

# Graph Decomposition for Constructing Blackstart Restoration Strategies in Benchmark Cases

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**Abstract**—This paper describes methods for constructing benchmark cases and solution strategies related to restoring an electric grid model from a blackstart condition. Existing public cases for grid restoration problems are limited in size and scope—this paper delineates the features required to create new synthetic, detailed datasets for this purpose. As part of validating these datasets, benchmark results are included for an electric grid restoration strategy based on a formulation of the restoration problem as a time sequence of ac power flow solutions. The algorithm produces a benchmark restoration sequence for an example 200-bus case, showing how critical loads can be restored within 45 minutes, the majority of the grid within 6 hours, and all loads within 36 hours. At the core of the solution strategy is a directed graph decomposition heuristic, as the algorithm builds a bus energization spanning forest. Because these datasets are built synthetically, they can have a high degree of realism in features such as geographic coordinates and modeling complexities, while avoiding concerns of data confidentiality, meaning that the data produced in this work can be made publicly available for the benefit of the research community.

**Index Terms**—Synthetic power grids, blackstart, power system restoration, complex networks, graph decomposition

## I. INTRODUCTION

The power grid is designed to deliver electric energy reliably and continuously every day of the year, but, in the event of a full or partial system blackout, it is critical that restoration strategies and tools be in place to minimize outage time and restore ordinary operation as safely and effectively as possible. By standard (for example, NERC emergency operations standard EOP-005 [1] in the USA and Canada), many transmission grid operators and reliability coordinators are required to prepare restoration plans. Because of the complexity of the problem and the rarity and uncertainty of actual extreme event scenarios, there has for several decades been an active research effort to improve techniques for automatic grid restoration, [2]–[6]. Some key recent developments are associated with selecting strategic priorities [7]–[9], identifying topological island partitions and cranking paths [10], [11], and optimally ordering the restoration actions [12]–[15].

A continued challenge in this area is to test and validate restoration frameworks and algorithms on realistic test cases.

Due to security concerns, much actual electric grid information is not public. And for detailed restoration plans of actual power networks, data confidentiality is even more pronounced. Smaller test cases are typically used for initial research testing, mostly modified from standard IEEE test cases [16], [17]. Recently, large-scale synthetic electric grids—fictitious test cases built by network generating algorithms—are helping to address the challenge of data availability for power system research [18]–[20].

This paper focuses on constructing and benchmarking public, synthetic test cases for blackstart restoration scenario modeling. The methodology described here uses base synthetic electric grid networks built with the process of [20] and augments them with the appropriate, realistic additional data to facilitate modeling restoration scenarios under a variety of conditions. Then the datasets and scenarios are validated using a restoration planning algorithm to evaluate the realism and performance under blackstart simulation, leading to benchmarked restoration profiles that can be compared against literature- and industry-based typical results.

There is substantial prior work on restoration modeling and planning, with Section II.A providing an overview of key aspects. Specific work on data requirements and validation of test cases for this problem are quite limited. Many prior studies use modified IEEE test cases, for example, [4], [12], [13], [21]. Others use actual industry cases [10], [22], which are very important for ensuring proposed strategies work, but these datasets typically cannot be released for cross-validation purposes. Two studies [9], [14] have used larger synthetic grids for demonstration, with some augmented data. The present work builds on all of these by focusing on the datasets themselves, specific modeling parameters, and the validation process.

## II. POWER SYSTEM RESTORATION MODELING

### A. Background

Electric grid restoration starts with a power system in an abnormal, degraded state following some inciting, detrimental event. Such an event could include extreme weather, other natural disasters, cascading failure, voltage collapse, outages due to cyber or physical security, or a combination of multiple causes [6]. The degraded state may involve at least some load being unserved, portions of the transmission system

deenergized, and multiple generating units tripped offline. This paper is primarily concerned with blackout scenarios, in which the entire system becomes deenergized. The purpose of restoration is to find a sequence of actions that will return the system from a degraded state towards normal operations.

