Determination of the Optimal Power Plants' Start-Up Sequence in Power System Restoration

S. Barghinia, H.A. Shayanfar, S. Jadid

Abstract—**A set of activities, carried out to return a power system to the normal stage following a blackout, is called power system restoration. It is the process of restoring power plants, re-energizing transmission lines and restoring customer loads. This process should be conducted as soon as possible to prevent any failure or damaging any equipment.**

In the planning process of the power system restoration, one of the foremost important steps is to determine the optimal sequence of the power plants' start-up. In this paper, an initiative method for this purpose is presented. In order to reach the maximum or required generation energy in the shortest possible time, the algorithm is developed and is based on the ratio of the total power generation capacity in time for each power plant. To investigate the validity of the method, it is applied to the IEEE 39-bus test (New England) system.

***Index Terms*-- Power Plants' Start-Up Sequence, Power System Restoration, Shortest Path Finding, System Islanding**

I. INTRODUCTION

THE Power System Restoration (PSR) problem, followed by a complete or partial blackout, has an oldness equivalent to the power industry history. In recent years, due to the power system deregulation and economic competition, power systems are operated closer and closer to their limits. At the same time, power systems have increased in size and complexity. Both mentioned factors increase the risk of major power outages. After a blackout, power systems need to be restored as quickly and reliably as possible and consequently, detailed restoration plans are necessary [1]-[5].

In fact, the PSR is the optimizing problem with some objective functions. One of the aims of the PSR is to provide the 70-90% of the system total load. Thus, many power plants are required, and shut down power plants must be energized [6] to overcome the problem. Some of the power plants such as diesel, combustion and hydroelectric can be start-up quickly, and they are called the self start power plants or black-start plants. But in the real power system, for providing the required energy, great power plants such as the big gas, steam and nuclear plants must be start-up [7] and [8]. Therefore the foremost important step of the PSR process is to determine the optimal sequence of the power plants' start-up.

There are several papers about PSR, but in the field of the determination of the power plants' start-up sequence in the PSR, there is only a few documents. Some papers only mentioned that the power plants' start-up sequence is the important part of the PSR but the suitable solution for that problem has not been recommended [2], [6], [8] and [9].

In references [5] and [9], this subject is considered by the comparison of two power generation curves, and any of them are considered for the special scenarios. In these curves the MWh values are computed for two scenarios and it is mentioned that if power plants' start-up sequence in power system is selected suitably, it may be generated rather MWh in the PSR duration.

In [10], a general method is proposed for the determination of the power plants' start-up sequence. This method is based on the backtracking search algorithm, which determines the power generation starting times to maximize the MWh load served during the restoration period.

In [11], for the determination of the power plants' start-up times, the $\frac{p}{t}$ calculation method is used. In this paper after the starting up of the black-start power plants, the sequence of the non black-start power plants is based on the greatest $\frac{p}{t}$. Because, in this paper, important factors, such as: path finding of power transmission from one power plant to another one, the rate of power generation and critical time intervals are not considered. Thus this paper for the operational use, needs to modify.

The implemented method in this paper is based on the ratio of the total power generation capacity in time for each power plant. In this algorithm, the system is divided into some islands. With system islanding, the scenario and the restoration planning can be developed separately for each of the islands. The principle preference of the system islanding is to distribute the restoration activities and to reduce the restoration time. Optimal switching of the transmission lines is also considered. A method for reaching the possible shortest path between system buses and achieving the minimum time of the switching during restoration is presented. To ensure that the results are applicable, a bus voltage assessment and path

This work was supported in part by the center of excellence for power system automation and operation, department of Electrical Engineering, Iran University of Science & Technology (IUST), and also, by the electrical power system research center, Niroo Research Institute (NRI), Tehran, IRAN.

S. Barghinia is with the department of electrical engineering of IUST, and also with NRI, Tehran, Iran (e-mail: sbarghinia@nri.ac.ir).

