Black Start Capability Assessment in Power System Restoration

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Abstract—**Black start (BS) capability assessment is important for system planners to prepare the power system restoration (PSR) plan. To achieve a faster restoration process, installing new BS generators can be beneficial in accelerating system restoration. While additional BS capability does not automatically benefit the restoration process, power systems have to update the PSR plan and quantify the benefit based on appropriate criteria. In this paper, a decision support tool, developed in an EPRI project, using Generic Restoration Milestones (GRMs)-based strategy is utilized to provide a quantitative way for assessing the optimal installation location and amount of BS capability. Based on the proposed criteria, the benefit from additional BS capability is quantified in terms of system restoration time. The IEEE Reliability Test System (RTS) 24-bus test system is used for validation of the proposed strategy, using the System Restoration Navigator (SRN) restoration tool. It is shown that power systems can benefit from new BS generators to reduce the restoration time. However, there is a threshold beyond which system restoration time cannot be further reduced from additional BS capability. Economic considerations should be taken into account when assessing additional BS capabilities.**

Index Terms—**Black Start Capability, Generic Restoration Milestones, Power System Restoration, Restoration Time Estimation, System Restoration Navigator**

I. Introduction

In recent years, there were several catastrophic and cascading failures of power systems throughout the world (e.g., the Aug. 14, 2003 blackout in USA and Canada, Aug. 28, 2003 blackout in London, U.K., Sept. 23, 2003 blackout in Sweden and Denmark, Sept. 28, 2003 blackout in Italy, and May 24-25, 2005 blackout in Moscow, Russia [1-2]). While blackouts are rare events, PSR is one of the most important and challenging tasks for power system dispatchers in the control center. Dispatchers rely on off-line restoration plans and available BS capabilities to restore the system back to normal operation conditions [3-5].

After a partial or complete system blackout, BS resources initiate the process of system restoration and load recovery to return the system to a normal operating condition. Black start is a process of restoring a power station to operation without relying on external energy sources. A typical black start scenario includes BS generating units providing power to start large steam turbine units located close to these units. It also involves the supply of auxiliary power to nuclear power stations and off-site power to critical service load, such as hospitals and other public health facilities, and military facilities. Transmission lines must be available to deliver cranking power to non-black-start (NBS) units or large motor loads, and transformer units, including step-up transformers of BS units and steam turbine units, and auxiliary transformers serving motor control centers at the steam plant [6].

During PSR, BS generation availability is fundamental for all restoration stages [7]: stabilizing the system, establishing the transmission path, and picking up load. Available BS generating units must provide cranking power to NBS generating units in such a way that the overall available generation capability is maximized [8]. It may be helpful to install additional BS generators to accelerate the restoration process. After new BS generating units are installed, system restoration steps, such as generator startup sequence, transmission path, and load pick-up sequence, will change. However, there is a point where benefits of additional BS capabilities will not increase further. Therefore, power systems need to evaluate the strategy of both placement and size of new BS generators [9].

To better support dispatchers in the decision making process, several approaches and analytical tools have been proposed for assessment of BS capability. The knowledge-based system (KBS) system restoration tool is developed in an *EPRI* project [10] to integrate both dispatchers' knowledge and computational algorithms for system analysis. In [11], the Critical Path Method is applied to estimate system restoration time based on pre-selected PSR strategies. In [13], the Mixed Integer Linear Programming (MILP)-based optimal generator start-up strategy is proposed to provide the overall system generation capability and update the solution throughout the BS process. The concept of Generic Restoration Actions (GRAs) is proposed in [6] to generalize various restoration steps in different system restoration strategies. In [12], the Petri Net algorithm is proposed to coordinate the schedule of GRAs. While different system restoration strategies share some characteristics, GRMs are proposed in [14] to generalize power system restoration actions. Utilizing the concept of

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GRMs, the System Restoration Navigator (SRN) is developed by *EPRI* to serve as a decision support tool for evaluating system restoration strategies.