Before any restorative actions take place, an initial challenge is that there may be degradation to communications, monitoring, and analysis systems such as SCADA and the EMS. If these systems are not available it may take some time before enough of the actual state of the system is known to implement a restoration plan [3], [23]. Depending on the nature of the inciting event, it may be that some devices have been damaged. This potential for line, transformer, or generator non-availability underscores the need for flexibility and multiple options in developed restoration plans.

A typical design of a restoration plan starts by identifying *restoration milestones*. There are a number of strategies that depend on the nature of the system [3], [4]. Most generating units require auxiliary power to start up. Under blackout conditions, initial milestones will be associated with *black-start units*, generators specifically configured to have onsite resources sufficient to start without any external power [24]. Some loads are considered *critical loads*, like hospitals, first responders, military installations, nuclear station service, and natural gas pumping [23]. Another key milestone is providing the auxiliary power to start up (crank) non-blackstart generating units. The transmission corridor from an energized bus (such as at a blackstart unit) to a generator targeted for the next startup is known as the *cranking path*.

Another milestone is energizing the main high-voltage transmission backbone, particularly if connecting with an energized neighboring area is feasible. For certain systems or areas, building the transmission backbone is an early priority. For most systems, though, the strategy involves multiple islands that operate independently for the initial stages of restoration. This parallel strategy involves adding load and generation to segmented parts of the network and then uniting them through a synchronization process [23]. Some recent papers have proposed analytical techniques for segmenting a system to enhance the process [10], [11].

In any restoration effort, the overall goal is to return to normal operations, and time is of the essence. Generators are constrained by how much time it takes to put them back online after a shutdown, so an incorrect ordering could delay generation capacity by many hours. Furthermore, as loads and generators remain out of service, their characteristics change. Loads, especially with cooling or heating functions, may increase their demand with outage time, and generators which are too long out of service may move from a hot-start condition to a warm- or cold-start condition [4].

The actions taken as part of an electric grid restoration plan include line and transformer switching, load pickup, generator cranking, and island synchronization. When starting a large system from blackout, many thousands of these actions need to be taken. The ordering and timing of these actions are at the center of typical restoration planning [7]–[9], [12]–[14].

The extensive technical challenges involved in designing, optimizing, and evaluating electric grid restoration plans are part of what make this an exciting and important ongoing research area. They also show why realistic, detailed test cases have great potential to drive innovation in this area, particularly given the sensitivity of publishing actual system data.

## B. Model Formulation

Synthetic test cases developed using the methodology of this paper are designed to be applicable to a variety of restoration-related studies, recognizing that the problem can be formulated in a number of different ways. This section gives one such formulation, which captures the main considerations for steady-state modeling and can easily be further augmented with additional complexities.

The formulation begins with a series of steady-state ac power flow snapshots indexed by  $t$  and separated by some time interval  $\Delta t$ , similar to [13], [21]. Because this formulation is making steady-state power flow assumptions, it is expected that  $\Delta t$  will be at least 5 minutes. The core of the formulation is the balance of complex power at each bus indexed by  $i$ ,

$$\sum_j s_{ijt} = (p_{Lit} + jq_{Lit}) - (p_{Git} + jq_{Git}) \quad (1)$$

where, at time  $t$ , variables  $p_{Lit}$ ,  $q_{Lit}$ ,  $p_{Git}$ , and  $q_{Lit}$  are the active (real) and reactive power for the load and generation at bus  $i$ , respectively, and  $s_{ijt}$  is the complex power entering branch  $ij$  from bus  $i$  to bus  $j$ , defined as

$$s_{ijt} = x_{Bijt} \cdot (|v_{it}|^2 y_{ii}^* - v_{it} v_{jt}^* y_{ij}^*) \quad (2)$$

with  $v_{it}$  as the complex voltage at bus  $i$  and  $y_{ii}$  and  $y_{ij}$  as the standard complex admittance parameters for the branch. The binary variable  $x_{Bijt} \in \{0, 1\}$  gives the state of branch  $ij$  at time  $t$ .

