2018 Twentieth International Middle East Power Systems Conference (MEPCON), Cairo University, Egypt

Transmission Lines Restoration Using Resilience Analysis

Yasser Khalil
Demonstrator at Electrical Power and Machine department
faculty of engineering at Helwan University
Cairo, Egypt
yasserkhalil2013@gmail.com

Rasha El-Azab
Assistant Professor at Electrical Power and Machine department
faculty of engineering at Helwan University
Cairo, Egypt
r_m_elazab@yahoo.com

Maged A. Abu Adma
Associate Professor at Electrical Power and Machine department
faculty of engineering at Helwan University
Cairo, Egypt
Consultant_group@hotmail.com

Said Elmasry
Associate Professor at Electrical Power and Machine department
faculty of engineering at Helwan University
Cairo, Egypt
drsaidelmasry@yahoo.com

***Abstract*— Restoration from total blackout is a critical and confusing process. This paper proposes transmission lines capacitance as an indicator of optimal transmission path based on resilience factors. Two IEEE test networks are studied to declare the effectiveness of the proposed resilience algorithm. Proposed algorithm defines the most resilient path that keeps bus voltages in acceptable range with least possible restoration time.**

Keywords—Resilience analysis, power system restoration, resilience transmission paths.

I. INTRODUCTION

Restoration after total blackout is a very important task for planning and operation of power system. The process of restoration should return collapsed grid to work in normal operation within acceptable ranges of different parameters, accepted frequency and voltage ranges.

On the other hand, Blackouts cause economic and social losses that increase exponentially with restoration process time [1][2]. Power system restoration concerns recovering of a large number of generators, transmission lines and distribution systems, which increases the difficulty of defining optimal restoration strategy [3].

Power system restoration divided into three stages, as preparation, restoration and load pick up stages [3][4][5][6][7]. Status of collapsed grid is determined in preparation stage. Restoration stage defines suitable arrangement of reenergized generating units and related transmission restoration paths. In load pick up stage, suitable arrangement of Load pick-up is identified. Determination of optimal restoration paths is very important in minimizing restoration time.

From practical view, preparation stage should last within two hours only. While, restoration one can be extended to four hours, to confirm restoring adequate and stable generated power. Finally, third stage may be relaxed to ten hours for completion of the whole restoration. [4]

Restored transmission lines is needed to transfer power for reenergizing different generating units during restoration stage. Proper selection of transmission path during restoration process minimizes the possibility of re-collapsing occurrence.

Overvoltage problem on high voltage transmission lines may occur due to light loading nature during restoration stage. Transmission line path should concern expected overvoltage and related protection action and avoid any undesired re-outages. Severe sustained overvoltage also may lead to multi problems, such as generator self-excitation, transformer over-excitation, harmonic distortions and restoration failure [1].

Resilience of power systems usually concerns rerouting electricity to customers using alternative paths during natural disasters [8]. Therefore, resilience can be considered as a disasters management science that reduce magnitude and duration of blackout with high technical performance.

Resilience analysis estimate restoring behavior through some related parameter known as resilience factors, minimum capacitance, shortest path and switching time.

This paper proposes new selection algorithm for restoring transmission paths based on resilience analysis. Proposed algorithm concerns line capacitance, line length and switching time as resilience factors to determine optimal transmission paths.

After this introductory section, section II discusses technical background of restored transmission path selection. Proposed selection algorithm is presented in section III. Results of suggested algorithm with two IEEE test networks are discussed in section IV. Finally, main conclusions and contributions of the paper are highlighted in section V.

II. TECHNICAL BACKGROUND

Medium transmission line can be modelled by series impedance or $\boldsymbol{Z}$ with shunt capacitance in both sides, this

978-1-5386-6654-8/18/$31.00 ©2018 IEEE

capacitance is increases with increasing the length of line lumped at each end of the bus, as shown in Fig. 1. [9]

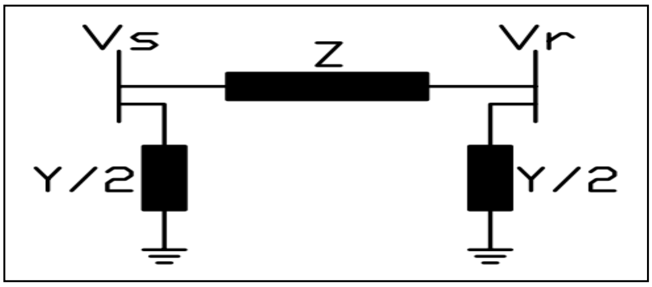

Fig. 1: Transmission line model

Total series impedance of transmission line and total admittance of transmission line are calculated as follow:

$$Z= (r + j\ w\ l)\ L \tag{1}$$

$$Y= (j\ w\ c)\ L \tag{2}$$

Where, Z is the total series impedance of transmission line, r is resistance of transmission line per unit length, l is inductance of transmission line per unit length, L is total length of transmission line, Y is the total shunt admittance of transmission line and c is capacitance of transmission line per unit length.