In this paper, the BS problem is discussed first, including BS resources and BS service procurement in an electricity market. Then, a GRMs-based algorithm for evaluation of additional BS capability is developed. The criteria of Restoration Time and BS Capability are proposed to determine the optimal location and amount of additional BS capability. The IEEE RTS 24-bus test system is used to validate the proposed strategy, utilizing the SRN restoration tool.

II. Black Start Procedure

A. Black Start Resources

Following an outage of the power system, power stations usually rely on power provided from the station's own generators. For example, small diesel generators can provide electric power to start larger generators (of several MW capacity), which in turn can be used to start the main power station generators. However, steam turbine generators require station service power of up to 10% of their capacity for boiler feed water pumps, boiler forced-draft combustion air blowers, and fuel preparation [8]. It is not economical to provide such a large standby capacity at each station, so BS power is provided over the transmission network from other stations. If part or all of the plant's generators are shut down, station service power will be supplied from the grid.

According to the start-up power requirement, generating units can be divided into two groups: BS generators, e.g., hydro or combustion turbine units, which can be started with its own resources, and NBS generators, such as steam turbine units, require cranking power from outside. Typical BS generators are:

Hydroelectric generating units. These generators need very little initial power to open the intake gates, and have fast response characteristics to provide power to start fossil fueled or nuclear stations.

Diesel generating units. Diesel generators usually require only battery power and can be started quickly to supply power to start larger generating units. They are small in size, and generally cannot be used to pick up any major transmission system elements.

Gas turbine generating units. Aero-derivative gas turbine generators can be started remotely with the help of local battery power. Large gas turbine generators are coupled with on-site diesel generator sets, which are started and used to energize plant auxiliary buses and start the gas turbine or steam turbine. Gas turbine generators can be started and pick up load in a short time. The time to restart and available ramping capability depend on the duration over which the unit was off-line [8].

Typical generators contracted for BS service are 10 to 50 MW small hydro or gas turbine units and, in a few cases, 200 to 400 MW steam units. The bus voltage values can be 6.9 kV for hydro units, 12.8 or 13.8 kV for gas turbine units, and 22 kV for steam turbine units. However, not all generating plants are suitable for BS service. For example, wind turbines are connected to induction generators that are incapable of providing power to a de-energized network. Mini-hydro or micro-hydro plants rely on a power network connection for frequency regulation and reactive power supply. Therefore, BS units must be stable when operated with the large reactive load of a long transmission line. Traditional high-voltage direct current converter (HVDC) stations cannot operate without the commutation power from the system at the load end.

During the implementation of the BS plan, voltage, rotor angle and frequency stability have to be maintained as important components in the stability assessment of the plan. Therefore, BS plans must be validated by tests or simulation in terms of steady state and transient operating conditions. A step-by-step simulation is required to verify the BS plan's feasibility and compliance with required operational limits on voltage and power flows. The robustness of a BS plan needs to be verified to ensure its ability to compensate for equipment unavailability.

B. Black Start Service Procurement

Black start is an ancillary service that is procured for power system restoration after a complete or partial outage. These BS resources must be able to energize buses and have on-site diesel or gas turbine generators to provide power for the auxiliary systems of the generating unit, which then can be used to start the unit. In North America, Independent System Operators (ISOs) identify and contract resources with BS capability and establishes financial agreements with them to provide this obligatory service.

There are three methods of procuring BS service. The most common one is Cost of Service, in which generating units are identified for BS resources and BS service costs are rolled into a broad tariff for cost recovery from ratepayers. This simple and traditional method is currently used by the California Independent System Operator (CAISO), the PJM Interconnection and the New York Independent System Operator (NYISO).