Both the bus voltage magnitudes and branch complex power magnitudes have limits.

$$v_{min} \leq |v_{it}| \leq v_{max} \quad (3)$$

$$|s_{ijt}| \leq s_{ij,max} \quad (4)$$

The loads can be switched in and out using the variable  $x_{Lit} \in \{0, 1\}$  based on the specified demand  $p_{SetLi}$  and  $q_{SetLi}$ . In more advanced formulations,  $p_{SetLi}$  and  $q_{SetLi}$  might also depend on both time and the prior state  $x_{Lit}$ , considering the change in demand over time and cold load pickup characteristics.

$$(p_{Lit} + jq_{Lit}) = x_{Lit} \cdot (p_{SetLi} + jq_{SetLi}) \quad (5)$$

Generators have a more complicated state  $x_{Git} \in \{0, 1, 2\}$ , where 0 is not yet cranked, 1 is started cranking, and 2 is fully cranked [5].

For any generator with  $x_{Git} = 0$ ,

$$p_{git} = q_{git} = 0 \quad (6)$$

For any generator with  $x_{Git} = 1$ ,

$$p_{git} = -p_{gi,crank} \quad (7)$$

$$q_{git} = -q_{gi,crank} \quad (8)$$

with  $p_{gi,crank}$  and  $q_{gi,crank}$  being the active and reactive power required for cranking the generator. For any generator with  $x_{Git} = 2$ , the generator is limited by the machine limits ( $p_{gi,min}$ ,  $p_{gi,max}$ ,  $q_{gi,min}$ , and  $q_{gi,max}$ ), the prior power setpoint  $p_{gi,t-1}$  and the ramp rate  $r_{gi}$ .

$$p_{git} \geq \min(p_{gi,t-1}, \max(p_{gi,min}, p_{gi,t-1} - \Delta t \cdot r_{gi})) \quad (9)$$

$$p_{git} \leq \min(p_{gi,max}, p_{gi,t-1} + \Delta t \cdot r_{gi}) \quad (10)$$

$$q_{gi,min} \leq q_{git} \leq q_{gi,max} \quad (11)$$

Load and branch states  $x_{Bit}$  and  $x_{Lit}$  are allowed to change at each time step freely. Generator states  $x_{Git}$  can change from 0 to 1 at any point and from 2 to 0 at any point. The transition from 1 to 2 can occur after the generator has been in state 1 for a time greater than or equal to the cranking time,  $t_{Gi,crank}$ .

The set of equations given in (1)–(11) must be valid for every time step  $t$  and every bus  $i$ . The cost of the overall solution  $C$  is measured according to load served throughout the time series,

$$C = \sum_t \sum_i (1 - x_{Lit}) c_{Li} \quad (12)$$

where the load at bus  $i$  has a value of  $c_{Li}$  per time point. This need not be specified in monetary units, although it may. Its function is to convey that loads may have different priority levels for restoration. Generator costs are usually not considered in power system restoration scenarios.

Together this model can be viewed as an optimization problem with objective  $\min(C)$  subject to the constraints of (1)–(11). An additional constraint that makes this a *restoration scenario* is that the value of all variables at  $t = 0$  are given as an input, with most or all of the  $x$  values set to 0. In addition to this, there may be some devices for which  $x$  is fixed to 0 for all values of  $t$ , because they have longer-term damage and are not available for use in restoration. Note that if all the  $x$  variables are 0 throughout time, there is a trivially feasible solution that amounts to leaving the system in outaged condition without doing any restoration. It is a nonlinear and nonconvex problem with mixed real and integer variables. The number of variables will scale linearly both with the number of buses and the number of time points.

### III. CONSTRUCTING SYNTHETIC DATASETS FOR RESTORATION STUDIES

This section outlines how datasets can be created for blackstart restoration scenarios. The objective is to create cases systematically, with an emphasis on statistical methods that can avoid having to individually design each component.