The sending end voltage is calculated as follows:

$$Vs= (1+ (Z*Y/2))\ Vr + Z\ Ir \tag{3}$$

Where, V_s is the sending end voltage, V_r is the receiving end voltage and I_r is the receiving end current.

From previous equation 3, the receiving end voltage can be increased with light loading due to line shunt capacitance effect. During restoration process, cranking power is transmitted through transmission network to start auxiliary equipment of non-black start generating units. Under these conditions, sustain overvoltage at receiving bus may occur according to light load capacitance effect [10].

The transmission line capacitance can be calculated as follows:

$$c= 2\pi\varepsilon_o / \ln(GMD/GMR) \tag{4}$$

Where, c is The transmission line shunt capacitance per unit length, ε_o is the permittivity of free space, GMD is the equivalent geometric mean distance which depends on tower configuration and GMR is the equivalent geometric mean radius which depend on bundle configuration.

According to previous equation, total transmission line capacitance depends on many factors, as length, tower geometry which depends on transmission voltage, bundle or parallel configurations. Therefore, line capacitance doesn't have direct proportion with length in the following cases:

- The same transmission path has overhead lines and cables.
- More than one tower between any two buses.
- Transmission path has different voltage levels.
- Tower of the same voltage level has more than configuration according to manufacture.

Acceptable restoring voltage has high priority restoration stage [1]. Some actions are executed to protect power system such as: operating generators at minimum voltage levels, disconnecting static capacitors, connecting shunt reactors and adjusting transformers taps [2].

Existing experiences defines optimal restoration paths according to shortest distance between restored generating units and number of connection. Shortest distance is chosen to minimize overvoltage because line length has direct proportion with line capacitance [4]. According to [3] [5] [11], initializing process for transmission lines and transformer may take five minutes. Therefore, number of connection is selected to minimize restoration time.

While, transmission line capacitance is affected by other factors such as tower construction, transmission voltage, bundle circuits…etc. Therefore, line length only can't provide accurate prediction about overvoltage occurrence.

This paper proposes an algorithm using a new resilience factor to provide a practical and accurate transmission restoring process, as will be discussed in the following section.

III. Proposed Algorithm

Resilience analysis compares all available paths between buses based on resilience factors. For safe resorting process, three conditions should be confirmed, as follows:

- Power transmitted through line path.
- Voltage level at receiving end.
- Time required for path restoration which affects on generation restoration timing.

As transmitted cranking power is usually small compared to line capacity. Power confirmation can be neglected or set as a resilient factor.

Voltage level at receiving end can be considered as the most critical and confusing constraint in line restoring process. During restoration, lines produce large amounts of reactive power resulting in over voltages for some buses.

High voltage reactors can help to consume excess reactive power and accelerate the recovery process. Therefore. capacitance of transmission line including any fixed reactors will give better vision about line restoration voltage than path length only.

Path capacitance indicator is proposed as an additional resilience factor, as follows:

$$C_{ave} = \frac{\sum C_{line}}{\sum L_{line}} \tag{5}$$

Where, C_{ave} is the proposed capacitance average indicator, C_{line} is individual line capacitance in the path including any fixed shunt reactors and L_{line} is individual line length in the path.

Restoration time has a second priority in restoring process after voltage level confirmation. As, restoration strategy should minimize restoring time as possible without any violation in grid parameter such as bus voltage.

Proposed algorithm uses number of connections required for the path as an indicator of path restoring time, as shown in Fig. 2.

Dijkstra algorithm is very wide used to determine optimal restoration paths [4] [5] [7] [13]. Dijkstra algorithm is typically single-source path algorithm. It depends on network topology and branches weights.

Dijkstra compares between branches weights. The weights of branches in Dijkstra method has non-negative values. A branch has the highest start-up priority when its weight is zero and vice versa.