The second method is a new scheme that uses a flat rate to increase BS remuneration to encourage provision. Then the monthly compensation paid to a generator is determined by multiplying this flat rate by the unit's Monthly Claimed Capability for that month. This new method is aimed at simplification of the procurement process and incentivizing provision of BS. It is currently used by the Independent System Operator of New England (ISO-NE).

The last method is a competitive annual bidding process as used by Electric Reliability Council of Texas (ERCOT), which runs a market for BS services. Interested market participants submit bids of hourly standby cost for their generators to provide the service, which is named an availability bid that is unrelated to the unit capacity. ERCOT evaluates these bids and selects the capable BS resources that meet the BS selection reliability criteria, including the required amount of load to be recovered and the minimum time to recover that load, at a minimum cost. After each BS unit demonstrates its ability to start another unit, the selected units are paid as bid [15].

In the deregulated environment, there can be more BS resources available to provide BS service. Therefore, it is important for system operators to provide adequate but not overly redundant BS capabilities considering BS service costs. The BS capability assessment is required to assist PSR plans.

III. Black Start Capability Assessment

A. Black Start Capability

The system BS capability is the sum of MW generation capabilities over all units in the power system minus the startup power requirements. Following a system blackout, some fossil units may require cranking power from outside in order to start the unit. Some units may have time constraints within which the unit can be started successfully or else they have to be off line for an extended period of time before they can be restarted and re-synchronized to the grid. It is important that, during system restoration, the available system generation capability is maximized. Given limited BS resources and different system constraints on different generating units, the maximum available generation can be determined by finding the optimal startup sequence of all generating units in the system.

In the literature, various objectives or criteria to develop PSR strategies have been proposed, for example, maximizing the total system generation capability [8], minimizing the unserved energy [16], maximizing the total (or certain percentage of) restored load within the given restoration time [17], and minimizing the total restoration time [18]. However, there are difficulties in direct applications of the previous work on the BS capability assessment. The KBS system restoration tool [10] requires special software tools and, furthermore, the maintenance of large knowledge bases is a difficult task. The Critical Path Method [11] requires the actual and optimal sequence of restoration actions. However, for different installation strategies of new BS generators, it is difficult to provide and compare the updated PSR strategies. The MILP-based optimal generator startup strategy [13] needs further development and coordination with transmission path search and constraint checking to provide the actual system generation capability. Therefore, appropriate criteria and methods are required for BS capability assessment.

B. Installation of New Black Start Generators

To achieve faster restoration, additional BS generators might be useful to accelerate the restoration process. After new BS generating units are installed, system restoration steps, such as generator startup sequence, transmission path, and load pick-up sequence, will change. Then each system restoration stage [7] will adjust the restoration steps to accommodate the additional BS capability. A total of seven tasks in three restoration stages can be performed to update the restoration plan with installation of additional BS capability. This is illustrated in Fig. 1.

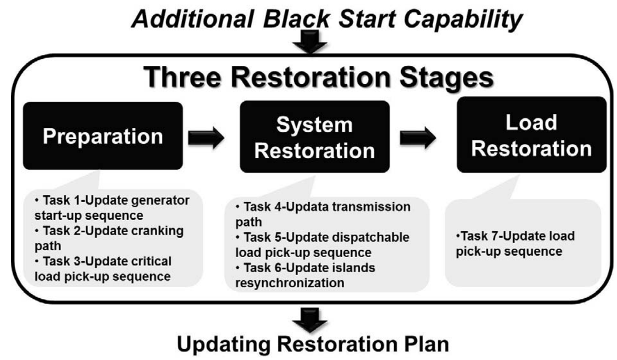

Fig. 1. Updated restoration plan with additional BS capability

The seven tasks shown in Fig. 1 will provide an updated restoration plan. However, these tasks will change with different systems or different installation strategies. Among different PSR strategies, there are several general actions to perform these seven restoration tasks, such as:

- Generator Startup Sequencing
- Transmission Path Search
- Load Pick-up Sequencing
- Optimal Power Flow Check

Restoration tools, for example, GRMs-based restoration tool, can be utilized to provide algorithms of these general restoration actions to perform the seven tasks shown in Fig. 2.