The validation of the case will involve two parts (see [18], [20] for more details on synthetic grid data validation). The first part is individual parameter validation. This process is discussed in this section in parallel with the dataset creation. It

involves comparing synthetic data to data from public sources, industry reports, and literature studies. The parameters set must be reasonable according to expected distributions.

The second aspect of the validation has to do with operational performance of the overall system. This is done by applying the model described in the prior section with a simulation framework. Validation results from this process are given in the remaining two sections of this paper. The idea with this validation task is that the system performance metrics should follow expected performance of the system, as compared to other restoration metrics obtained from literature and industry reports.

#### A. Example System

The methods described here are demonstrated by developing a 200-bus synthetic test case. Fig. 1 shows an overview of this system. The power flow topology and base power flow case have been previously created, with details about the creation and validation process given in [18]. As a synthetic test case, it does not model any actual grid. The goal is to obtain realistic performance from the model while remaining separate from any real data. The version built for this paper, including all restoration parameters and benchmark results, is available online [17]. There are 49 generating units of varying fuel types. The system serves 2100 MW of peak load through a 115/230 kV transmission grid. The system is organized into six zones and 111 substations. All system equipment in the model is geographically mapped.

#### B. Loads

Power flow modeling of loads will often have only a single load value associated with each substation. This is no different with the example 200-bus case, with several buses having a single 50-100 MW load block. While there may be some loads that need to be switched on in blocks that large, typically there is a higher level of granularity in the control of load restoration. Load switching is a discrete variable, but the granularity is higher than typical power flow datasets indicate. So for this analysis the base load blocks were broken up into smaller blocks that represent the more reasonable size of the lowest level of granularity accessible by transmission operators, which is usually a single distribution feeder or industrial customer. Based on statistical data from [25], loads were divided into blocks that ranged in size up to 20 MW (see Fig. 2). For the example test case, there are a total of 300 load blocks.

Additional parameters for load include its benefit (priority)  $c_{Li}$  and availability. Following normal practice, a small number (5 in the example, marked in Fig. 1) of loads are designated as critical with  $c_{Li} = 1000$  and the rest as non-critical with  $c_{Li} = 10$  (for a subset of slightly more important loads) or  $c_{Li} = 1$ . Critical loads were selected in coordination with the blackstart units [23].

