]. In this figure, while node 12 is ranked lower than nodes 10 and 11, it is the more important than those are.

In 2007, Xueping et al. introduced an index for ranking network buses, which also considers the degrees of adjacent buses together with the bus degree itself for ranking the buses. In their approach, they used a parameter called node importance degree (α) [15].

While, this index may be preferred to node degree for ranking network buses, in some cases, it may result in inappropriate ranking.

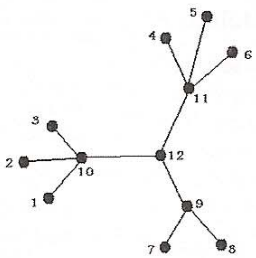

Fig. 1. Example of improper ranking of network buses by the total number of buses directly connected to it

For example, for the network in figure 2, it can be easily seen that node 12 in compare to node 11 should be ranked higher, node importance degrees for these two nodes will be equal (α=0.0625).

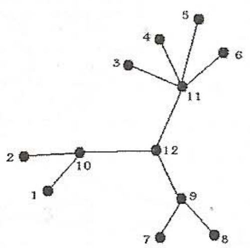

Fig. 2. Example of improper ranking of network buses by node importance degree

Some other indices presented to measure the importance of buses in complicated network are: Betweenness index [16], Closeness index [17], Eigenvector index and Sub-Graph index [18]. While most ranking indices, proposed so far, are simple, as they normally consider only one aspect of buses for ranking, they show ill functioning in ranking buses of some complicated power networks.

Graph indices, which are used for ranking nodes of different graphs, are divided in two main categories. The first category is indices which are based on the idea that importance of a network node is related to how it is near to other nodes such as nodes degree and closeness centrality. The second category is based on the idea that an important node should be between others, Betweenness centrality and flow centrality are two examples of these this category [19]. Since both of these characteristics are important in power system restoration both of these two categories are used in proposing a new index in this article.

In this paper, a new index, composed of three different ranking indices, is proposed for ranking the importance of network buses for restoration problem. The Topological and Economical Importance Degree (TEID) (η), *which is proposed in this paper is a weighted* summation of three different indices and therefore, it benefits the advantages of ranking features of all those indices. The index in flexible and weighting coefficients can be modified according to the importance-ranking feature.

The index is defined as follow:

$$\eta(i)=w_1\times\beta(i)+w_2\times\gamma(i)+w_3\times\delta(i) \qquad (1)$$

In this equation, w_1, w_2 and w_3 are weighted coefficient for each index such that $w_1+w_2+w_3=1$.

Betweenness index for each node is calculated as follow [17]:

$$\beta(i)=\sum_{j,k\in N,j\neq k}\frac{n_{jk}(i)}{n_{jk}} \qquad (2)$$

Then, dividing 1 by the summation of distances between that node and other network nodes, closeness index (γ) for each node will be obtained. It is obvious that the less the sum of distances to other nodes is, the bigger the index will be. The bigger the index value, that node will be considered more important [17]:

$$\gamma(i)=\frac{1}{\sum_{j\in N}d(i,j)} \qquad (3)$$

Table I shows the values of ranking index, betweenness index and closeness index for buses 11 and 12 of the network shown in Fig. 2. As it can be seen, although the value of node importance degree is the same for both nodes, the amounts of betweenness and closeness indices for node 12 is more than those of node 11, which implies that node 12 should be considered more important than node 11.

TABLE I
COMPARISON OF NODE IMPORTANCE DEGREE, BETWEENNESS AND CLOSENESS

Node no.	γ	β	α
11	0.0476	0.4242	0.0625
12	0.0526	0.5909	0.0625

The third part of η is δ which is the economical part of this index and is defined as follow:

$$\delta(i)=\frac{1}{\sum_{i\in N}IC(i)} \qquad (4)$$

Now, the fitness function is defined as below:

$$f=\frac{\sum_{j\in L}l(j)}{\left(\sum_{i\in N}\eta(i)\right)\times k} \qquad (5)$$

$$k = t(n-t) \quad (6)$$

The constraints of the problem are:

$$\Delta U < \Delta U_{max} \quad (7)$$

$$\Delta P < \Delta P_{max} \quad (8)$$

where:

$$\Delta U = \frac{n_{\Delta U}}{t} \quad (9)$$

$$\Delta P = \frac{\sum_{i \in L} (MP_i - CP_i)}{L_c} \quad (10)$$

For solving the restoration problem, which is a multi-objective, multi-constraints and a complicated nonlinear function, traditional optimization algorithms cannot be beneficial. Therefore, in this article, to solve this optimization problem, genetic algorithm has been used. Genetic algorithm is an algorithm based on repetition that its premier principles are adopted from genetic science. This algorithm uses the natural selection principle to find an optimal answer or path [20]-[21]. In this article, a GA solution is defined by the state sequence assigning the lines selected to take part in skeleton network. When a certain transmission line is selected for skeleton network, corresponding position in state sequence equals one. Otherwise, it equals zero. For instance, IEEE standard 30-bus network that is illustrated in Fig. 3 has 41 branches. Therefore, GA chromosome for this network consists of 41 genes. If the value of sixth gene in a GA chromosome was 1 this would mean that branch number 6 which is between busses number two and six, is selected to participant in skeleton network or if the value of the 22nd was zero bus number 22 wouldn't select for skeleton network.

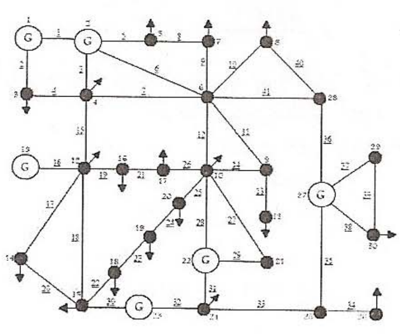

Fig. 3. IEEE 30-bus network

III. Methodology

Fig. 4 shows a general structure of the algorithm proposed in this paper.

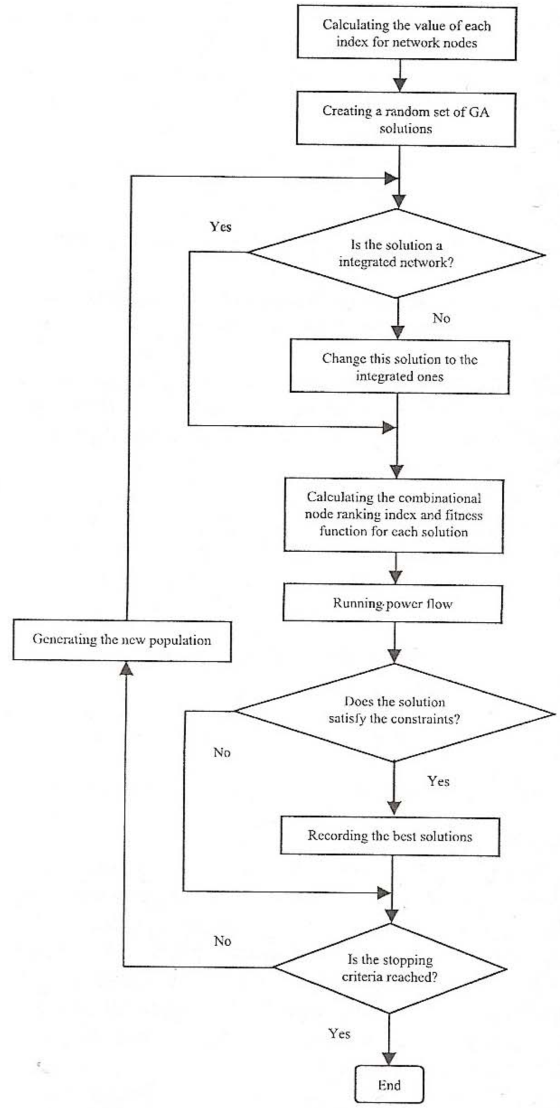

Fig. 4. Flow of the main program

In the first step, values of betweenness, closeness indices and the inverse of interruption cost for each node is calculated and normalized.

To normalize the values obtained for each index, the calculated value is divided to the maximum value obtained for that index. Then, a random set of GA solutions are created. Since skeleton network should be connected, the next step is to check the connection of the solution.

If a solution consists of some separated parts, it should be changed to connected network one by adding some branches to separated one. After this step, fitness function is calculated. Then, considering network constraints, power flow is performed and the best solutions are recorded. This process will be repeated until it reaches the stop criteria.

