OPTIMAL PATH IDENTIFICATION NEW APPROACH FOR POWER SYSTEM RESTORATION USING PMUs

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***Abstract*. An effective approach is proposed to obtain the optimal restoration path sequence after blackout using Phasor Measurement Units (PMUs). Two algorithms are introduced to apply the proposed planning approach. The first algorithm is used to start all Non Black Start Units "NBSUs" from BSU by identifying the optimal shortest path between any two buses. The Power Transfer Distribution Factor (PTDF) and Restoration Performance Index (RPI) are employed in the second algorithm to energize the load buses. Observable paths, avoiding thermal overloading and preventing connecting lightly loaded lines to prevent overvoltage are ensured when identifying the optimal restoration path by starting NBSUs as early as possible. The proposed approach is capable to deal with both the buildup and build down restoration strategies. The New England 39 bus and IEEE 118 bus power systems are** applied to **verify the efficiency of the proposed approach.**

KEYWORDS— **Blackout, Power system restoration, observability, Phasor Measurement Unit (PMU), Power Transfer Distribution Factor (PTDF), Restoration Performance Index (RPI)**.

NOMENCLATURE

A	: Network connectivity matrix.
a_{ij}	: Binary variable that shows if busi and j is connected
BSU	: Black Start Unit
GRAs	: Generic Restoration Actions.
NBSU	: Non Black Start Unit
NL	: The total number of transmission lines
NB	: The total number of buses
OI	: Power system Observability Index
PMU	: Phasor Measurement Unit
RPI	: Restoration Performance Index
$\bar{S}_{p,\,thermal}$	: The thermal limit of line p
T	: Represents the index of restoration steps.
WAMS	: Wide Area Measurement System
WF_p	: Weighting factor for line P
Z_{bus}	: Bus impedance matrix referenced to the swing bus
ΔSq	: The power injection change on bus q
$\overline{\Delta Sp}$	: The power flow change on transmission line p in the current system.
ρ	: Power Transfer Distribution Factor (PTDF)

I. INTRODUCTION

The restoration process returns the system back to a normal operating condition by assessing system conditions, restarting BS units, establishing the transmission paths to crank NBS generating units, and picking up the necessary loads to stabilize the power system [1].

Two well-known strategies to restore a power system are developed. One of them involves reenergizing the network before resynchronizing generators which is called the build-down strategy. The other strategy involves sectionalization of the power system into some islands, restoring each island, and then synchronizing of the islands by interconnecting them which called the build-up strategy. The advantage of the buildup strategy is to replace a big complex problem with simpler ones which are easier to deal with that leads to speed up the restoration process. Also one of the major advantages of the buildup strategy is the recurrent blackout would only occur in the affected island only, besides reducing the restoration time in case of large disturbance [1-3].

The methods used to deal with the restoration strategies are the rule-based methods and the model-based methods. The researches proved that model-based methods are preferred to the rule-based methods. The rule-based approaches use knowledge-based techniques based on either operator judgment or previous experiences. This leads to inability to deal with unpredicted cases and the difficulty of maintaining large knowledge bases. The model based method is able to deal with unforeseen conditions, complicated and large scale power systems. New method to sectionalize the power system into proper number of islands satisfying restoration constraints is introduced in [4-5]. New method for the optimal restoration planning is also introduced in [6]. Finally a method to build these islands and identify the order of interconnecting them is presented in [7].

Smart grid technologies are expected to enable a grid to be restored from major outages efficiently and safely

[8-12]. The introductions of WAMS using Phasor Measurement Units (PMUs) results in online power system monitoring and control [10]. WAMS enable operators to measure and define power system variables synchronously in more detailed time scale and analyze the power system with new techniques [11-12]. The importance of data provided by the PMUs has been recognized with the occurrence of major blackouts in many power systems around the world. Utilizing synchronous measurements during the restoration process, the operators can monitor the voltage angle across every line and differentiation between tie lines and close the circuit breaker with the very small phase angle difference [11]. It would be economic to find the minimum numbers of PMUs for system observability as PMUs are expensive devices. Indeed a bus is observed if it has PMU or it is connected to a bus has PMU. Different methods have been developed to solve the minimal PMUs placement problem [8-9].

Optimal generator startup strategy during power system restoration is a critical, complex and multistage decision optimization problem. Identifying the optimal path to crank NBSUs or defining the optimal startup sequence lead to start NBSUs as early as possible, minimize restoration time, maximize generation capability, maximize the total load served at restoration early stages and to minimize the restoration time [13-19].

The novelty of the proposed approach in this paper is to plan restoration by calculating the PTDFs for candidate lines to be closed or load buses, in other words connecting branches and picking loads [13-18]. In the developed approach, RPIs are calculated to rank the candidate lines to be closed and the optimal restoration sequence of load buses is identified. In this study, a computational algorithm is proposed to be a decision tool to support the operator during restoration process. So that system restoration can adapt the changing system conditions and deal with unforeseen cases. Optimal restoration path during restoration for both strategies of restoration are introduced using two algorithms. The first algorithm is established to find the optimal path to crank NBSUs from BSUs and the second algorithm determines the optimal restoration sequence to energize load buses without violation for any of the proposed constraints. Both algorithms ensure starting NBSUs as early as possible, obtaining observable paths, not connecting lightly loaded lines to avoid overvoltage and not overloading transmission lines. The New England 39 bus power system and the 118-bus power system are applied to demonstrate the approach capabilities.