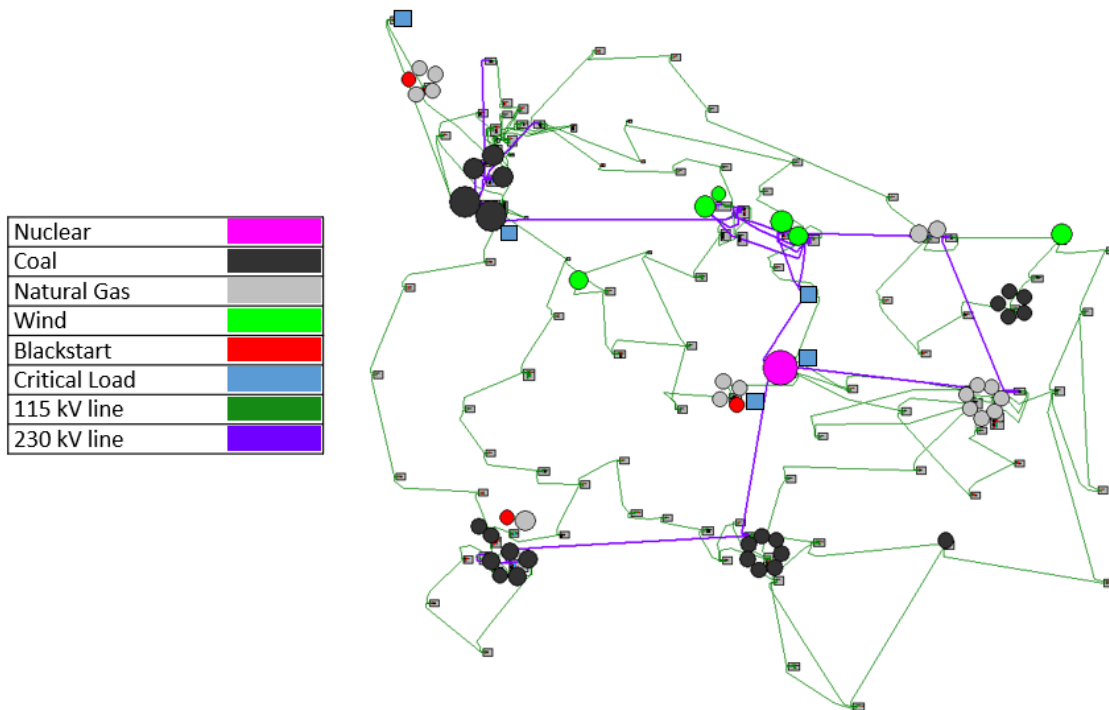


Fig. 1. Oneline diagram of the 200-bus test case. Circles show generators and rectangles show loads. The generators are color-coded according to fuel type and sized relative to maximum MW output. Blackstart units and critical loads are highlighted as indicated in the legend.

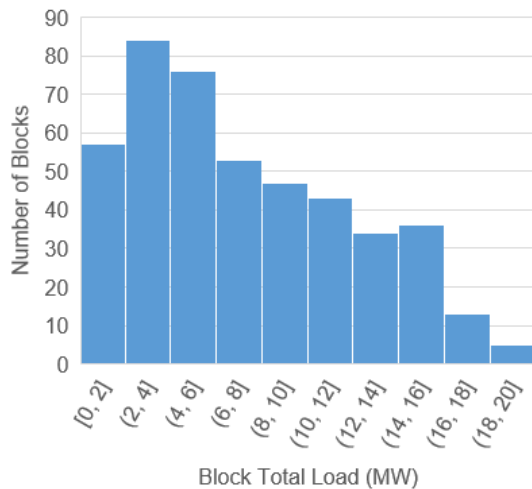


Fig. 2. Histogram of load block size from [25].

### C. Hydro and Thermal Generators

For system restoration according to the model given above, generators must be characterized by a cranking power  $p_{gi,crank}$ , a cranking time  $t_{Gi,crank}$ , and a ramp rate  $r_{gi}$ .

A blackstart unit would be identified by  $p_{gi,crank} = 0$ , meaning that it can be started with a non-energized bus at the first time point. Blackstart units are essentially all hydro and natural gas plants [26]. As one indication of the number of blackstart units to have, industry reports indicate 14 blackstart units for a system with about 700 total units, and 74000 MW

TABLE I  
GENERATOR PARAMETER RANGES BY FUEL TYPE, AGGREGATED FROM LITERATURE AND INDUSTRY REPORTS.

Generator Type	$p_{gi,crank}$ (% of capacity)	$t_{Gi,crank}$ (minutes)	$r_{gi}$ (% of capacity/min)
Hydro	0-1	0-60	10-30
Fast natural gas	0-5	0-90	10-30
Slower natural gas	3-8	60-480	5-15
Faster coal	5-10	60-240	0.2-5
Slow coal	5-10	240-960	0.1-0.5
Nuclear	5-10	1440-2880	0.1-1.0
Wind	2-4	30-90	10-30
Solar	2-4	10-20	10-30

of peak demand, or about 2% of total units and one per 5000 MW [24]. This 200-bus system is initialized with three blackstart units, which is on the high end for realistic systems, but serves to demonstrate multiple island restoration schemes. The three units are selected among the small natural gas units.

The parameters for other thermal and hydro generators are based on statistics collected from EIA-860 [27] reports and data given in [6], [26], and [28], which have been checked to be generally consistent with other studies. The ranges designated for validating the data in the example cases are given in Table I.

### D. Nuclear, Wind, and Solar Generators

Nuclear generator are normally not used in early stages of system restoration [6]. This is because they require reliable

external power supply to safely start up and they take 24 hours or longer to start up. However, during later stages of restoration, when the network is stable and the last loads are coming online, they may become involved.