H. A. Shayanfar is with the center of excellence for power system automation and operation, department of electrical engineering, IUST, Tehran, IRAN (e-mail: hashayanfar@yahoo.com).

S. Jadid is with the center of excellence for power system automation and operation, department of electrical engineering, IUST, Tehran, IRAN (e-mail: shjadid@iust.ac.ir).

978-1-4244-2235-7/09/$25.00 ©2009 IEEE

load capability checking are considered.

The rest of the paper is outlined as follows. Section II describes the generator characteristics for the restoration. Optimal transmission lines switching is described in section III. The proposed algorithm for system islanding is presented in section IV. In section V, optimal sequence of the power plants start-up is discussed. In section VI, selection of the method for the determination of the power plants' start-up sequence is described. The determination of power plants' start-up sequence algorithm is presented in section VII. The performance and simulation results are presented in section VIII. Finally, section IX concludes the results of the paper.

II. The Generator Characteristics

Generation units have different physical characteristics and requirements. In the start-up sequence planning, the power plants constraints must be considered. Table I, presents the start-up characteristics of different types of the power plants. If a power plant with a critical maximum interval is not started within the interval, there may be a delay of hours before the power plant can be available again. A power plant with a critical minimum interval can not be started until the interval ends.

TABLE I
START-UP CHARACTERISTICS OF DIFFERENT TYPES OF THE POWER PLANTS

Power Plant Type	Crank Power	Critical Maximum Interval	Critical Minimum Interval
Black Start	No	No	No
Drum	Yes	Yes	No
SCOT	Yes	No	Yes

Figure I, shows the time characteristic curve for a typical power plant:

t_0 : Time of unit restart up;

t_1 : Time of synchronization;

$t_2 - t_1$: Time to reach minimum load;

$t_3 - t_2$: Time to reach maximum power.

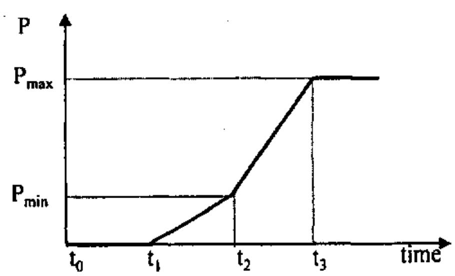

Figure I: Start-Up Time Characteristic Curve of a Typical Power Plant

During the blackout, the initial power sources must be found to crank non black-start generators. The initial source is provided by quickly starting black-start generators. Different physical characteristics and the starting requirements in each power station must be considered. Different types of boilers have different start-up requirements and also the maximum and minimum starting intervals after a blackout must be considered. The goal of the start-up sequence is to maximize the total MWh that can be served during the restoration process.

III. Optimal Transmission Lines Switching in PSR

In planning the PSR, one of the important steps is to determine the optimal switching of the transmission lines. The main goal of this part of PSR is the path finding with minimum time and switching. The shortest path finding between the system buses and achieving the minimum switching time during the restoration must be considered.

The implemented algorithm is based on the two sections [12]. In the first section, a data bank of the power system structure is made by the backtracking search algorithm. This data bank involves all the paths between any two buses of the system. The second section includes the path selection with minimum switching and observance of the dominant constraints. Therefore, in the selected paths between two buses, first the path with minimum switching time is selected. It must be considered that in the power plants' start-up stage for the connection path buses, overvoltage problem is the important factor, which is caused by the line charging. Therefore, during early stages of the PSR, it is necessary to keep the system voltage within the allowable, usually upper than normal range, for example 1.2 p.u.

Transmission lines are usually represented by their constant impedance and admittance in a nominal Π circuit. For ensuring that the results of path finding are applicable, a bus voltage assessment based on the Thevenin equivalent circuits is considered. Therefore, in the selected path, the voltages of path buses are computed by the proposed method and compared with the allowable value. If all buses have the suitable voltage, then the path load capability is checked until it provides the minimum power of units for ensuring the stability of the system.

