Robust Online Simulation Framework for Grid Restoration Under Loss of SCADA

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Abstract—Secure and fast grid restoration from a collapsed state is increasingly critical as blackouts are becoming a common occurrence around the globe. Generally, the restoration of grid during a blackout is achieved with the help of Supervisory Control and Data Acquisition System (SCADA) based central control; however, with the threat of cyber-blackouts, this presumption of an available and secure SCADA system is not valid. This is also true for grids in developing countries as well as for many distribution grids that lack SCADA. In this paper, we introduce an online framework for localized grid restoration that validates and updates a pre-defined crank path in real-time based on the vital grid states of voltages, currents and frequency. The proposed framework maintains an online network topology of the localized grid that can continuously sample measurements and update the grid model, thereby circumventing SCADA based central control. In the results section we demonstrate the efficacy of this framework for black start by ensuring a feasible crank path with voltage and frequency within bounds, while further assisting in synchronization of two disconnected sub-grids during the re-energization process.

Index Terms—blackstart, collapsed grid, cyber-attack, frequency modeling, grid restoration.

I. INTRODUCTION
Blackouts have become prevalent threats around the world in both countries with developed grids as well as countries with fragile grids. In strong central grids, the advent of cyber-attacks, equipment failures, extreme weather as well as increased renewable penetration have escalated the occurrences of these blackouts [1]. Similarly, in case of fragile grids, the stability challenges have resulted in large volume of rolling blackouts [3]. In most instances, grid restoration following such blackouts is driven by SCADA-driven central control. However, recently, the likelihood of blackouts due to a new class of cyber-based attacks has emerged [2]. During such events, centralized SCADA and Energy Management Systems (EMS) based control may become inoperable or even worse, compromised such that existing processes for grid restoration may not work, thereby requiring manual engineering intervention. Likewise, developing fragile grids [3] and smaller distribution grids without a centralized SCADA control rely on experienced engineers to restore power as well.

Critical resources in the grid such as hospitals, military installations and transport systems may see delayed energization times under loss or unavailability of central SCADA based control. Therefore, there is a need for an online localized framework for secure and fast re-energization of such resources. Restoration is generally devised into numerous stages of turning certain buses, generators and network elements, known as crank path steps. In it, for each incremental crank step, the system stability should be maintained by ensuring that vital health states (i.e. voltage, currents, and frequency) of the system are within bounds through proper matching of load and generation. If found otherwise, corrective actions must be recommended to achieve that goal. For larger interconnected transmission networks, it is a followed practice to validate system performance during blackout through off-line planning analysis. However, for critical localized grids during an actual event, the analyzed crank path may not be feasible due to loss of equipment, thereby requiring an on-line analysis framework.

An online or offline analysis tool for grid black start must consider various health bases of the grid while assisting in its restoration. The most critical amongst these are the voltages, currents, and frequency. Existing simulation-based frameworks for assisting black start often lack the representation of physical characteristics of the grid. For instance, [4]-[7] considers loss-less networks or uses DC approximations to represent the network flows in the line that assumes a constant or approximate voltage characteristic, and almost all of the steady-state methodologies [4],[8]-[9] do not consider the impact of frequency. Frequency is an important variable to model while simulating grid failure modes. For instance, consider a recent power failure in the U.K. grid due to an N-2 contingency, where five percent of the system load was dropped by an automatic under-frequency load shedding (UFLS) scheme that actuated at 48.8 Hz [10]. A steady-state simulation framework without frequency as a variable will not able to accurately simulate this event. Therefore, a robust framework for black start must account for accurate representation of voltage and frequency states. Any large deviation in these states during a cranking step can result in actuation of under-voltage or under-frequency protective devices, which can cause of collapse of the energized sections, while further delaying the critical grid recovery and increasing the likelihood of damaging the equipment.

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In this paper, we develop a novel online localized framework for grid restoration that can assist in black starting the localized grid under a cyber-attack with compromised SCADA-driven central control or under unavailability of SCADA based control. In the proposed framework, we deploy a novel circuit-theoretic simulation with unified grid analyses and renewables – restoration (SUGAR-R) platform in the critical distributed locations in the grid. The platform maintains an online network topology of the localized grid that continuously samples and synchronizes various classes of measurements within the localized grid and maps them into the system models. Due to the circuit-theoretic approach, the framework allows for sampling and modeling of any physics-based measurements that are available through proliferation of Internet of Things (IOTs) and other sensor networks. Finally, under a black starting event where access to SCADA/EMS based central control is unavailable, the SUGAR-R platform can simulate various “what-if” scenarios to result in robust energization of the grid.

The remainder of the paper is structured as follows; Section II describes the circuit-theoretic components required for modeling and maintaining the online network model of the localized grid sections. Section III describes the optimization-based grid-blackstart framework, while Section IV demonstrates the method to simulate synchronizing islands. Finally, the simulation results are discussed in Section V.

II. EQUIVALENT CIRCUIT FRAMEWORK

A. Steady-State Framework for Evaluation of Grid Black start

Modeling the steady state is sufficient for black start studies, as we can overlook transient behavior such as oscillations. Generally, black start simulations are concerned with the feasibility of each crank path step while ensuring that the frequency and voltages past the immediate transients are within certain bounds. This is fully captured by the steady state of the system. Although dynamic simulation would capture electromechanical transients, it is significantly more computationally intensive and less effective for light-weight online studies. A frequency dependent power flow analysis on the other hand, is proven as an efficient approximation that accurately captures the changes in steady state by including frequency control actions, which is effective in this setting and has been used before in simulating sequential steps such as cascading outages [11].