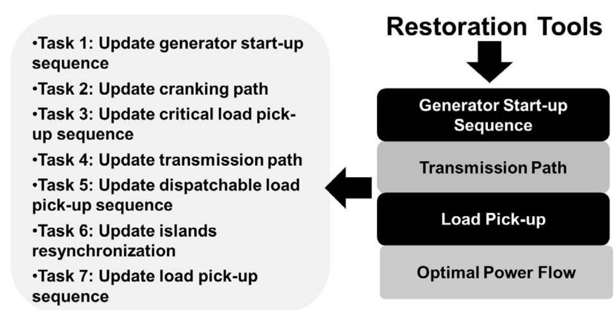

Fig. 2. Restoration tools for updating restoration plans

While restoration plans are updated by installing new BS generators, the benefits of additional BS capabilities need to be evaluated. There are multiple options for installation sizes and locations. Each option will bring a different restoration time. Therefore, the restoration time can be used as a criterion to quantify the benefit. However, there is a point where the benefits will not increase further. Therefore, power systems need to evaluate the strategy of both placement and size of new BS generators and quantify the benefits with the appropriate criteria.

C. Criteria of Restoration Time and Black Start Capability

An objective of PSR is to reconnect as more load as possible within the shortest time possible. After installing additional BS generating units, the reduced restoration time can be obtained from the updated restoration plan. Each installation strategy, including different locations and sizes of new BS generators, will lead to a different restoration time. The value of additional BS capability will be evaluated in terms of the system restoration time. However, from the cost-benefit point of view, the cost to install additional BS capability is also a criterion to evaluate the strategy. These two criteria of reduced restoration time and cost to install BS capability will decide the installation plan, as shown in Fig. 3:

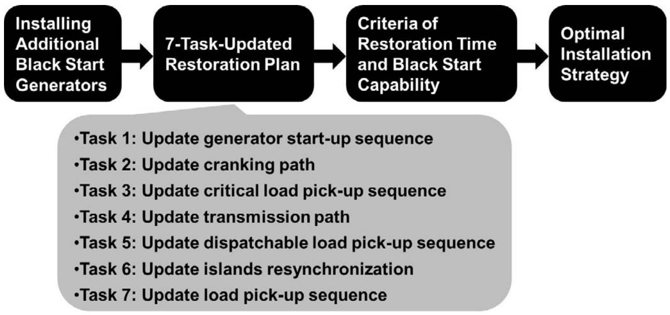

Fig. 3. Updated restoration plan with additional BS capability

These two criteria can provide information on the benefit based on the cost of installation, for example, installing additional BS capability will reduce the restoration time by a certain amount. Power systems can develop their best installation strategies according to their perspectives. Therefore, based on the criteria of the total restoration time and installed additional BS capability, power systems can determine the optimal installation strategy for the location and amount of BS capability.

D. GRMs-Based Algorithm for Installation Strategy

In a previous project funded by *EPRI*, GRMs were developed and implemented as the decision support tool for evaluation of system restoration strategy options [14]. After installing new BS generators, GRMs will help to update seven restoration tasks. The relationship between seven tasks and GRMs are illustrated in Fig. 4.