IV. Power System Islanding

For distribution of the restoration activities and also in order to reduce the restoration time, the power system can be divided into some islands. Each island is the subset of the system and consists of power plants, transformers, lines and buses. According to the suitable documents, the main indexes for the islanding are considered in [13]-[15]:

- In each island, there must be at least one black-start power plant or energized power plant until starting the other power plants in the islands, can be possible.
- The generation and load must be balanced in each island.
- For ensuring the stability in islands, the minimum power of black-start power plants must be provided.
- Transformers and its terminals should be taken in one island.
- For considering two special buses in one island, all buses in the shortest path between them, should be taken in the mentioned island.
- The number of non-energized buses must be approximately equal in the islands.

Islanding algorithm is based on the suitable shortest paths between black-start and non black-start plants and also between the power plants and system loads [15].

V. Optimal Sequence of Power Plants Start-up

After the system collapse, PSR is a control problem and complex decision for the system operators and operation planners. Optimization in the power plants' start-up sequence is that, in the minimum time, the required power of the system is provided and for considering technical and economical problems, at the first times of the PSR, fewer power plants are energized.

For solving this problem, some specifications are required, and the times of the power plants start-up can be determined. These specifications are:

- The type of power plants, whether they are black-start or non black-start.
- Time characterized curve (start-up and generation characteristics) of the power plants, in which these characteristics includes parameters such as: maximum generation capacity, minimum load of the units, time of unit restart up, time of synchronization, time to reach minimum load and time to reach maximum load according to figure I.
- The required crank power for starting the power plants.
- Minimum critical time interval for the power plants with once through boilers.
- Maximum critical time interval for the power plants with drum boilers.

VI. Selection of The Method for Determination of The Power Plants' Start-Up Sequence

The selected method for solving the determination of the power plants' start-up sequence is based on the $\frac{p}{t}$ priority. Considering all conditions such as critical time intervals, the priority of the power plants for start-up is based on the greater $\frac{p}{t}$. The power plant which has the greatest $\frac{p}{t}$, can be start-up quickly and also the generated power will be increased with more speed. These two subjects will result the most MWh in time, and it may provide the optimization of the power plants' start-up and also because of selected power plants with greater $\frac{p}{t}$ have the most capacity of the generation, can start-up fewer power plants. The important factors that must be considered are as the following:

- The required target power of the system should be determined.
- For plants with once through boilers, the minimum critical interval must be considered in "t" computation of $\frac{p}{t}$.
- Switching times will be considered between starter power plants and the power plants that should be started.

The advantages of the selected method are:

- It contains the loading speed of the generators.
- It provides the maximum MWh.
- It contains the optimization of time.
- This method is simple.

VII. Determination of Power Plants' Start-Up Sequence Algorithm

For distribution of the restoration activities and to reduce the restoration time, the power system can be divided into some islands. In each island, there must be at least one black-start power plant until starting the other power plants in islands. Also the generation and load must be balanced in each island. Islanding algorithm is based on the suitable shortest paths between black-start and non black-start plants and also between the power plants and the system loads [15]. After a suitable islanding for the collapsed power system, optimal sequence of the generation power plants start-up must be identified. In each island, the objective is to supply the station service or cranking power immediately and simultaneously to large thermal plants by black-start combustion turbines or if available by hydroelectric units. Combustion turbine behavior is quite different during the normal operation and when it is parallel with a large system as compared to during the restoration when they are the prime or the only source of the power. In the starting steam units, it is important to coordinate certain critical time intervals, such as the maximum time interval beyond which certain thermal units can not safely restarted hot, or the minimum time interval required before a thermal unit can be started. In the restarting steam units, it is often necessary to supply auxiliary power from a remote station.

Transmission lines are usually represented by their constant impedance and admittance in a nominal Π circuit. The selection of a path between the black-start plant and non black-start plants should be limited only to the feasible paths. Optimal switching of the transmission lines must be considered. The shortest path between the system buses and achieving the minimum switching time during the restoration must be considered [12]. During early stages of the PSR, it is necessary to keep system voltage within the allowable, usually upper than normal range. For ensuring the applicable results, a bus voltage assessment based on the Thevenin equivalent circuits and path load capability checking for providing the minimum power of units are considered.