As shown in Fig. 2, proposed algorithm defines two optimal paths by using Dijkstra method. First, minimum capacitance path to confirm the best available bus voltage profile. Second, shortest path is identified according to line length.

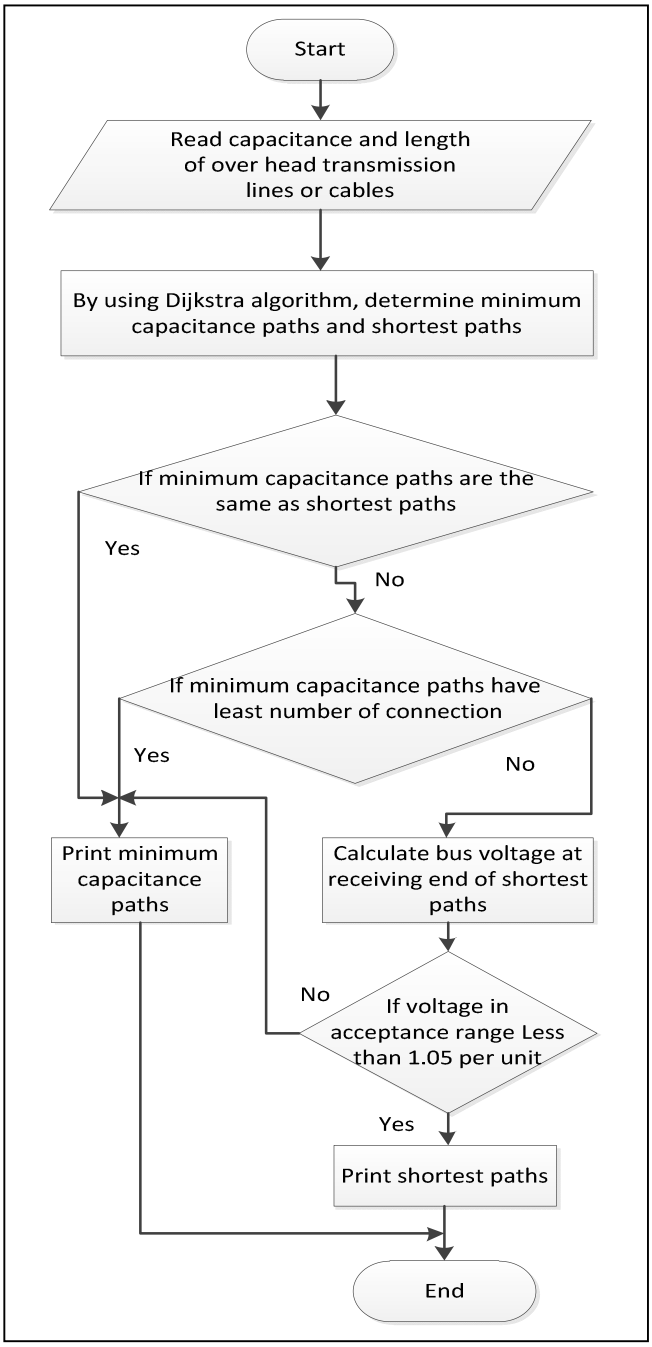

Fig. 2: Resilience path algorithm

If minimum capacitance path has lower number of connection than shortest one, it will provide the best voltage profile with the least restoring time.

Otherwise, bus voltage should be calculated and confirmed, before choosing well-known shortest path. To verify proposed algorithm, IEEE 24 and 39 bus networks are studied, as will be discussed in the following section.

IV. Study Cases

Two IEEE test network are studied by defining optimal paths between black start generating units and nonblack start ones after total blackout, as will be discussed in the following sub sections.

A. *IEEE 39 bus system*

The suggested restoration method is tested on IEEE 39 bus system as shown in fig. 3. It has 10 generators, 46 branches and 39 Bus. MATLAB programing language is used to determine optimal resilience transmission lines paths.