II. Proposed Approach And Methodology

The main contribution of this paper is to find the optimal restoration path sequence to energize the minimum number of lines from BSU to crank NBSU and loads which will lead to reduce restoration time. Other contribution of this paper is the investigation of the network connectivity matrix [A] that describes the topological construction of the network in finding the shortest path between any two buses. The optimal restoration path can be categorized into two stages. The first stage is utilized to provide cranking power to start NBSUs from BSU. This stage of algorithm is considered as a good tool to assist the operator to restore the loads as early as possible because the generating units will be in service faster than before. This approach depends mainly on the shortest path solver program defined also here. The second stage of algorithm utilizes the concept of PTDF to determine the optimal restoration sequence to energize the rest of transmission lines or load buses while building the skeletal network. Various constraints are considered such as ensuring the path observability using the least number of PMUs, speed up the remote cranking of NBSUs, avoiding both transmission line thermal overloading and over voltage. Two algorithms are investigated to identify the proposed approach, the remote cranking of NBSUs and the PTDF to energize load buses. One computational and integrated tool is proposed for both algorithms and can be used as guidance for the operators in the real operational environment during restoration. So that the restoration can adapt the changes in system conditions i.e. "updating network status". The actual restoration timing table of each island is derived based on the GRA time table that represents the total time to complete different generic restoration actions.

A. The proposed Shortest Path Algorithm

A new algorithm to find the shortest path between two buses (starting bus “source node” and ending bus “destination node”) is introduced and shown in Fig.1. It depends mainly on the connectivity Matrix [A] which describes the topology of the electrical network and how different buses of the network are connected.

$$A = [a_{ij}] \tag{1}$$

$$aij = \begin{cases} 1, & if\ i = j\ or\ if\ i\ and\ j\ are\ connected \\ 0, & Otherwise\ . \end{cases}$$

Where a_{ij} is the connectivity between buses (i and j). The topology and the status of buses connectivity of the electric network can be described and expressed by the network connectivity matrix [A]. The shortest path solver is utilized using the network connectivity matrix [A] to find the shortest path which is simpler, reliable and easier to be solved than before. This algorithm helps to find the shortest path between two buses with minimum number of lines.

All buses connected to the starting bus and not energized are identified from the connectivity matrix [A]. The target bus is checked between the identified buses. If it is found, its path is defined and the process stopped. If not, all identified buses are considered as new buses in the route. The search continues by taking each of the identified buses as starting point to the target bus until it is found. The algorithm can be summarized as follows:-

Step 1: The starting bus is taken as the initial bus in the path sequence matrix,
Step 2: Find all buses (*j*) connected to the starting bus (*i*) and add it to the path sequence matrix,
Step 3: If the target bus is found, stop and save the path; otherwise go to step 4,
Step 4: **A**ll buses connected to the last bus (*i*) in the path sequence matrix are identified and added to the path sequence matrix, and
Step 5: Go back to step 3 and continue iterations until the target bus bar is found.

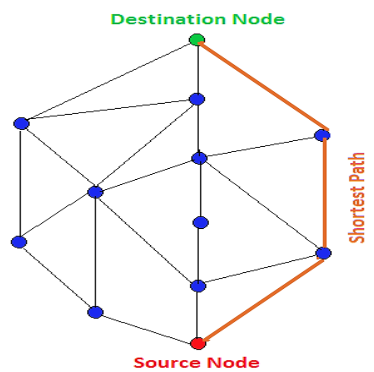

Fig.1: The Shortest Path Algorithm Description

B. The proposed Optimal Cranking Path Algorithm

The second contribution of this paper is identifying the optimal cranking path algorithm based on defining the shortest paths from the island BSU bus going to all its NBSUs. Energizing the minimum number of lines should be considered when selecting the path. This algorithm deals with both restoration strategies and it is the first time to be used with the buildup strategy. This approach makes it easier to plan the restoration process for small and large scale power systems faster and with high accuracy and reliability. Traditional rule-based approaches that use knowledge-based techniques based on either operator judgment or previous experiences leads to inability to deal with unpredicted cases and the difficulty of maintaining large knowledge bases. The proposed approach is able to handle the unforeseen conditions, complicated and large scale power systems.

The restoration operation is planned to start from the BSU to the NBSU using the predefined shortest path. All buses of the shortest path will be considered as starting restoration point to all remaining NBSUs of the island and so on until energizing all NBSUs in the island. The algorithm is indicated in flowchart shown in Fig.2.

The algorithm is explained in details as follows:
Step 1: One of the BSU buses is considered the first restored bus in the system (Initial bus)
Step 2: Depending on the shortest path solver program defined in the previous section, all possible paths to all un-energized NBSUs (*j*) from energized bus (*i*) are identified.
Step 3: Energize the NBSU between the candidate NBSUs that has the shortest path and record it to the path.
Step 4: Now, every energized bus in the previous step can be used as cranking source (*i*) to energize the un-energized NBSUs (*j*).
Step 5: Repeat step.2 to find all possible paths from each cranking source (*i*) to each un-energized NBSU (*j*)
Step 6: Go to step 3
Step 7: If all NBSUs are cranked, stop and record restoration path; otherwise go to step 4.

To enhance the reliability of the proposed approach new rule is developed to differentiate between optimal paths that have the same number of lines. If all candidate paths to crank the NBSU have the same number of lines i.e. “same energization time ", choose the least impedance path to crank NBSU. This process not only leads to reduction in the restoration time but also achieve the proposed constraints of voltage stability.

C. Optimum Load Buses Restoration Path Sequence

After identifying the optimal cranking path to each NBSU, the optimal restoration path for the load buses should also be specified for each island considering the following constraints:-

1. Enhance restoration path observability by energizing PMU buses
2. Avoid energizing lightly loaded lines
3. Ensure thermal stability of energized transmission lines

The Power Transfer Distribution Factor (PTDF) algorithm [6] is applied to differentiate between the candidate lines loading without lost time in calculating load flow using the standard software programs.