In each island, optimal sequencing of the start-up must be done for starting the non black-start units. This sequence is based on the ratio of the total power generation capacity in time for each power plant, i.e. for shut down plants i and j if: $\frac{P_i}{t_i} > \frac{p_j}{t_j}$, then the restoration priority of the plant "i" will be higher than of the plant "j". For plants with once through boilers, the minimum critical interval must be considered in "t" computation. So, these plants have the lowest priority for starting. Therefore, the initial sequence of plants start-up is identified. Then, this subject is considered in each time interval, the black-start plant can provide the crank power of the non black-start plants. After providing the crank power of the non black-start plant, and passing t_1 time (according to the figure I), this plant can be considered for providing the crank power of the other non started plants. Shortest path between the black-start and non black-start plants and then the minimum switching time are computed. If the minimum switching time becomes greater than the starting time, this minimum switching time is considered as the new starting time.

Since at the early stages of the PSR, the generated power of the starter power plants is increased, load pickup must be done, until the system frequency is maintained within the allowable limits imposed by the turbine response and system stability, load and generation balance is established.

VIII. The Performance And Simulation Results

This section presents the performance of the developed algorithm. For evaluating the results of this algorithm, the IEEE 39-bus test system (New England) is used in this paper. The schematic of this system is presented in figure II:

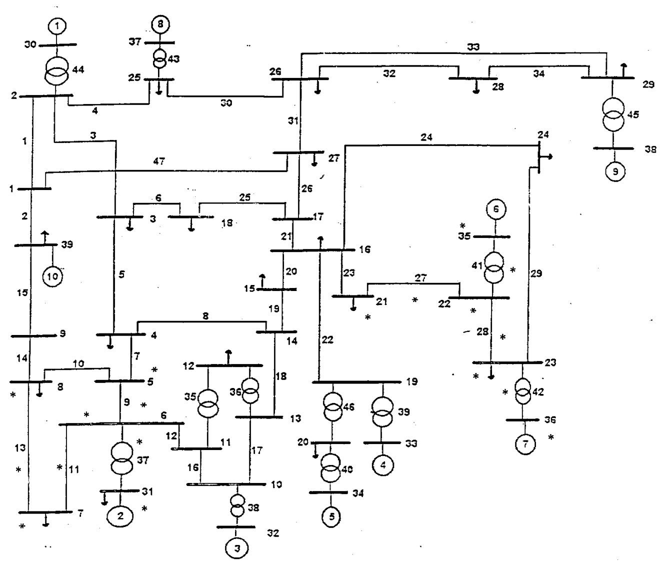

Figure II: Schematic of the IEEE 39-Bus Test System

IEEE 39-bus test system has two black-start plants in buses 30 and 31. In general consideration, we assume that system is collapsed and all units of the power plants and transmission lines and buses are de-energized. Islanding developed program, divides this system into two islands according to the two black-start plants presented in figure III.

Samples of the information about the power plants in the 39-bus test system for black-start plants in buses 30 and 31 are presented in table II.

The total power of this system is 6240MW. Because in the early stages of the PSR, the aim is to provide the 70-90% of the system total load, so we assume that the 80% of the system total load is required. Therefore, we consider that the target power in the early stages of the restoration is 5000MW (50 p.u.). The time for each switching is considered 1 minute.