IV. Case Study and Simulation Results

In order to analyze the performance of combinational node ranking index proposed in this paper, the method was applied to modified IEEE 30-bus network (Fig. 3) and the values of indices for the nodes of this network are calculated. To show the relative importance of nodes, value of each index for each node should be normalized in terms of maximum of that index. Table II shows the normalized values of all indices for the nodes of this network. Based on load importance and the amount of load for each node, an interruption cost is assigned to each load node of the network.

TABLE II
VALUE OF INDICES FOR NETWORK NODES

Node no.	β	γ	Node no.	β	γ
1	0.0057	0.6168	16	0.0590	0.6667
2	0.2296	0.8148	17	0.0902	0.7333
3	0.0227	0.6535	18	0.0652	0.6055
4	0.5087	0.8800	19	0.0666	0.6055
5	0.0057	0.6168	20	0.1488	0.7079
6	1	1	21	0	0.7021
7	0.0482	0.7174	22	0.1989	0.7765
8	0	0.7500	23	0.1776	0.6804
9	0.1587	0.8049	24	0.3207	0.7333
10	0.6509	0.9167	25	0.2768	0.6667
11	0	0.6000	26	0	0.5197
12	0.4941	0.7952	27	0.4355	0.7021
13	0	0.5946	28	0.4138	0.8148
14	0	0.6471	29	0	0.5455
15	0.3080	0.7333	30	0	0.5455

To define the values of weighted coefficients, w_1, w_2 and w_3 Analytical Hierarchy Process (AHP) is used in this paper. AHP is a systematic method for comparing a set of objectives and choices, which was introduced by Saaty in 1977 [22]-[23]. The method is practical for definition of weighted coefficients in solving optimization problems. The coefficients which have been gained by this method are: $w_1 = 0.723$, $w_2 = 0.206$ and $w_3 = 0.071$.

By applying the introduced method to IEEE 30-bus network the optimal skeleton network is obtained which is shown in Fig. 5. Eleven branches labeled in bold lines are identified to participate in skeleton network. Fig. 6 shows the skeleton network suggested by Xueping et al. [16]. Fitness functions of these networks are 0.3976 and 0.4036, respectively. In order to compare our proposed method with that proposed in [16], the total number of switching required for energizing each network is calculated. It is obvious that the lesser the sum of required switching, the cost and the time for restoration process will be less. Table III shows the total number of switching required for energizing the rest nodes of these two networks. As it can be observed from this table, using the proposed method in this paper, the average number of switching required for energizing the remnant of the network will be less than that required in the method proposed by Yan and Xueping [16]. This means that energizing the whole network using this skeleton-network will be faster and cheaper.

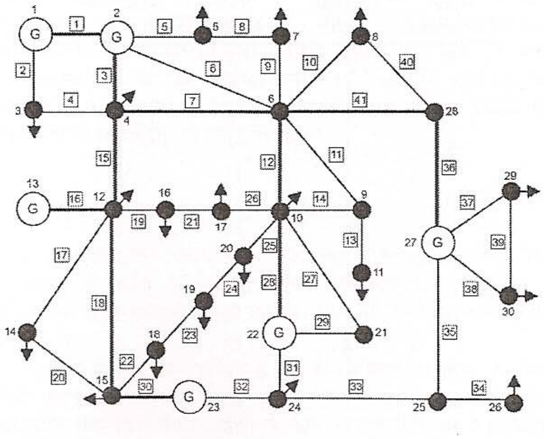

Fig. 5. Skeleton-network suggested in this paper

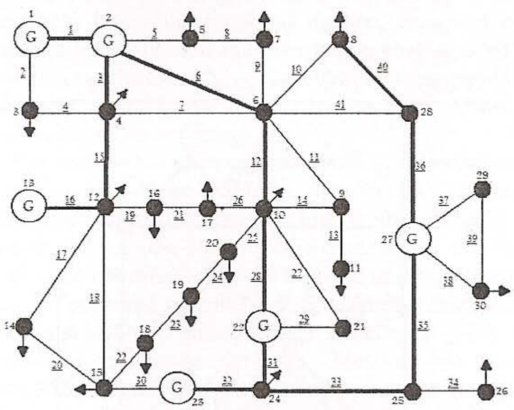

Fig. 6. Skeleton-network suggested in past

To show the validity of introduced index, it has been examined in different situations. First of all, it is assumed that interruption costs of nodes 19 and 20 are very high. This new condition has no influence on the skeleton network gained from the previous method, because the interruption cost was not considered in that index. In this situation three skeleton networks are calculated in three different ways. One with consideration of Betweenness and interruption cost (Fig. 7), another with closeness and interruption cost (Fig. 8.) and the last one is obtained by considering the topological and economical importance degree which is introduced in this paper (Fig. 9.). These three networks are compared in Table IV.