Wind and solar plants, having variability in their production capability, are not included in early stages of system restoration [7]. So normally they would be set to “not available” in a restoration scenario. However, recent research has suggested that some wind resources might have capability to aid in restoration in the future [21] with appropriate consideration of the stochastic nature of the resource. Hence these units are still included with parameters in the case (with availability 0% by default).

Nuclear, wind, and solar typical parameters are given in Table I and in the example dataset, recognizing that for many studies they will not be included.

#### E. Scenario-Specific Parameters

A distinction in these datasets is made between the grid-specific parameters and scenario-specific parameters. The main scenario-specific parameter is whether a given power system asset is available to use in restoration. In this way, scenarios can be set up with varying levels of availability, representing ideal and highly constrained restoration problems.

#### F. Transient Dynamics Modeling

The various switching actions, cold load pickup, and generator cranking must be done in a way that ensures stable transient behavior of the system. Sometimes this is approximated through additional steady-state constraints, such as constraints on the angle differences across a closing line [12]. Full analysis requires modeling of generator and load dynamics. For this case, existing stability dynamics models have been created according to the methodology of [19]. These models include generator machine models, generator exciters, and turbine governors for the major generating units. These dynamic models can provide the starting point for more detailed transient switching action validation, including, for example, frequency constraints.

### IV. BLACKSTART RESTORATION SOLUTION ALGORITHM

To support the validation of the cases, a computationally-efficient blackstart restoration solution algorithm is described here. Its overall strategy is designed to mimic the milestone-based planning approach, to build up islands and correctly prioritize restoring loads and cranking generators in order to minimize the total cost of load outages.

#### A. Graph Decomposition

The first stage of the algorithm is to decompose the network graph into islands. This is done using multiple parallel breadth-first searches to form a spanning forest rooted at the blackstart units. The goal is that each bus is rooted through a path to the electrically nearest blackstart unit. In this case, electrical closeness is measured by total branch capacitive shunt susceptance  $B$ . This is because, in the early stages of restoration, voltage

regulation due to branch capacitance is of key concern. In more advanced formulations, additional considerations could be taken, such as the size of the overall island.

The decomposition works by processing a priority queue of branches. At the beginning, only the root blackstart unit buses have been visited, and all branches connected to these are enqueued by their  $B$  value. When a branch is processed, the opposite bus, if unvisited, is added to the tree. Each of the new bus’s outgoing branches is enqueued by the  $B$  value added to the value of the return branch. In this way the  $B$  values add as the search expands from the root. If a dequeued branch’s opposite bus has already been visited and has the same root bus (a loop), this is marked as an intra-island additional transmission branch. It can be used to strengthen the transmission system but will not be used for initial bus energization. If a dequeued branch’s opposite bus has already been visited and has a different root bus, this is marked as a tie-line between islands. It will not be energized until the two islands are being synchronized.

When the decomposition is complete, there will be a bus energization spanning forest: each bus will be connected to a tree rooted at a blackstart unit, with the minimal line capacitance needed to energize it. The branches not part of the forest will be grouped into intra-island transmission support and island tie-lines. This decomposition will form the framework for the restoration strategy.

#### B. Target Selection

Next, the algorithm lists and prioritizes restoration targets, or milestones. The targets are the set of available loads and generators. Each one is classified by its priority, with critical loads coming first, followed by generators, followed by other loads. Ties in the priority ordering are based on the sum of real and reactive power required to energize the target. That would be the cranking power for a generator or the load power for a load, plus the total reactive power that would be generated by the lines along the energization path from the root. This ordering is not necessarily the order in which they will be restored, but the order in which they would be restored except for limiting constraints, considered in the next stage.

#### C. Action Selection

Finally, the full power flow solution is solved iteratively and restoration actions are chosen. At each iteration, one of the islands is given the opportunity to take an action. If it does, a new power flow is solved and the island chooses a next action. If an island decides it cannot take an action at this time, the next island is given the same opportunity. Finally, when all the islands are finished, time advances by 5 minutes, allowing generators to crank and ramp.