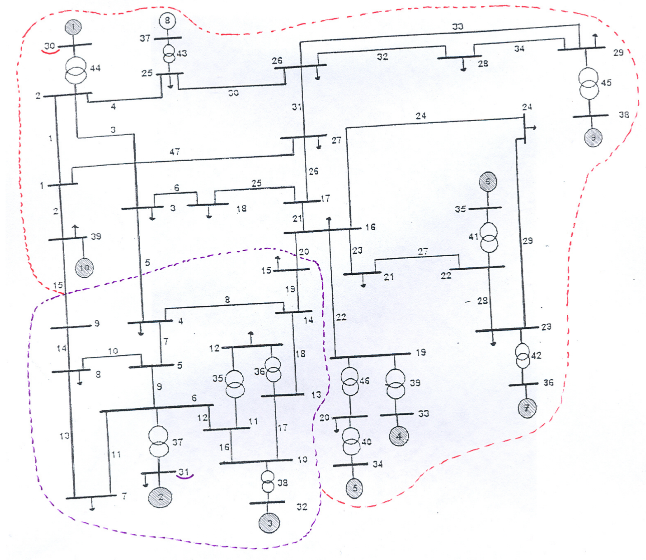

Figure III: Islanding of the IEEE 39 Bus System

The target power of the system is divided into the ratio of the power generation in each island, and generated power of all power plants is computed. In order to remind, the crank power should be reduced from the maximum power of the plants. Because steam plants with once through boilers need along time for starting, so they will never be consider in the early stages of the PSR. In the IEEE 39-bus test system, the plant in bus 38 is a steam plant with once through boiler. The generated power in islands is as the following:

TABLE III
Generated Power in Islands

Island Number	Total Generated Power in Islands (p.u.)	Generated Power in Islands Except Once Through Boilers (p.u.)
1 (Island with Center in Bus 30)	50.88	42.84
2 (Island with Center in Bus 31)	11.51	11.51

If the sum of the generated power in islands except plants with once through boilers will be greater than the target power of the system, then this target power is divided into the ratio of the plants power generation except with once through boilers. Thus, the target power (50 p.u.) will be divided into the ratio of 42.84 and 11.51 p.u. Therefore, the target powers in island 1 and 2 are:

(42.84 / (42.84+11.51))*50= 39.4112

(11.51 / ((42.84+11.51))*50= 10.5888

In each island the generated power of black-start plants in buses 30 and 31 are computed from their time characterized curves. Then, it is considered that this generated power can start which of the shut down plants. For example, the generated power of plant 30 in minute 3 can provide simultaneously the crank power of both plants in buses 33 and 35 and in minute 4 the crank power of plants in buses 34, 36 and 39 and in minute 5 the crank power of plant in bus 37. In table IV, plants that can be started in island 1, are presented:

TABLE IV

STARTING THE PLANTS IN ISLAND 1

Power Plant	Time (Minute)	Generated Power of Plant 30 (p.u.)	Crank Power (p.u.)	$\frac{p}{t}$ Ratio
33	3	0.33	0.15	0.1708
34	3	0.33	0.14	0.0254
35	4	0.67	0.15	0.1548
36	4	0.67	0.16	0.0278
37	5	0.67	0.16	0.0220
39	4	1	0.3	0.0465

Now in each time interval, the priority of the plants start-up is done according to the $\frac{p}{t}$ criteria and so in the specified time, the plants that can be started are determined according to the defined priority.

After the determination of the plants starting conditions, these plants are considered as the starter plants. Shortest path between the black-start plants and these plants is determined, and then the minimum switching time is computed. If the minimum switching time becomes greater than the starting time, this minimum switching time is replaced as the new starting time. The optimal sequence of the plants start-up in considered islands is presented in table V.

The generation capability of the system in the mentioned conditions in each island and in the total system is presented as the following figures:

Figure IV: Generation Capability in Total System for Receiving the 50 p.u. Target Power

Figure V: Generation Capability in Island 1 for Receiving the 39.4112 p.u. Target Power

Figure VI: Generation Capability in Island 2 for Receiving the 10.5888 p.u. Target Power

IX. CONCLUSION

In this paper, an algorithm for optimal sequence of the power plants start-up is presented. The goal of the early stages of the PSR is the starting of the power plants to provide the restoration target power and it must be provided in the shortest time. This algorithm determines the generating starting times to maximize the MWh load served over a restoration period and guarantee the optimality of the start-up sequence. The dynamic characteristics of different types of units and system constraints have to be considered. The proposed method is compared with the other methods. Simulation tests on the IEEE 39-bus test system, verify the effectiveness of the proposed method.