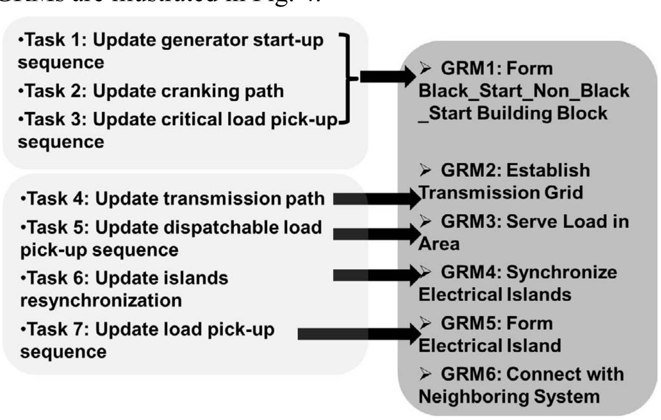

Fig. 4. Relationship between seven tasks and GRMs

After all six GRMs are used to update the restoration plan, the updated restoration time will be obtained. As the installation location and amount of additional BS capability change, the six GRMs can continue the iterations. All the updated restoration times will be presented for power systems to compare and determine the installation strategy. In this way, a method will be developed to determine the optimal sizes and locations for new BS units:

- **Step 1**: Select the installation location and amount of additional BS capability.
- **Step 2**: Based on restoration tools, the seven tasks are performed to obtain the updated restoration plan.
- **Step 3**: Based on the criteria of RTBC, the installation choice is evaluated.
- **Step 4:** Update installation strategy, continue the previous steps to achieve the optimal installation strategy.

The GRMs-based installation strategy for additional BS capability is illustrated in Fig. 5.

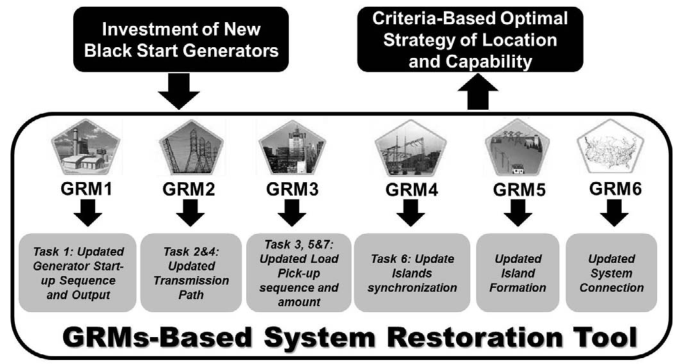

Fig. 5. GRMs-based installation strategy of new BS generators

IV. Numerical Results

Numerical analysis has been performed to validate the proposed installation strategy of additional BS capability. After installing new BS generators, the restoration process needs to be analyzed using the restoration tool. By the methods reported in the literature, either large computational burden (KBS-tool [10]) affects the effectiveness of the installation strategy or detailed and complete PSR plans are difficult to assess (MILP-strategy [13]). The proposed SRN restoration tool is able to compute the total restoration time and provide detailed restoration steps, facilitating the GRMs-based installation strategy of additional BS capability.

IEEE RTS 24-bus test system is used in the case study, as shown in Fig. 6 [19].

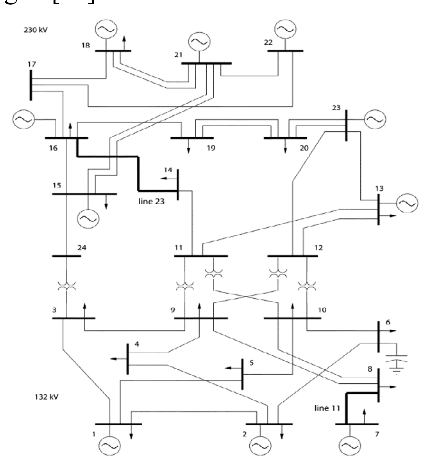

Fig. 6. IEEE RTS 24-Bus test system

In this system, there are one black-start unit (BSU) and nine non-black-start units (NBSUs). Based on the generation data in PECO system [10], the characteristics of all generators are shown in Table I.