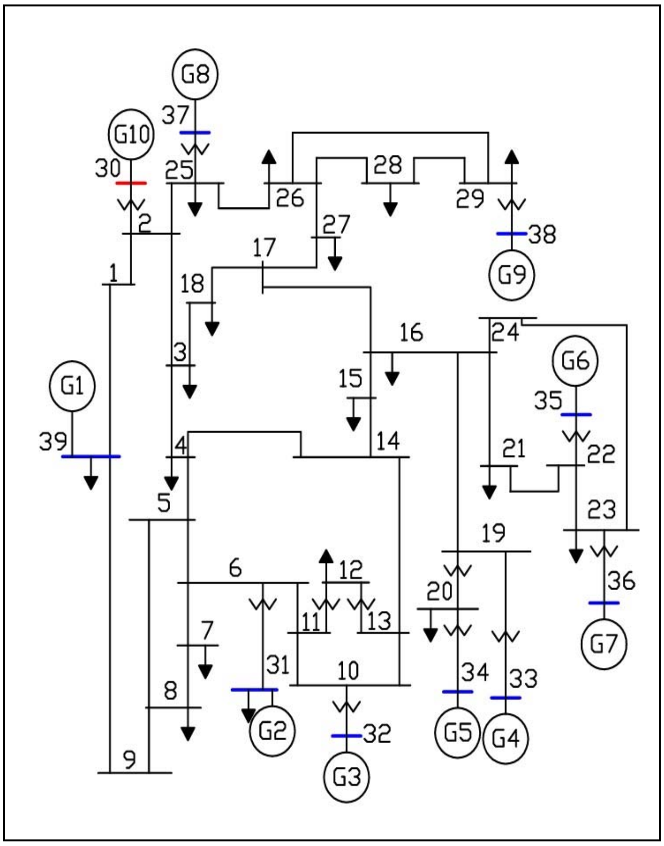

Fig. 3: IEEE 39 Bus system

One black start generating plant is assumed at bus 30. Other generating plants are assumed as nonblack start ones, at buses (31, 32, 33, 34, 35, 36, 37, 38 and 39), as shown in Table I.

Dijkstra algorithm will be used to find both pre-described optimal transmission lines paths, i.e. minimum capacitance and shortest paths, between black start unit and others.

TABLE I: IEEE 39 BUS SYSTEM OTIMAL PATHS

Bus *from*	Bus *To*	Resilience paths
30	39	30-2-1-39
	31	30-2-3-4-5-6-31
	32	30-2-3-4-14-13-10-32
	33	30-2-3-18-17-16-19-33
	34	30-2-3-18-17-16-19-20-34
	35	30-2-3-18-17-16-21-22-35
	36	30-2-3-18-17-16-21-22-32-36
	37	30-2-25-37
	38	30-2-25-26-29-38

IEEE 39 bus test network has the same voltage level all over its transmission system. It also has the same type of transmission lines conductors and tower. Therefore, proposed algorithm gives the same selection based on minimum capacitance or shortest paths, as shown in table I.

Resilience transmission lines paths from black start bus (30) to all nonblack start buses (39,31,32,33,34,35,36,37,38 and 39) are shown in table I, for example resilience path between bus 30 and bus 39 is 30-2-1-39.

B. IEEE 24 bus system

IEEE 24 bus test network are also studied after total blackout, see Fig.4. It has 10 generators, 38 branches and 24 Buses. The transmission lines are at two voltages, 138 kV and 230 kV. The 230-kV system has 230/138 kV tie stations at Buses 11, 12, and 24.