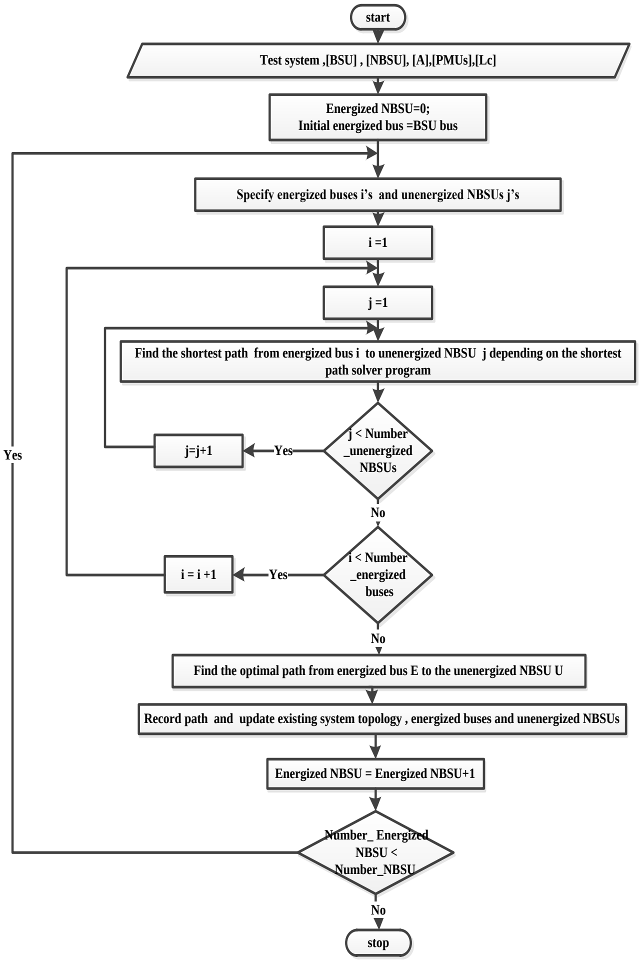

Fig.2: The optimal cranking path algorithm

Also it facilitates dealing with any electrical system even at unforeseen conditions and can manage any system changes. Also, Restoration Performance Index (RPI) is calculated in the developed approach to rank branch closures and take the observability into account when choosing the best candidate line to be firstly closed.

The restoration path selection algorithm is shown in Fig.3 for a totally blacked-out power system. Weighting factors are integrated to the PTDF algorithm to determine the correct sequence for energizing the transmission lines after cranking all NBSUs with the above mentioned algorithm [13].

For the transmission line between buses i and j, the power flow can be considered as a complex bus power injection into the existing system bus k. The PTDF is the relation between the loading increment in the line from bus i to bus j " ∂S_{ij}" with respect to the injected complex bus power S_k on bus k.

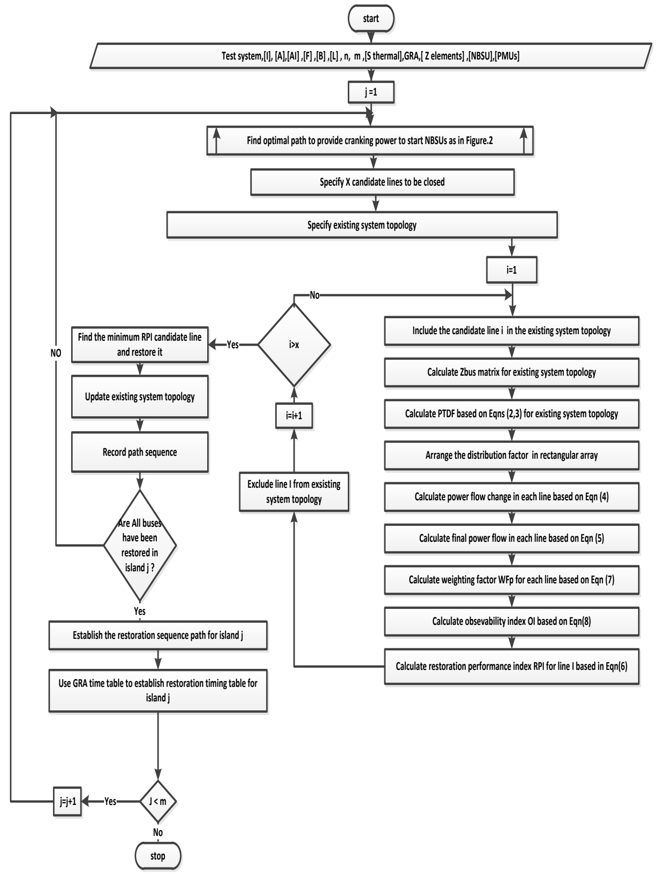

Fig.3: PTDF Based Selection Algorithm

It is denoted as $\rho_{ij,k}$ and can be defined as per the following Equation:-

$$\rho_{_{ij,k}} = \frac{\partial S_{ij}}{\partial S_k} = \frac{\partial I^*_{ij} \ * \ V_j}{\partial I_k V_k} \tag{2}$$

The approximation of near unity bus voltage magnitude is applied to result in

$$\rho_{_{ij,k}} = \frac{\partial \ I_{ij}^*}{\partial I_k^*} = \left(\frac{(Z_{bus})_{ik}\text{-}(Z_{bus})_{jk}}{z_{ij}} \right)^* \tag{3}$$

The elements of Z_{bus} in the above equation are obtained from the bus impedance matrix referenced to the swing bus. V_j and V_k are designated as the bus voltage at buses j and k respectively. Z_{ij} is assigned as the primitive impedance of the line connecting bus i to bus j. I_k represents the current injected at bus k. In the above equation, it is also assumed that the rms values of voltage phasors are close to the associated nominal values.

By arranging the distribution factors in a rectangular array, the PTDF matrix can be formed as Equation (4)

$$\begin{bmatrix} \overline{\Delta S_1} \\ \overline{\Delta S_2} \\ \dots \\ \overline{\Delta S_{NL}} \end{bmatrix} = \begin{bmatrix} \rho_{1,1} & \rho_{1,2} & \dots & \rho_{1,NB} \\ \rho_{2,1} & \rho_{2,2} & \dots & \rho_{2,NB} \\ \dots & \dots & \dots & \dots \\ \rho_{NL,1} & \rho_{NL,2} & \dots & \rho_{NL,NB} \end{bmatrix} * \begin{bmatrix} \Delta S_1 \\ \Delta S_2 \\ \dots \\ \Delta S_{NB} \end{bmatrix} \quad (4)$$