An island’s action choice is based on the restoration targets, which it considers in order. Load targets are skipped unless there is sufficient reserve generation, both immediately and in terms of the total capacity that has begun cranking. No loads are added if generator reactive power reserves are too low. Both loads and generators are skipped if negative reactive

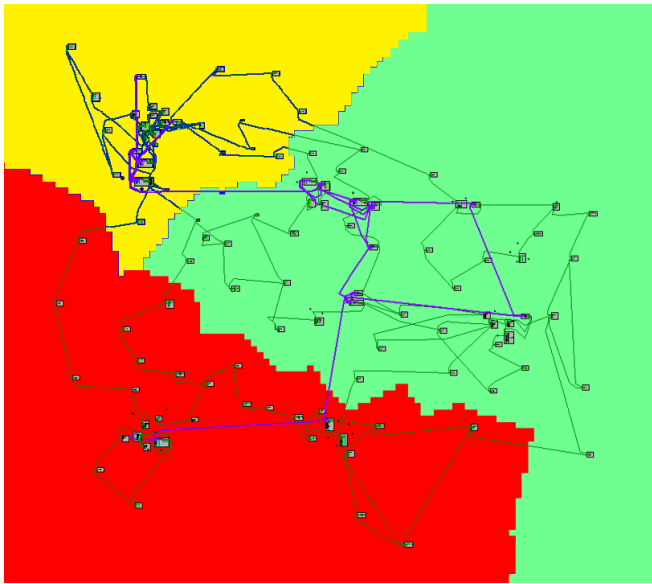


Fig. 3. Three areas resulting from the graph decomposition algorithm for 200-bus case.

power reserves are too low to handle the capacitive loading of the required energization path. If sufficient capacity is not available now, but it will be soon, the island does not skip to other targets; it simply declines to act. If the island does decide to pursue a target, it defines the actions along the energization path to close transmission facilities and executes the items in sequence. Finally, the intra-island branches are added when there are sufficient reactive reserves, to strengthen the voltage stability of the network. These actions proceed until the time limit is met or all load is served.

## V. VALIDATING THE EXAMPLE CASE

The blackstart restoration solution algorithm described in the prior section was applied to find a benchmark solution to the restoration problem for the synthetic case. This section describes the performance metrics and the simulation results.

With three blackstart units, the graph decomposition step divides the network into three islands, as shown in Fig. 3. The island shown in blue contains two critical loads and five large, slow-starting coal-fired unit. The island in green includes three critical loads (one to ensure proper shutdown of the nuclear unit). The island in red has the largest blackstart unit and the largest number of total generation units, mainly small- to moderately-sized coal generators.

The target selection and action phases of the algorithm proceed through the iterative power flow, using commercial simulation tool PowerWorld Simulator. At each time point, all the constraints are checked from the formulation in Section II.B. The solution produced by this algorithm was feasible in that it met the constraints. (Fig. 4 shows the voltage profile through the simulation.) It was also successful in that it terminated with all of the system load restored. The total objective value was 488,605. Of this, 115,000 was from the

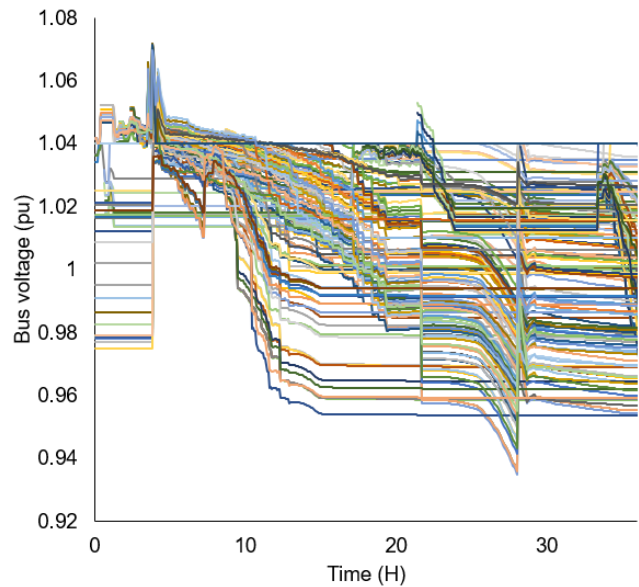


Fig. 4. Plot of all bus voltages through the restoration process.