TABLE I
GENERATOR CHARACTERISTICS

Bus	BS/NBS	T_{ctp} (min)	T_{cmin} (hr)	T_{cmax} (hr)	R_r (MW/hr)	P_{start} (MW)	P_{max} (MW)
22	BS	0	0	/	138	0	138
21	NBS	30	0	/	120	6.6	300
18	NBS	30	0	/	346	13.2	660
16	NBS	100	0	/	157	12	600
15	NBS	120	0	/	150	30	252
13	NBS	160	0	/	30	2.7	135
23	NBS	100	0	3.3	120	6	300
07	NBS	120	0	3.5	100	9	300
02	NBS	30	0	4	148	12	345
01	NBS	0	0	/	120	0	302

In the base case, the time to energize each branch or transformer (GRA3) is set at 2 minutes. Using the SRN tool, the time to restore all the generators is:

$$T_{restore} = 36 \text{ (mins)}$$

The steps to restore all the generators are shown in Table II.

TABLE II
SEQUENCE OF RESTORATION ACTIONS

Restoration Action	Time(min.)	Path
Restart BSU at Bus 22	0	-
Crank NBSU at Bus 18	12	22-17-18
Pick up critical loads at 19	12	17-16-19
Pick up critical loads at Bus 14	12	16-14
Crank NBSU at Bus 15	20	22-21-15
Pick up critical loads at Bus 9	20	14-11-9
Crank NBSU at Bus 16	20	
Crank NBSU at Bus 2	22	9-4-2
Crank NBSU at Bus 7	26	9-8-7
Crank NBSU at Bus 21	26	
Crank NBSU at Bus 23	30	19-20-23
Crank NBSU at Bus 13	32	11-13
Crank NBSU at Bus 1	36	11-10-5-1

A. Study 1: Install New BS Generating Units at Bus 22

If a new BS generating unit is installed at Bus 22, which is the same with the current BSU, the benefit of installing this new BSU will be analyzed using the SRN tool. The system now has two BSUs and nine NBSUs. The time to restore all the generators is:

$$T_{restore} = 28 \text{ (mins)}$$

Different restoration actions compared with the base case are shown in Table III.

TABLE III
DIFFERENT RESTORATION ACTIONS COMPARED WITH BASE CASE

Restoration Action	Time(min.)	Path
Restart BSU at Bus 22	0	-
Crank NBSU at Bus 15	8	22-21-15
Pick up critical loads at Bus 19	8	22-17-16-19
Pick up critical loads at Bus 14	8	16-14
Crank NBSU at Bus 18	12	17-18

After increasing BS capability at Bus 22, it provides more cranking power to first start NBSU at Bus 15 and then to crank NBSU at Bus 18, both at earlier times than in the base case. Compared with NBSU at Bus 18, NBSU at Bus 15 requires more cranking power but has a higher ramping rate and generation capacity. With the help of additional BS capability, it is started at an earlier time and helps to start other NBS generating units. It is shown that the installation of additional BS generators can benefit system restoration by shortening the total restoration time.

By gradually increasing the total BS capability at Bus 22, the SRN tool is used to calculate the restoration time. The comparison of restoration times under different BS capability is shown in Fig. 7.

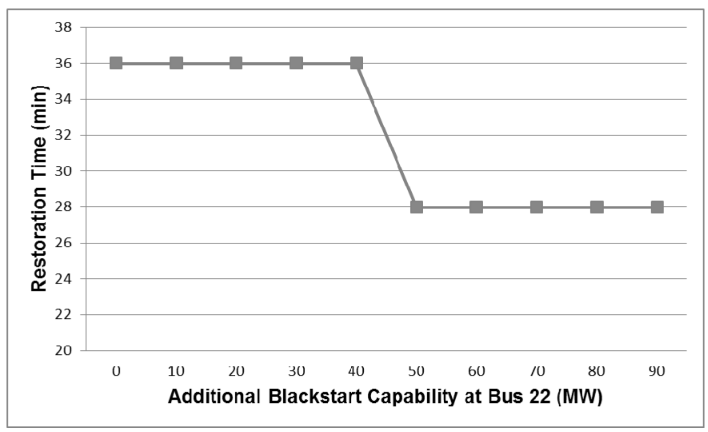

Fig. 7. Comparison of restoration times under different BS capabilities at Bus 22