After energizing and loading each transmission line, the power flow in the other lines, which have already been restored, will be changed. Improper energizing and loading of transmission lines will result violation of the system operational constraint. The change in power flow, relating each possible line addition, can be estimated using the PTDF calculation. This change, which is determined with respect to the existing system topology, is based on Equation (4). Power flow after each transmission line energization can be calculated using Equation (5).

$$\begin{bmatrix} \overline{S1} \\ \overline{S2} \\ \dots \\ \overline{SNL} \end{bmatrix}_{(t+1)} = \begin{bmatrix} \overline{S1} \\ \overline{S2} \\ \dots \\ \overline{SNL} \end{bmatrix}_{(t)} + \begin{bmatrix} \overline{\Delta S_1} \\ \overline{\Delta S_2} \\ \dots \\ \overline{\Delta S_{NL}} \end{bmatrix} \quad (5)$$

The Restoration Performance Index (RPI) [13] can be developed in order to properly take the concept of power system observability into account. The RPI is evaluated for each candidate transmission Line. The RPI is the sum of the products of the weighting factors and power flow changes in each existing transmission line. For each candidate transmission line, the associated RPI is the sum of elements in an [NL * 1] vector. Subsequently, the candidate transmission line with the lowest RPI value is primarily restored. In other words, the island organization is optimized based on the Dynamic Programming approach. The most fitting RPI is to select the next action throughout the island organization process.

$$RPI = \left[\sum_{P=1}^{NL} \overline{\Delta S_p} \; * \; WF_p \right] * \; [1 - OI] \quad (6)$$

Where

$$\mathrm{WF_p} = \frac{\bar{S}_\mathrm{p}}{\bar{S}_{\mathrm{p\;,\;thermal}}} \quad (7)$$

$$\mathrm{OI} = \frac{Observed\ Energized\ Bus}{total\ number\ of\ Energized\ Buses} \quad (8)$$

OI is also utilized as power system observability index after energizing the next transmission line. OI is a real index between 0 and 1. In Equation (6), there is a term comprising (1.0 – OI). If there are more observed buses due to energizing the next candidate line, the OI is increased and the term (1- OI) is decreased so the RPI will be minimized and the line that increases the observability will be restored. The existing power flow expressed as a percentage of the thermal limit on each restored line will be used as a weighting factor (WF). If the change in the power flow of the restored lines due to energizing the next candidate line is small, the term representing the thermal loading of lines in the RPI Equation is decreased. So the candidate line that minimizes the power flow in the restored lines will be restored. Finally, the mix between the observability and thermal loading of restored buses and lines in the RPI equation will help the operator to restore the most suitable candidate line that increase the observability of the restored buses and decrease the thermal loading of the restored lines.

D. Restoration Timing Table Evaluation

After finalizing the restoration path selection step, the next step is to plan the restoration actions time schedule. Table.1 represents the total time to complete different types of GRAs [18].

Table.1: Time to complete GRA [18]

GRA Time	(min.)
Restart BSU	15
Energize a bus from a BSU/bus/line	5
Connect tie line	25
Crank a NBSU from a bus	15
Synchronize between bus/lines	20
Pick up load	10

Considering the required time for accomplishment of different GRA, restoration timing can be evaluated.

III. SIMULATION RESULTS

IV. An integrated Matlab software program code is created to replace the previous proposed algorithms for power system restoration planning. The program contains a number of subroutines to perform the different optimized functions. The proposed code enables specifying the optimal restoration paths to restore the test systems which make the process of restoration planning easier and faster. Two different large scale power systems are used to test the proposed approach and both restoration strategies are applied to each system to prove the approach capability and reliability in practical systems .The following sections discuss the obtained results.

A. The New England 39 Bus Power System Case Study

In order to demonstrate the proposed approach and verify the results, the New England 39 bus power system is used assuming complete shutdown then the results are discussed.

(1) System Description

The typical New England 39-bus power system as presented in [20] is used for the application of the proposed approach using build down restoration strategy. Some modifications are made on the New England 39-bus power system, when applying the buildup strategy to suite islanding and observability [4] as will be illustrated in Fig.4.

The New England 39-bus power system is divided into four islands shown in Fig.4. Thirteen PMUs are placed at buses 2, 6, 9, 12, 14, 17, 22, 23, 29, 32, 33, 34 and 37. All the islands are observed and each one–contains the active load more than minimum power generation to ensure its stability. In addition, the generators located at buses 30, 33, 36 and 37 are assumed to be BSG (slack buses of the islands).

(2) Build Up Strategy Simulation Results for All Islands

The detailed results of the buildup strategy application using the New England 39 bus power system are discussed as follows:-

(3) Island 2 Simulation Results

In order to indicate and validate the results of these algorithms, the restoration path of island 2 is discussed in more details as an example. The restoration path of island 2 is divided into two parts; the first involves the identification of the cranking path to energize NBSUs from BSU and the second involves the identification of the sequence to energize the rest of load buses at the proposed island.

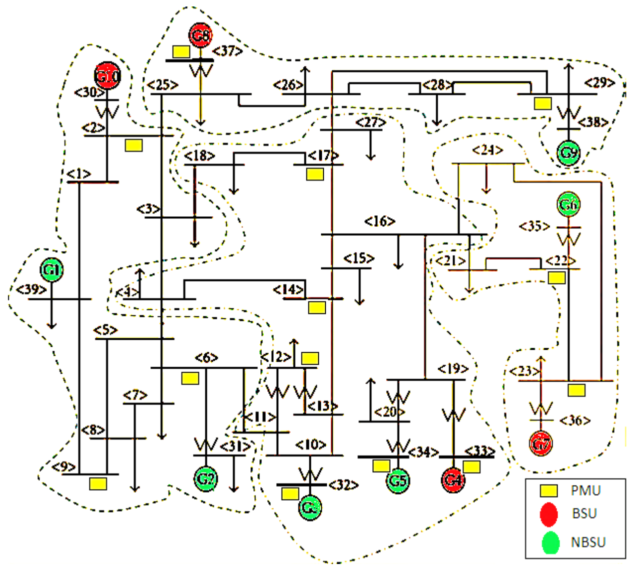

Fig.4: The modified New England 39 bus power system.