This table shows that the topological and economical importance degree, which is a weighted combination of betweenness, closeness and interruption cost, has the best possible performance. Restoring the IEEE 30-bus network by using TEID is cheaper and faster than other indices.

TABLE III
COMPARISON BETWEEN TWO SUGGESTED NETWORKS

Suggested network in this paper		Suggested network in 2007	
Node number	Shortest path	Node number	Shortest path
3	1	3	1
5	1	5	1
7	1	7	1
8	1	9	1
9	1	11	2
11	2	14	1
14	1	15	1
16	1	16	1
17	1	17	1
18	1	18	2
19	2	19	2
20	1	20	1
21	1	21	1
24	1	26	1
25	1	29	1
26	2	30	1
29	1	---	---
30	1		
average	1.166	average	1.187

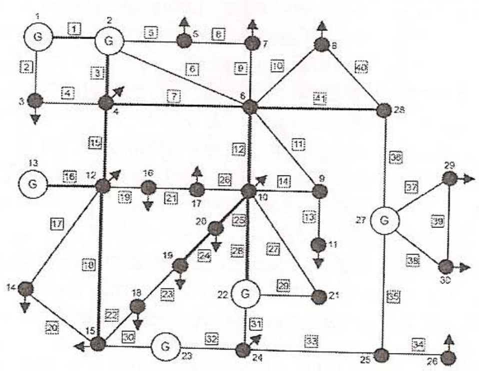

Fig. 7. Skeleton-network of a system with high interruption costs obtained by betweenness

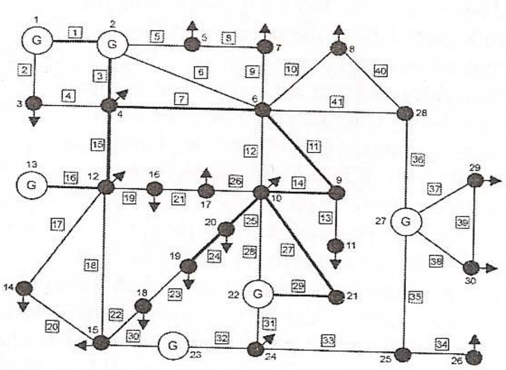

Fig. 8. Skeleton-network of a system with high interruption costs obtained by closeness

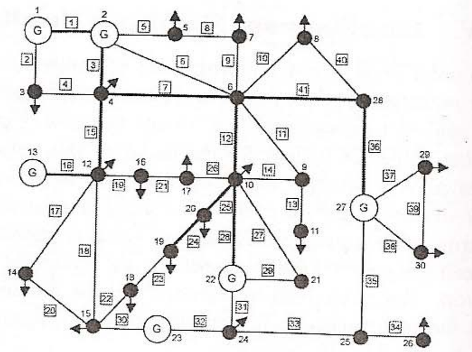

Fig. 9. Skeleton-network of a system with high interruption cost by topological and economical importance degree

TABLE IV
COMPARING SKELETON NETWORKS OF SYSTEMS WITH HIGH INTERRUPTION COSTS

Skeleton-network	Interruption Costs(k$/h)	Average Switching Remains
Fig. 7	428.6	1.333
Fig. 8	422	1.5
Fig. 9	357	1.167

Since usually in power system restoration, some parts of system are unavailable, this fact is considered in this paper and skeleton networks of systems which have some limitations are identified in this part. Fig. 10 and Fig. 11 are the skeleton networks of IEEE 30-bus network obtained by applying topological and economical importance degree and node importance degree when nodes number 7 and 15 are out of order. In addition, Figures 12 and 13 are the skeleton networks when the generators in bus 22 are non-blackstart, therefore this generation node is unavailable during the first stage of restoration and cannot participant in skeleton network. These networks are compared in Table V which confirms the advantageous topological and economical importance degree.

From Table V, it can be noted that average switching remains for restoring the whole network in Fig. 10 and Fig. 12 are less than switching remains in Fig. 11 and Fig. 13, which confirms TEID has better topological performance than former index'.