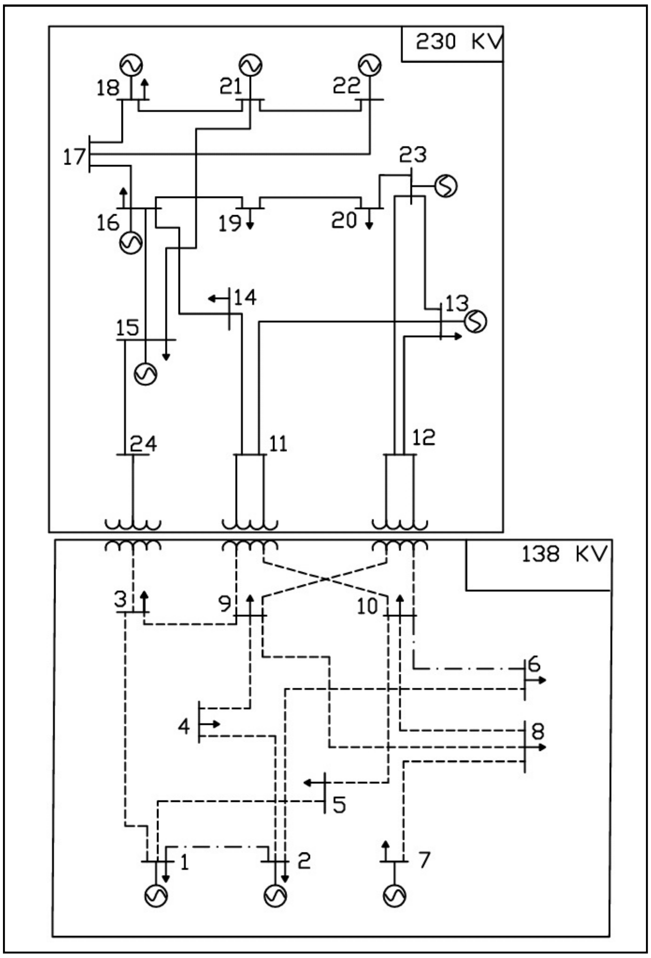

Fig. 4: IEEE 24 Bus system

As shown in Fig. 4, the 230-kV system is in solid line type, 138 kV system is in dashed line type and 138 KV cables in dash dot line type. Equivalent lines are used for parallel transmission lines, so number of transmission lines is reduced to 34 lines.

One black start generating plant is assumed at bus 2. Other generating plants are assumed as nonblack start ones, at buses (1, 7, 13, 15, 16, 18, 21, 22 and 23).

By using Dijkstra algorithm, optimal transmission paths are defined for both resilience factors, see Tables II & III. Minimum capacitance and shortest paths give different optimal paths, due to the following reasons:

- Path between buses 2 and 7, resilience path based on minimum capacitance has least number of connection, so resilience path by using minimum capacitance is better than shortest path.
- For path between buses 1 and 2, shortest path has least number of connections. Therefore, voltage calculation is needed to confirm voltage constrain acceptance. If voltage is within acceptable range, shortest path should be used, to minimize restoration time. otherwise, using minimum capacitance path will be an essential need due to overvoltage problem.

TABLE II: MINIMUM CAPACITANCE PATHS OF IEEE 24 BUS SYSTEM

Bus *from*	Bus *To*	Resilience paths based on minimum capacitance paths
2	1	2-4-9-12-10-5-1
	7	2-4-9-8-7
	13	2-4-9-12-13
	15	2-4-9-3-24-15
	16	2-4-9-12-10-11-14-16
	18	2-4-9-12-10-11-14-16-17-18
	21	2-4-9-3-24-15-21
	22	2-4-9-3-24-15-21-22
	23	2-4-9-12-23

TABLE III: SHORTEST PATHS OF IEEE 24 BUS SYSTEM

Bus *from*	Bus *To*	Resilience paths based on Shortest paths
2	1	2-1
	7	2-1-5-10-8-7
	13	2-1-5-10-11-13
	15	2-1-3-24-15
	16	2-1-5-10-11-14-16
	18	2-1-5-10-11-14-16-17-18
	21	2-1-3-24-15-21
	22	2-1-3-24-15-21-22
	23	2-1-5-10-12-23

The shortest paths have less transmission lines length than the minimum capacitance paths, also the minimum average capacitance paths have less transmission lines capacitance than the shortest paths as shown in table IV and V.

TABLE IV: IEEE 24 BUS MINIMUM CAPACITANCE PATHS PARAMETERS

Bus		**Resilience paths based on minimum capacitance paths**	
from	***To***	***Length (mile)***	***C_{ave} (p.u / mile)***
2	1	105	0.00104
	7	119	0.00103
	13	93	0.00174
	15	127	0.00160
	16	116	0.00200
	18	144	0. 00220
	21	161	0.00190
	22	208	0.00215
	23	127	0.00208

TABLE V: IEEE 24 BUS SHORTEST PATHS PARAMETERS

Bus		**Resilience paths based on Shortest paths**	
from	***To***	***Length (mile)***	***C_{ave} (p.u / mile)***
2	1	3	0.1537
	7	107	0.00531
	13	81	0.00750
	15	94	0.00667
	16	104	0.00651
	18	132	0.00577
	21	128	0.00570
	22	175	0.00498
	23	115	0.00618

By using equation (3) in section II, voltages at nonblack start buses (receiving ends) are calculated, see table VI. Assume that voltage at black start bus (sending end) is equal one per unit and no load at receiving end.

Resilience transmission lines paths are selected based on minimum capacitance paths and less number of connections, otherwise voltages at receiving ends are calculated for shortest paths. In case of shortest path has less number of connection and voltage at receiving end less than 1.05 per unit, shortest path become resilience factor as shown in table VI.