a) Optimal path to provide the cranking power to start NBSU located at buses 34 and 32 From BSU at bus 33

The main purpose to energize transmission lines 33-19, 19-20 and 20 -34 is remote cranking of the unit located at bus 34. Thus, the active load at bus 20 will be utilized to endure power system stabilization. The energization of transmission lines 19-16, 16-15, 15-14, 14 -13, 13-10 and 10 -32 is aimed to interconnect the unit located at bus 32. The results are shown in Fig.5.

b) PTDF based restoration path to energize loaded buses

As the final point, the energization of transmission lines 16-17 , 17-18 , 17 -27 , 13-12 and 14-4 results in the establishment of island 2 .only bus 11 in island 2 are left not energized. This decision is to decrease the energization of the lightly loaded transmission lines also bus 11 doesn’t affect the load restoration process. During the last stages of restoration, this bus can be energized without operational problems. The results are shown in Fig.6-a and b.

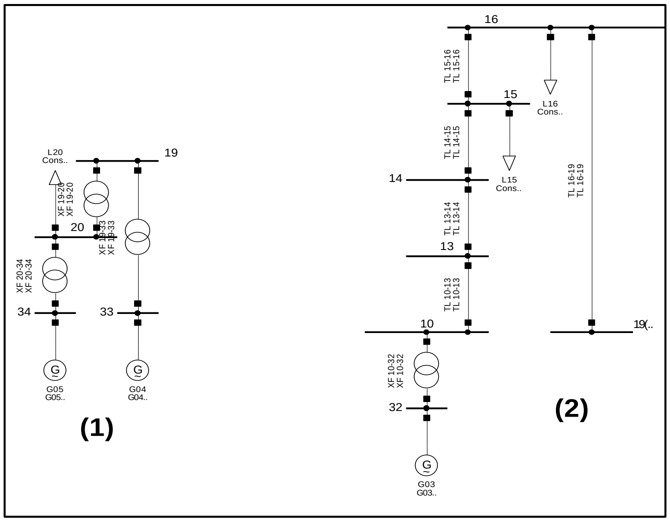

Fig.5: The optimal path to provide cranking power to NBSU at island 2

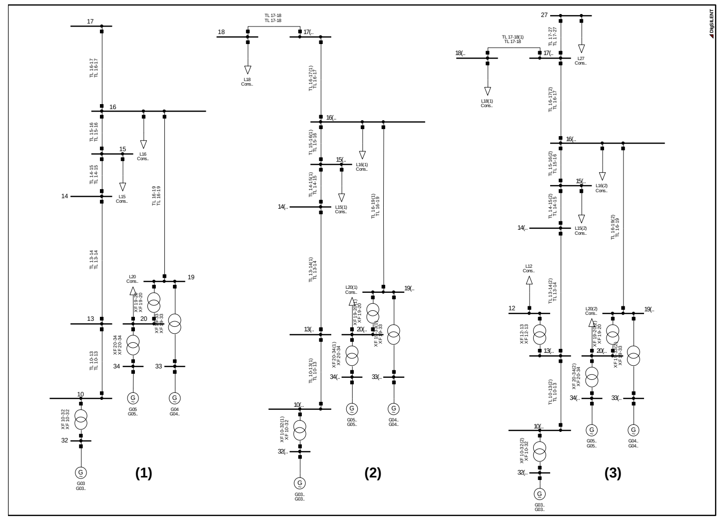

Fig.6-a: PTDF based restoration path to energize loaded buses at island 2

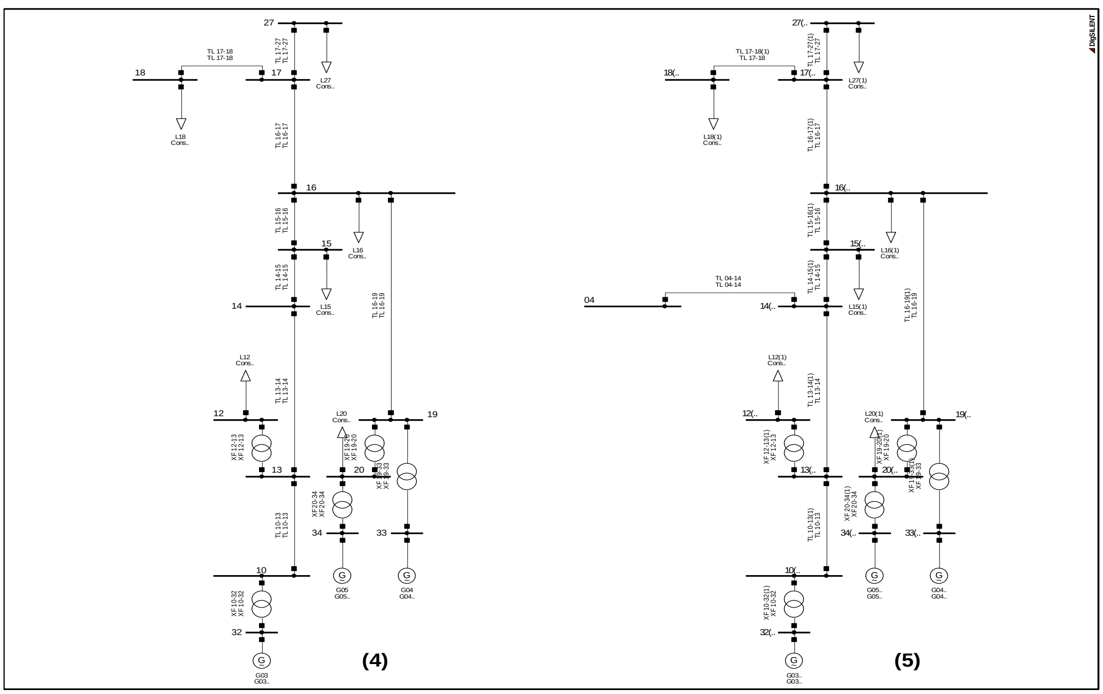

Fig.6-b: PTDF based restoration path to energize loaded buses at island 2

Table.2: Restoration sequence for applying build up strategy on the New England 39 bus