TABLE II

POWER PLANTS IN BUSES 30 AND 31 SPECIFICATIONS

Bus No.	Pmax	Pmin	Type	Pcrank	Tstart1	Tsyn1	Tpmax1	T1	Tstart2	Tsyn2	Tpmax2	T2	Tstart3	Tsyn3	Tpmax3
30	5	1	2	o	2	3	6	10	2	3	6	20	4	4	6
31	5.21	1.2	1	0	5	6	10	1000	5	5	10	1000	5	5	10

Pmax: The Maximum Power of the Power Plants (p.u.)
Pmin: The Minimum Power (Minimum Load) of the Power Plants (p.u.)
Type: 1, 2, 3, 4 and 5 are used respectively for the Hydroelectric, Black- start Gas, Non Black-Start Gas, Steam with Drum Boiler, Steam with Once Through Boiler.
Pcrank: The Crank Power for Starting the Power Plants (p.u.)
Tstart1: Time of unit Restart up to Synchronization in the Hot State (minute)
Tsyn1: Time of unit Synchronization to Reach The Minimum Load in the Hot State (minute)
Tpmax1: Time of The Minimum Load to Reach The Maximum Power in the Hot State (minute)
T1: The Time if it is Passed, The Power Plant Will be Changed from Hot State to the Warm State (minite)
Tstart2: Time of unit Restart up to Synchronization in the Warm State (minute)
Tsyn2: Time of unit Synchronization to Reach The Minimum Load in the Warm State (minute)
Tpmax2: Time of The Minimum Load to Reach The Maximum Power in the Warm State (minute)
T2: The Time if it is Passed, The Power Plant Will be Changed from Warm State to the Cold State (minite)
Tstart3: Time of unit Restart up to Synchronization in the Cold State (minute)
Tsyn3: Time of unit Synchronization to Reach The Minimum Load in the Cold State (minute)
Tpmax3: Time of The Minimum Load to Reach The Maximum Power in the Cold State (minute)

TABLE IV

POWER PLANTS START-UP SEQUENCE

Priority Number/Island	Bus No.	Cranking Power Provider	Selected Path for Energizing	Providing Crank Power Time	Switching Time	Start Time
--	30	Black Start	----	----	----	----
--	31	Black Start	----	----	----	----
1 in Island 1	33	30	30 2 3 18 17 16 19 33	3	8	8
2 in Island 1	35	30	30 2 3 18 17 16 21 22 35	3	9	9
3 in Island 1	39	30	30 2 1 39	4	4	4
4 in Island 1	36	30	30 2 3 18 17 16 24 23 36	4	9	9
5 in Island 1	34	30	30 2 3 18 17 16 19 20 34	4	9	4
6 in Island 1	37	30	30 2 25 37	5	4	5
1 in Island 2	32	31	31 6 11 10 32	7	5	7

X. References

[1] J. Huang,, "An Integrated Methodology for Power System Restoration Planning," Doctoral Thesis, McGill University, Montreal, Canada, August 1992.

[2] Liou, Kan-Lee,, "A Knowledge Based System for Generation Capability Dispatch During Bulk power System Restoration," Doctoral Thesis, Washington University, USA, 1993.

[3] M. M. Adibi, *Power System Restoration, Methodologies and Implementation Strategies*, IEEE Press Series on Power Engineering, Vol. 14, Jan. 2000.

[4] M. M. Adibi, "Power System Restoration- A Task Force Report," *IEEE Trans. Power Systems*, Vol. 2, No. 2, pp. 271 – 277, May 1987.

[5] M. M. Adibi, J. N. Borkoski, and R. J. Kafka "Power System Restoration- The Second Task Force Report," *IEEE Trans. Power Systems*, Vol. 2, No. 4, pp. 927 – 932, Nov. 1987.