For many reasons line length can't guarantee accurate selection of optimal restoring path. Results confirm the effectiveness of using proposed line capacitance factor besides line length as shown in table VI.

TABLE VI: RESILIENCE PATHS OF IEEE 24 BUS SYSTEM

Bus		**Resilience paths based on minimum capacitance paths**		**Resilience paths based on Shortest paths**		**Resilience factor**
from	***To***	***Voltage (p.u)***	***No. of conn-ection***	***Voltage (p.u)***	***No. of conn-ection***	
2	1	1	6	1	1	length
	7	1.007	4	1.009	5	capacitance
	13	1.005	4	1.008	5	capacitance
	15	1.008	5	1.012	4	length
	16	1.006	7	1.009	6	length
	18	1.007	9	1.01	8	length
	21	1.01	6	1.015	5	length
	22	1.015	7	1.02	6	capacitance
	23	1.013	4	1.015	5	length

V. CONCLUSION

Resilience transmission paths are very important in restoration stage. Dijkstra algorithm is used to determine resilience paths based on resilience factors. Line capacitance is proposed as resilience factor. Proposed algorithm verifies three criterions of line length, capacitance and restoring time.

Two IEEE networks are tested. Results show several differences in optimal transmission paths selection between proposed capacitance and existing length resilience factors.

Practically, Grids that have different voltage levels, mixed OHTL with cables path or several towers configurations, should consider proposed factor to guarantee optimal restoring voltage profile.

REFERENCES

[1] B. Chen, H. Wang, and X. Cao, "Dynamic Optimal Control of Sustained Overvoltage during Power System Restoration Process," 2015 IEEE Power & Energy Society General Meeting, Denver, CO, 2015, pp. 1-5.

[2] Yunhe Hou, C. C. Liu, Pei Zhang and K. Sun, "Constructing power system restoration strategies," 2009 International Conference on Electrical and Electronics Engineering - ELECO 2009, Bursa, 2009, pp. I-8-I-13.

[3] W. Sun, C. C. Liu and L. Zhang, "Optimal Generator Start-Up Strategy for Bulk Power System Restoration," IEEE Transactions on Power Systems, vol. 26, no. 3, pp. 1357-1366, Aug. 2011.

[4] J. Quirós Tortós and V. Terzija, "A smart power system restoration based on the merger of two different strategies," 2012 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe), Berlin, 2012, pp. 1-8.

[5] C. Liu, Minhao Wu and Yingsong Deng, "Start-up sequence of generators in power system restoration avoiding the backtracking algorithm," 2013 IEEE Power & Energy Society General Meeting, Vancouver, BC, 2013, pp. 1-5.

[6] R. Sun, H. Zhu and Y. Liu, "A r-NSGA-II algorithm based generator start-up for network reconfiguration," 2015 5th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT), Changsha, 2015, pp. 1332-1335.

[7] H. Zhong, X. Gu and X. Zhu, "Optimization Method for Unit Restarting during Power System Black-Start Restoration," 2012 Asia-Pacific Power and Energy Engineering Conference, Shanghai, 2012, pp. 1-4.

[8] R. Arghandeh, A. Von Meier, L. Mehrmanesh, and L. Mili, "On the definition of cyber-physical resilience in power systems," Renew. Sustain. Energy Rev., vol. 58, pp. 1060–1069, 2016.

[9] Hadi Saadat, "Power System Analysis," 3rd ed., 2010.

[10] IESO, "M. Manual, "Ontario Power System Restoration Plan," Market Manual 7: System Operationsno, Part 7.8, Jan. 2016.

[11] En Lu, Ning Wang, Zhijun Qin, Haoming Liu and Yunhe Hou, "Black-start strategy for power grids including fast cut thermal power units," 2013 IEEE Power & Energy Society General Meeting, Vancouver, BC, 2013, pp. 1-5.

[12] M. N. Albasrawi, N. Jarus, K. A. Joshi and S. S. Sarvestani, "Analysis of Reliability and Resilience for Smart Grids," 2014 IEEE 38th Annual Computer Software and Applications Conference, Vasteras, 2014, pp. 529-534.

[13] S. Hemalatha and P. Valsalal, "Restorative Path Selection For Power System Network Using Floyd Warshall Algorithm," ARPN Journal of Engineering and Applied Sciences, vol. 7, no. 4, pp. 472–477, 2012.