Restoration Sequence										
Island 01	Lines	30-2	2-1	1-39	39 --9	9-8	8-7	7-6	6-31	2-3
Island 02		33-19	19-20	20-34	19-16	16-15	15-14	14-13	13-10	10-32
		16-17	17-18	17-27	13-12	14-4				
Island 03		36-23	23-22	22-35	22-21	23-24				
Island 04		37-25	25-26	26-29	29-38	26-28	29-28			

Table.3: Restoration timing for applying build up strategy on the New England 39 bus

Restoration Timing										
Island 01	Line	30-2	2-1	1-39	39 --9	9-8	8-7	7-6	6-31	2-3
	Time	20	25	30	50	55	70	85	90	150
Island 02	Line	33-19	19-20	20-34	19-16	16-15	15-14	14-13	13-10	10-32
	Time	20	25	40	45	75	90	95	100	105
	Line	16-17	17-18	17-27	13-12	14-4				
	Time	125	130	135	180	185				
Island 03	Line	36-23	23-22	22-35	22-21	23-24				
	Time	20	35	40	60	75				
Island 04	Line	37-25	25-26	26-29	29-38	26-28	29-28			
	Time	20	35	50	55	130	180			

(4) Build Up Strategy Total Simulation Results

Applying the proposed approach for path selection on the proposed subsystems results in the optimal restoration sequence for each island as presented in Table.2 and Fig.7. Considering GRA's, the planning of the restoration timing table is listed in Table.3

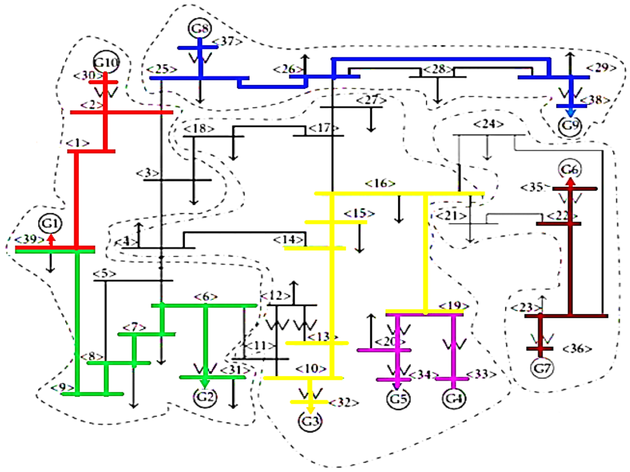

Fig.7: The islanded network with optimal cranking path for each NBSU

The optimal path to crank each NBSU was previously identified depending on the operator experience which may lead to crank NBSUs using large number of lines that prolong the restoration process. Now, it is the first time to apply this approach in the buildup strategy and the proposed approach proves its applicability.

It should be noted that, the results of restoration planning for the case under study clearly reveal that there is no need to connect all the buses to the bulk power system during the early stages of restoration. Through the process of islands organization, only buses 5 and 11 are left not energized. This decision is to decrease the energization of the lightly loaded transmission lines. During the last stages of restoration, these buses can be energized without operational problems. Considering the energization time, restart time, capacity and ramp rate of each generators at different islands, the total generation capacity is available after 280 min from the start of restoration as shown in the generation capability curve in Fig.8 and Fig.9.it should be noted, after 280 min, all the generators are at their full load generation and the total generation equals to 6192.9 MW, So, these buses should be energized not later than this time. After specifying the restoration plan the next actions are establishment of the islands and interconnection of the islands.

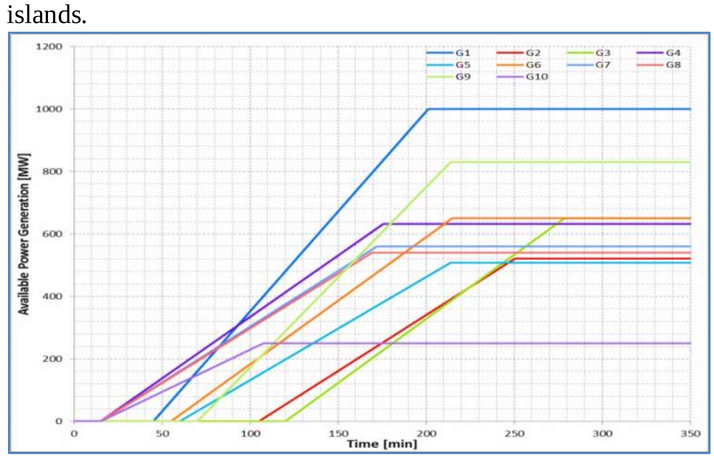

Fig.8: the New England 39 Bus power system Generators Capability Curves

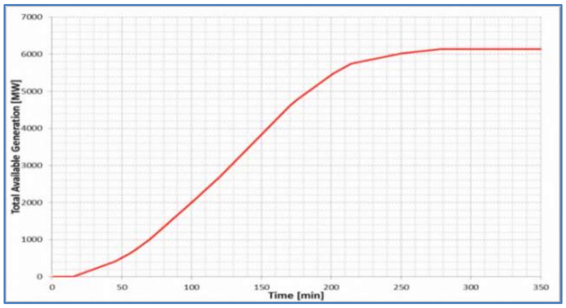

Fig.9: Total Generation capability curve of the New England 39 Bus power system during building subsystems.

(5) Build Down Strategy Simulation

If the test system is considered as one island, the path selection algorithm can be applied using the build down strategy.

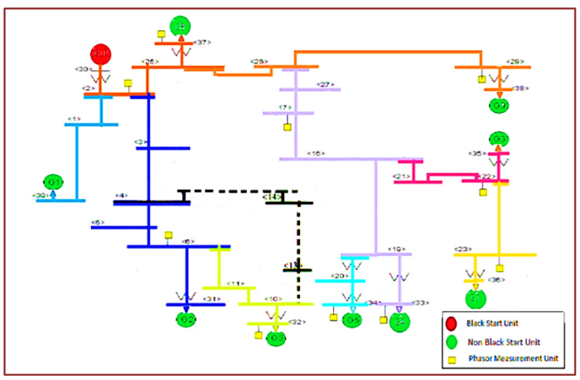

Fig.10: The optimal cranking path for the build down strategy on the New England 39 bus.