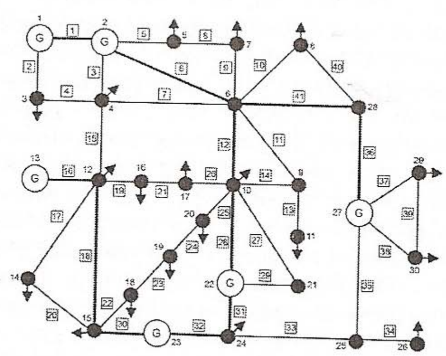

Fig. 10. Skeleton-network suggested in this paper with unavailable lines

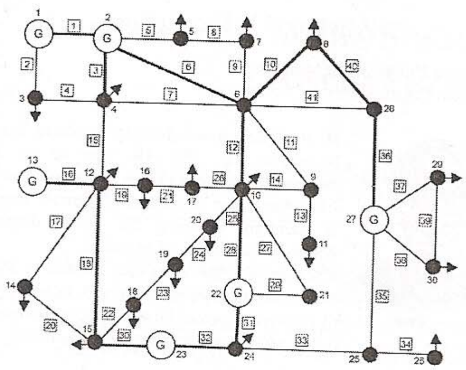

Fig. 11. Skeleton-network obtained from former index with unavailable lines

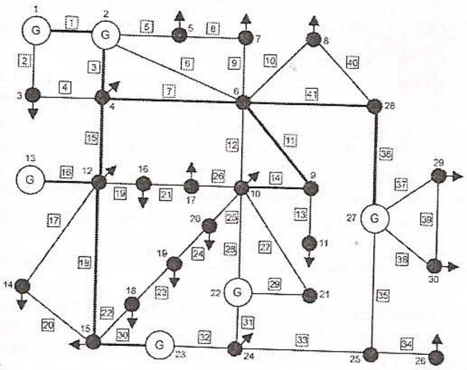

Fig. 12. Skeleton-network with non-blackstart generation

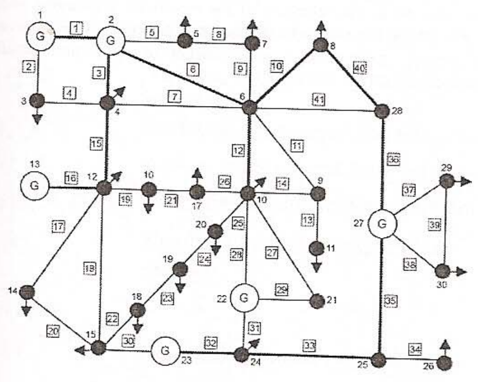

Fig. 13. Skeleton-network with non-blackstart generation obtained from former index

TABLE V
COMPARING SKELETON NETWORKS WITH CONSTRAINTS

Constraint	Skeleton-network	Interruption Costs(k$/h)	Average Switching Remains
Unavailable Lines	*TEID*	257	1.167
	Former Index	225.6	1.188
Non-Blackstart Generation	*TEID*	373	1.111
	Former Index	354	1.176

On the other hand, although, interruption costs of Figures 11 and 13 are less than interruption costs of Figures 10 and 12, average interruption costs of remaining nodes in Fig. 10 and 12 are less than average interruption costs of Figures 11 and 13. This happened because the number of remaining nodes in Figs. 11 and 13 are more than remaining nodes of Figs. 10 and 12. In conclusion, restoring these networks by using TEID is cheaper than using former index.

V. Conclusion

Blackouts in restructured power systems should be considered more seriously. Network restoration after a blackout is a complicated matter that should be managed properly.

In this paper, identifying the skeleton-network as the first step of restoration process is investigated. To identify the skeleton network for restoration of a power system, a new combined index is proposed for ranking network busses. The method is a market-oriented approach. Using the proposed method, time and cost required for restoration and interruption cost imposed on power networks are reduced. In addition to restoration by path this method can be applied to each island of restoration by zone strategy.

The method has been applied to IEEE 30-bus network for identifying the skeleton network in different situations such as a system with high interruption costs, a system with a non-blackstart generation and a system with some unavailable busses. Simulation results confirm that the proposed method is advantageous to previously used methods for assigning the skeleton network for restoration of power networks. Most of the power networks are small-world networks and the proposed index has the best performance in these networks. However, in other types of networks the performance of this index should be examined more.

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