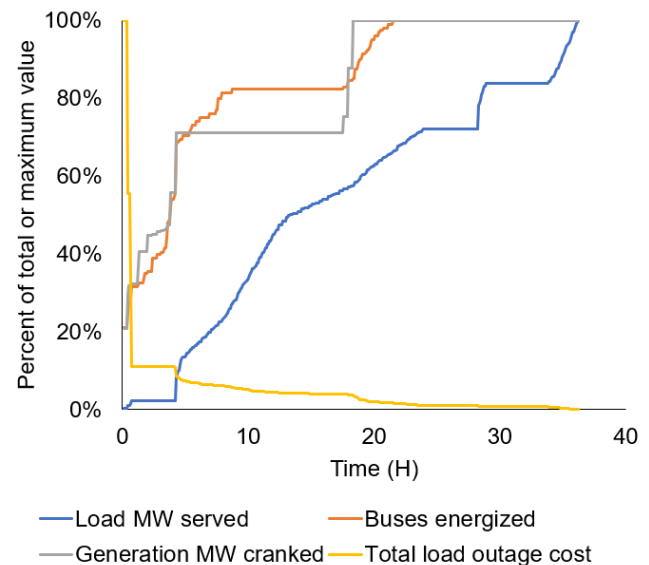


Fig. 5. Energization curves for validation of 200-bus test case.

5 critical loads valued at 1000 per minute, and the rest from non-critical loads at 10 or 1 per minute.

Fig. 5 presents the progression of the restoration process through the simulation. This data is used to validate both the scenario and the algorithm, by comparing with expected values from practical restoration problems.

First, the restoration of critical loads happens in 45 minutes. This can be seen in Fig. 5 by the sharp drop in the yellow trace, such that the total outage cost drops to 10% of its maximum value. Reference [4] says the damage from unserved load can increase exponentially with time. It should be noted that  $t = 0$  for this scenario is the moment at which the blackstart unit has been started.

In this scenario, the time to energize most of the transmis-

sion grid is about six hours. By the end of the fourth hour, several of the faster coal plants in the red island have cranked, so the transmission in that island can be largely energized, with load added regularly as the units ramp up. The green island likewise has several units operating by this point. The blue island is slower to energize the transmission system because the first few generators are used to supply the critical loads in this area and begin the cranking process for slow-start, large coal plants needed for later in the restoration. A similar metric is the time to restore 50% of the load, which for this scenario is about 12 hours. Reference [23] discusses a timeframe of 7-16 hours for most of the transmission grid to be restored, and simulated scenarios for industry training sessions in [29] involved about half the system load served by hour 13.

The time for full restoration was 36 hours, as can be seen in Fig. 5. The last set of load requires the second large coal unit to be cranked and ramp up so that there can be sufficient energy reserves. Reference [3] suggests 90% of the load to be restored in 6 hours as a goal, but this may be with assistance from neighboring transmission. Data reported from simulation in [29] suggests about 32 hours to full system restoration for that particular study.

## VI. SUMMARY

This paper presents a methodology to build and validate synthetic datasets for blackstart restoration scenarios. It delineates dataset feature requirements to be adequate for restoration studies and assembles test case datasets from synthetic base power flow cases, with restoration parameters gathered and validated from available public resources. Lastly, the paper presents a heuristic feasible strategy for solving the restoration problem based on directed graph decomposition. The purpose is both to provide a benchmark solution to the synthetic scenario case, and to validate the dataset overall against actual energization profiles. All of this is demonstrated on a geographically-embedded, realistic 200-bus test case for which all data is publicly available [17] including a benchmark restoration plan action sequence and associated time series simulation data.

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