Applying the proposed approach for path selection on the Bulk system results in the optimal restoration sequence as presented at Table.4 and the optimal cranking path as shown in Fig.10.

Table.4: Restoration sequence for build down strategy on the New England 39 bus.

Restoration Sequence									
30-2	2-25	25-37	2-1	1-39	25-26	26-29	29-38	2-3	3-4
4-5	5-6	6-31	6-11	11-10	10-32	26-27	27-17	17-16	16-19
19-33	19-20	20-34	16-21	21-22	22-35	22-23	23-36	4-14	39-9
6-7	9-8	10-13	13-12	17-18	29-28	23-24	14-15		

It should be noted that the optimal path to crank each NBSU is identified based on energizing the minimum number of lines. Decreasing the number of lines leads to reduce the restoration time and pick up loads quickly as each line take specific time to be energized as mentioned in GRA. Using the cranking path for G3 at bus 32 to compare between the proposed approach and the conventional method [51], it can be noted that:

- Conventional method uses bus 4 as the cranking power source to crank NBSU located at bus 32 and the optimal path contains four lines 4-14, 14-13, 13-10, 10-32.
- proposed approach uses bus 6 as the cranking power source to crank NBSU located at bus 32 and the proposed optimal path contains three lines 6-11,11-10,10-32.

It should be noted that the proposed approach helps to decrease the number of required lines to crank NBSU at bus 32; hence the restoration time is reduced and loads are picked quickly. Faster restoration process is achieved faster than before by energizing the minimum number of lines to crank NBSU.

B. THE IEEE 118 BUS CASE STUDY

In order to ensure the applicability of the proposed approach in practical systems, IEEE 118 bus power system is used as a large scale power system for application of the proposed approach. Assuming a complete shutdown then the results are discussed as following:

1. SYSTEM DESCRIPTIONS

The typical IEEE 118-bus power systems as presented in [21] is used for the application of the proposed approach using build down restoration strategy. Some modifications made on the IEEE 118-bus power systems when the proposed approach is applied to the buildup strategy to suite islanding and observability [4] as will be illustrated in Fig.11.

The IEEE 118-bus system is partitioned to eight islands as shown in Fig.11. The buses allocated to these islands are as shown in Fig.10. Considering 32 PMUs, allocated at buses 3, 5, 9, 12, 15, 17, 21, 23, 28, 30, 34, 37, 40, 45, 49, 52, 56, 62, 64, 68,71, 75, 77, 80, 85, 86, 91, 95, 101, 105, 110 and 114, the islands are observed .In addition, the generators located at buses 10,25,49,61,69,80,89,100 are assumed to be BSU (slack buses of the islands).

2. Build Up Strategy Simulation

Applying the proposed approach for path selection on the proposed subsystems results in the optimal restoration sequence for each island as presented at Table.5. Considering GRA's, the restoration timing table is presented in Table.6.

Table.5: Restoration Path Sequence for Applying the Buildup Strategy on the IEEE 118 Bus Islands.

Island No.	Restoration Sequence									
1	10-9	9-8	8-5	5-4	5-6	5- 3	3- 1	5-11		
2	25-26	25-27	27-32	32-31	32-113	25-23	23-24	31- 17	17-15	17-18
	17-16	16-12	17-30	27-28	32-114	28-29	27-115	23- 22	22-21	21-20
	12-14	12- 7	12-117	12- 2	15-13					
3	49-42	49-48	48-46	46-45	49-51	51-52	49-50	49- 47	52-53	45-44
4	61-59	61-62	59-54	59-55	59-56	62-66	66-65	65- 38	38-37	37-34
	37-40	34-19	34-36	62-67	37-33	34-43	37-39	56-57	56-58	37-35
	40-41	62-60								
5	69-70	69-77	70-74	77-76	69-68	68-116	70-71	71-72	71-73	74-75
	77-82	76-118	77-78							
6	80-99	80-97	97-96	80-79	80-98					
7	89-85	89-90	89-92	90-91	85-86	86-87	85-84	85-83	85-88	
8	100-103	100-104	103-105	103-110	105-107	110-111	110-112	105-108	110-109	100-101
	101-102	100-94	94-93	94-95	100-106					

Table.6: Restoration timing for applying the buildup strategy on the IEEE 118 bus islands.

Island No.	**Restoration Sequence[Line / Time]**									
1	**10-9**	**9-8**	**8-5**	**5-4**	**5-6**	**5-3**	**3-1**	**5-11**		
	20	25	45	50	70	90	110	130		
2	**25-26**	**25-27**	**27-32**	**32-31**	**32-113**	**25-23**	**23-24**	**31-17**	**17-15**	**17-18**
	20	40	60	80	100	120	135	140	155	160
	17-16-	**16-12-**	**17-30-**	**27-28**	**32-114**	**28-29**	**27-115**	**23-22**	**22-21**	**21-20**
	180	195	215	220	235	250	265	280	295	310
	12-14	**12-7**	**12-117**	**12-2**	**15-13**					
	325	340	355	370	385					
3	**49-42**	**49-48**	**48-46**	**46-45**	**49-51**	**51-52**	**49-50**	**49-47**	**52-53**	**45-44**
	20	40	55	75	90	105	120	135	150	165
4	**61-59**	**61-62**	**59-54**	**59-55**	**59-56**	**62-66**	**66-65**	**65-38**	**38-37**	**37-34**
	20	40	60	80	100	120	140	160	165	170
	37-40	**34-19**	**34-36**	**62-67**	**37-33**	**34-43**	**37-39**	**56-57**	**56-58**	**37-35**
	190	210	230	250	265	280	295	310	325	340
	40-41	**62-60**								
	355	370								
5	**69-70**	**69-77**	**70-74**	**77-76**	**69-68**	**68-116**	**70-71**	**71-72**	**71-73**	**74-75**
	20	40	60	80	100	105	125	130	150	170
	77-82	**76-118**	**77-78**							
	185	200	215							
6	**80-99**	**80-97**	**97-96**	**80-79**	**80-98**					
	20	40	55	70	85					
7	**89-85**	**89-90**	**89-92**	**90-91**	**85-86**	**86-87**	**85-84**	**85-83**	**85-88**	
	20	40	60	80	100	115	135	150	165	
8	**100-103**	**100-104**	**103-105**	**103-110**	**105-107**	**110-111**	**110-112**	**105-108**	**110-109**	**100-101**
	20	40	60	80	100	120	140	160	175	190
	101-102	**100-94**	**94-93**	**94-95**	**100-106**					
	205	220	235	250	265					