It can be seen that when increasing somewhat the BS capability, the system restoration time will not be reduced. There is a threshold where restoration time is reduced due to the additional BS capability. However, after this threshold, further increase in BS capability will not help to reduce the restoration time. In this case study, the threshold at Bus 22 is to install additional 50 MW BS capabilities to reduce restoration time by 8 minutes, about 20% of the restoration time in the base case. Therefore, when making decisions on installing additional BS units, the benefit analysis needs to be performed to find the optimal capability of additional BS units.

B. Study 2: Install one New BS Generator at Different Buses

With the additional BS generators, system restoration steps will change. At different installation locations, the new restoration strategy can be established using GRMs-based restoration tool. In this study, one new BSU, same with the BSU at Bus 22, is installed at different buses. The times to restore all the generators are shown in Fig. 8.

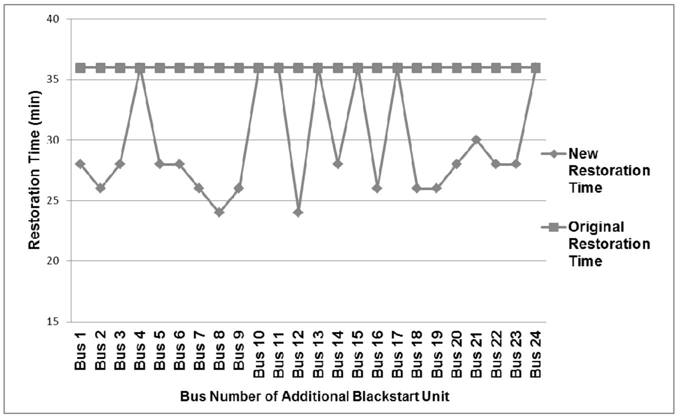

Fig. 8. Comparison of restoration times of installing one new BSU at different buses

From the comparison, it is shown that after installing one new BS generating unit at different buses, some benefit from the additional BS capability to reduce the restoration time, while others have the same restoration time. In this case study, the optimal locations for installing a new BS generating unit are Bus 8 and Bus 12. The restoration steps of installing an additional BS generating unit at Bus 8 are shown in Table IV. Compared with the restoration steps by increasing BS capability at Bus 22, NBSU at Bus 7 and Bus 21 are started earlier, which brings a shorter restoration time.

TABLE IV
SEQUENCE OF RESTORATION ACTIONS

Restoration Action	Time(min.)	Path
Restart BSU at Bus 22	0	-
Restart BSU at Bus 8	0	-
Crank NBSU at Bus 15	6	22-21-15
Pick up critical loads at 19	6	22-17-16-19
Pick up critical loads at Bus 14	6	16-14
Pick up critical loads at Bus 9	6	14-11-9
Crank NBSU at Bus 18	12	17-18
Crank NBSU at Bus 16	12	17-16
Crank NBSU at Bus 2	14	9-4-2
Crank NBSU at Bus 7	14	9-8-7
Crank NBSU at Bus 21	14	
Crank NBSU at Bus 23	18	19-20-23
Crank NBSU at Bus 13	20	11-13
Crank NBSU at Bus 1	24	11-10-5-1

C. Study 3: Optimal Installation Strategy of Additional BS Capability

The installation of additional BS generating unit does not automatically benefit system restoration. In the previous study 1 and 2, it is shown that when installing new BS generators, both the location and amount of BS capability need to be decided to achieve an optimal installation strategy. In this study, the developed GRMs-based algorithm is utilized to calculate the optimal installation location and amount. Increasing the amount of additional BS capability at each bus, the restoration times are obtained.