[6] M. M. Adibi, and L. H. Fink, "Special Consideration in Power System Restoration Working Group," *IEEE Trans. Power Systems*, Vol. 7, No. 4, pp. 1419 – 1427, Nov. 1992.

[7] J. Ancona, "A Framework for Power Systems Restoratoin Following a Major Power Failure," *IEEE Trans. Power Systems*, Vol. 10, No. 3, pp. 1480-1485.

[8] K. L. Liou, C. C. Liu, and R. F. Chu, "Tie Line Utilizatoin during Power System Restoration," *IEEE Trans. Power Systems*, Vol. 10, No. 1, pp. 192-197, Feb. 1995.

[9] M. M. Adibi, and R. J. Kafka, "Power System Restoratoin Issues," *IEEE Computer Applicatoin on Power*, Vol. 3, pp. 19 - 24, Apr. 1991.

[10] A. Ketabi, H. Asmar, A.M. Ranjbar, and R. Feuillet, "An Approach for Optimal Units Start-up during Bulk Power System Restoration," *Proc. 2001 IEEE Conference on Power Engineering,* pp.190 – 194, July 2001.

[11] Y. Kojima, and S. Warshina, "The Development of Power System Restoration Method for A Bulk Power Systems by Applying Knowledge Engineering Techniques," *IEEE Trans. Power Systems*, Vol. 4, No. 3, pp. 1228 - 1235, Aug. 1998.

[12] S. Barghinia, P. Ansarimehr, and M. Vadiati, "Determination of Optimal Transmission Lines Switching in Power System Restoration," *Scientific and Research Electrical Magazine*, Vol. 16, No. 38, pp. 1 - 11, Feb. 2004.

[13] B. A. Archer, and J. B. Davies, "System Islanding Consideration for Improving Power System Restoration at Manitoba Hydro," in *Proc. 2002 IEEE Canadian Conference on Electrical and Computer Engineering,* Vol. 1, pp. 60 – 65, May 2002.

[14] M. Yarian, N. Fathali, and P. Ansarimehr, "System Islanding for Power System Restoration," *presented at the 16th Int. Electrical Conf.*, Tehran, Iran, Nov. 2002.

[15] S. Barghinia, H. A. Shayanfar, and SH. Jadid, "An Algorithm for Power System Islanding after a Blackout Used in Power System Restoration," *presented at the 23th Int. Electrical Conf.*, Tehran, Iran, Dec. 2008.

XI. Biographies

Saeedeh Barghinia was born in Tabriz, Iran on April 28, 1976. She received the B.Sc. degree in power engineering from the Tehran University, Department of Electrical & Computer Engineering in 1999 and M.S.E. degree in power systems engineering from the Iran University of Science and Technology, Department of Electrical Engineering in 2008. Since 1999, she has been working at the Niroo Research Institute (N.R.I). Her main research interests are in the area of power system operation and artificial intelligent methods and their application in power systems. She has 25 papers in international conferences and magazines. She is a member of Iranian Association of Electrical and Electronic Engineers. In 2008, she has selected as one of the top researcher in Iran.

Heidarali Shayanfar received the B.S. and M.S.E. degrees in Electrical Engineering in 1973 and 1979, respectively. He received his Ph. D. degree in Electrical Engineering from Michigan State University, U.S.A., in 1981. Currently, he is a Full Professor in Electrical Engineering Department of Electrical Engineering, Iran University of Science and Technology, Tehran, Iran. His research interests are in the Application of Artificial Intelligence to Power System Control Design, Dynamic Load Modeling, Power System Observability Studies and Voltage Collapse. He is a member of Iranian Association of Electrical and Electronic Engineers and IEEE.

Shahram Jadid received the Ph.D. degree in 1991 from the Indian Institute of Technology, Bombay, India. He is an Associate Professor in the Department of Electrical Engineering, Iran University of Science and Technology, Tehran, where he is also currently Head of the Center of Excellence for Power Systems Automation and Operation. His main research interests are power system operation and restructuring, load and energy management.