It should be noted that, the results of restoration planning for the case under study clearly reveal that there is no need to connect all the buses to the bulk power system during the early stages of restoration. Through the process of islands organization, only buses 64, 63 and 81 are left not energized. This decision is to prevent the energization of the lightly loaded transmission lines. During the last stages of restoration, these buses can be energized without operational problems.

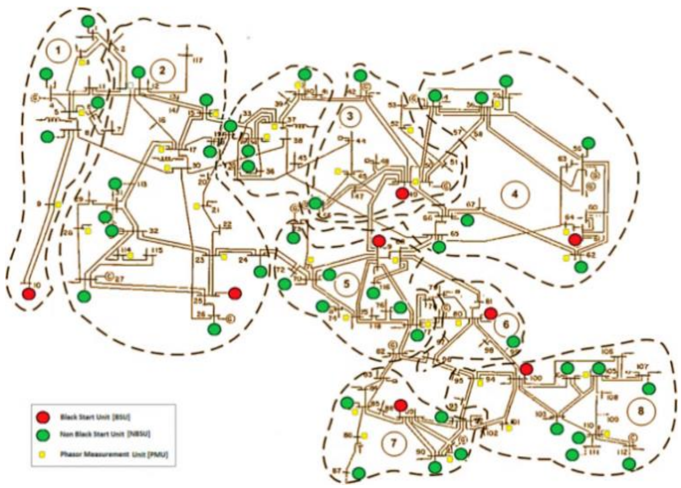

Fig.11: The modified IEEE 118 bus power system

3. Build Down Strategy Simulation

If we consider the test system as one island, the path selection algorithm can be applied using the build down strategy. Applying the proposed approach for path selection on the Bulk system results in the optimal restoration sequence as presented at Table.7.

Table.7: Restoration sequence for applying the build down strategy on the IEEE 118 bus.

Restoration Sequence									
10-9	**9-8**	**8-5**	**5-4**	**5-6**	**8-30**	**30-26**	**26-25**	**25-27**	**27-32**
32-31	**32-113**	**5-3**	**3-1**	**3-12**	**30-17**	**17-15**	**17-18**	**15-19**	**19-34**
34-36	**30-38**	**38-65**	**65-66**	**66-49**	**66-62**	**49-42**	**49-54**	**49-69**	**62-61**
42-40	**54-55**	**54-56**	**54-59**	**69-70**	**69-77**	**70-24**	**70-74**	**77-76**	**77-80**
24-72	**80-99**	**99-100**	**100-92**	**100-103**	**100-104**	**92-89**	**92-91**	**103-105**	**103-110**
89-85	**89-90**	**105-107**	**110-111**	**110-112**	**65-68**	**68-116**	**49-48**	**48-46**	**70-71**
71-73	**85-86**	**86-87**	**34-37**	**59-63**	**61-64**	**68-81**	**25-23**	**105-108**	**32-114**
23-22	**22-21**	**15-14**	**27-28**	**92-102**	**21-20**	**56-57**	**56-58**	**110-109**	**100-94**
80-97	**76-118**	**27-115**	**28-29**	**17-16**	**34-43**	**43-44**	**15-33**	**12-7**	**12-117**
12-2	**15-13**	**37-39**	**37-35**	**57-50**	**58-51**	**51-52**	**52-53**	**94-93**	**5-11**
44-45	**40-41**	**49-47**	**62-67**	**85-84**	**59-60**	**74-75**	**80-98**	**100-101**	**80-79**
85-83	**80-96**	**96-95**	**77-82**	**77-78**	**105-106**	**85-88**			

This large number leads to large number of possible cranking paths to each NBSU hence it leads to complex optimization problems that search for the optimized path between large numbers of possible paths. This problem is complicated and may take much time to determine the best path .Operator experience doesn't help in such situations and incorrect identification of optimal cranking path to each NBSU may prolong the restoration process. It should be noted that it is the first time to apply this approach on IEEE 118 bus as a large scale power system. It can be noted that the optimal path to crank each NBSU is identified based on energizing the minimum number of required lines. The proposed approach proves its capability in case of large scale power systems and it is able to find the optimal cranking path faster and accurately.

V. CONCLUSION

A new method is proposed to identify the optimal transmission restoration path sequence after a complete blackout based on WAMS for the restoration planning. The proposed approach guarantees starting the NBSUs in service as early as possible, obtaining an observable restoration process, satisfying the paths active power balance and avoiding overvoltage and thermal overloading using the concept of the PTDF. The restorative actions are carried out considering RPI for the best selection between the candidate lines. At the end, the restoration timing table is developed based on the time schedule for the achievement of different GRAs. For an extensive verification, the New England 39 bus test system and IEEE 118-bus system are used to demonstrate the comprehensive capabilities of the proposed algorithms. Moreover, the proposed approach is applied to the test systems using both build up and down strategies of restoration and the restoration sequence table is created. The simulation results indicate the applicability of the presented approach in power system restoration planning. It is proved that the approach avoids overvoltage by preventing the lightly loaded transmission lines to be energized at early stages as resulted when applying New England 39 bus power systems, buses 5 and 11 are not energized and when applying the IEEE 118-bus system, only buses 64, 63 and 81 are left not energized.

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