The comparisons of restoration times are shown in Fig. 9. It is seen that after installing new BS generating units, the restoration time decreases in most cases, while it remains the same for some buses. For each situation with reduced restoration time, there is one threshold beyond that restoration time reaches the minimum value. However, for some buses, such as Bus 2 and Bus 16, there are multiple break points. They provide multiple choices for increasing BS capability to reduce the restoration time.

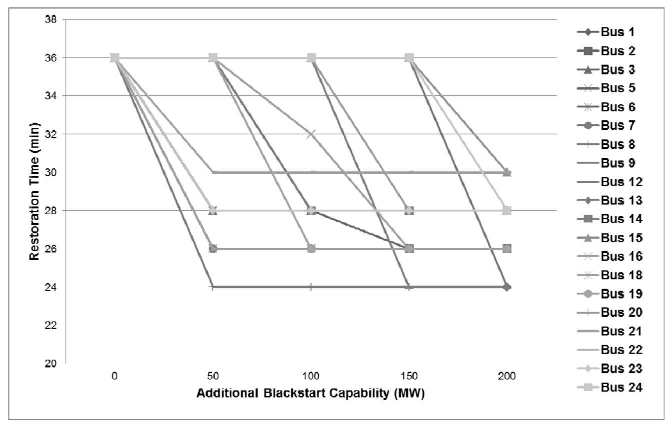

Fig. 9. Comparison of restoration times at different buses with additional BS capability

However, the optimal installation strategy of additional BS capability needs to consider both the reduced restoration time and installed BS capability. The comparisons are shown in Fig. 10.

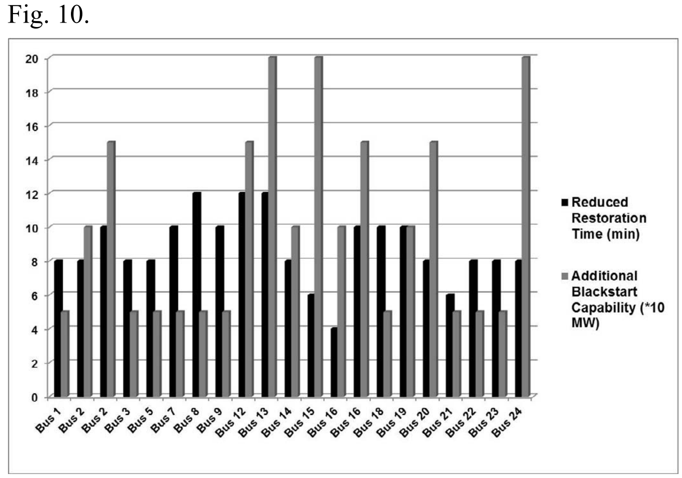

Fig. 10. Comparison of reduced restoration time and installed BS capability at each bus

By installing 50 MW additional BS capabilities at Bus 8, the restoration time is reduced by 12 minutes. By installing 100 MW additional BS capabilities at Bus 18, the restoration time is reduced by 10 minutes. By installing 150 MW additional BS capabilities at Bus 12, the restoration time is down by 12 minutes. By installing 200 MW additional BS capabilities at Bus 13, the restoration time is down by 12 minutes. Therefore, in this system, the optimal installation strategy is to install additional 50 MW BS generating unit at Bus 8 to reduce restoration time by 12 minutes, or 33% of the restoration time in the base case.

V. Conclusions

A restoration time based BS capability assessment methodology is proposed in this paper. BS capability assessment is an important task; it is highly system dependent and lacks universal solutions. The proposed methodology provides a systematic way to assess the optimal installation location and amount of BS capability by utilizing the decision support tool to evaluate system restoration time.

This study shows that by increasing BS capability, power system can benefit by reducing system restoration time. However, there is a threshold beyond which system restoration time can no longer be reduced from additional BS capability. Each bus has a different threshold. The benefit analysis of new BS generators is conducted utilizing the SRN restoration tool. The algorithm will be extended based on the optimization tools in the future work.

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VII. Biographies

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