Nonetheless using a power flow formulation to study the state at each crank path requires a robust steady-state (power flow or three-phase) analysis tool that can clearly distinguish a “hard-to-solve” case from an “infeasible” case. Unlike normal grid analysis, good initial conditions for solving each step of the crank path may be unavailable and a “feasible” solution may not always exist, thereby requiring a steady-state analysis approach that can robustly find a solution from arbitrary initial starting conditions [12]-[13]. The SUGAR approach described in [12], includes options for homotopy algorithms and infeasibility identification [14] within the power flow tool. SUGAR maps the different network models of the grid (e.g. PV, PQ etc.) into their respective equivalent circuits and further aggregates them to create the whole network model to solve for the node voltages and branch currents. This approach has also been previously extended with circuit simulation methods to preserve the physical behavior of the grid elements by avoiding solutions that include low voltages and generators operating in an unstable region [12].

B. Measurement based modeling of grid components

Under a system blackout (especially under loss of SCADA), grid measurements provide vital system information. The ability to capture these measurements to improve the online system model can assist in restoration of the grid while enhancing the applicability of simulation-based actions. Using a circuit-theoretic framework based on voltage and current state variables, allows for direct incorporation of measurements (majority of which are voltages and currents) into the system model without loss of generality.

Newer frameworks have been successful in capturing grid data cheaply and making it available to a common platform [15]. Assuming access to this localized measurement data in a distributed location, we consider creation and maintenance of an online network model. To better capture the physical characteristics of the loads in the system, we first represent the load consumption via using the linear BIG load model [16]-[17] that is shown in Figure 1.

Similar to a ZIP model, but more naturally representing the true sensitivities with respect to voltages across the load, the BIG model is defined by a parallel constant current source ($\alpha R_{BIG}$ + $\beta I_{BIG}$), conductance ($G_{BIG}$) and susceptance ($B_{BIG}$) and whose real and imaginary currents are given by:

$$\left(\begin{array}{c} R_{BIG} + jG_{BIG} \\ \beta_{1}\end{array}\right)$$

and

$$\left(\begin{array}{c} R_{BIG} + jG_{BIG} \\ \beta_{1}\end{array}\right) \left(\begin{array}{c} V_{R_{BIG}} + jV_{I_{BIG}} \\ jB_{BIG}\end{array}\right) = \left(\begin{array}{c} V_{BIG} \\ + jB_{BIG}\end{array}\right)$$

(1)

![Figure 1: BIG Load Model.](image)

![Figure 2: BIG model representation of 12 days for the LBNL data; BIG model is clearly shown to capture the voltage variability of the load characteristics [17].](image)

A BIG load model can be fitted with online streaming measurement data from a large variety of measurement devices (such as the smart meters, remote terminal units, micro phasor...
measurement units and other IOTs) to accurately represent the nominal characteristics of the load while also capturing its voltage sensitivity. Moreover, BIG load circuit models can be aggregated (in parallel) to create larger bulk loads models, without loss of generality, while preserving both nominal as well as the sensitivity behavior of the load.

For instance, Figure 2 [17] represents the comparison between loads currents produced from the fitted BIG load model and those from true measurements using data from a sensor at Lawrence Berkeley National Laboratory (LBNL) [18]. For each time instance that is indicated by the blue line in Figure 2, the BIG load model parameters are updated to capture the variation in load. Not only does the fitted BIG load capture the nominal measured data, but it also models the voltage-sensitive nature of the load currents, as is shown by the red circles in the Figure 2.

Similarly, real-time measurements can also determine and update the real power (P) and voltage (V) setpoints of the PV bus generator model while also updating the branch and switch status to maintain accurate online network model.

C. Governor Power Flow

In order to accurately simulate a black start event, the steady state change in frequency must be modeled to capture the responses of generators, control actions and changes in load. Notably, a large deviation in frequency can actuate protective devices and result in re-collapsed system [10]. Therefore, a frequency variable must be incorporated into the steady state analysis of black start.

To simulate the steady state change of frequency, we build upon previous work [19], to integrate a frequency deviation term, \( \Delta f \) into power flow while eliminating any outer loops for enforcing the active power limits for the generators. This enables accurate modeling of frequency-dependent grid components and controls including the primary frequency response of generators based on the change frequency \( \Delta f \):

\[
\Delta P_R = \frac{P_R}{R} \Delta f
\]

where, \( \Delta P_R \) is the frequency-adjusted change in set real power output of the generator, \( P_R^{SET} \), and \( P_R \) and \( R \) define the primary frequency response of the generator based on droop control, and inertia respectively. In this approach, the primary response is also extended for slack generators, thereby constraining the slack power to a realistic output.

In addition, the authors in [20] have implicitly modeled the active power limits of a generator using a continuous function, as shown in Figure 3. This implicit model is represented by a smooth first-order continuous function (with five regions) and eliminates the use of outer loops to model the generator active power limits, thereby significantly improving convergence.

D. Development of crank path (Real time monitoring of the crank path)

In [4]-[6], extensive literature is presented on developing the crank path for grid restoration processes. The methods that exist today develop these crank-paths in offline mode. However, during a blackout, equipment maybe damaged and network topology maybe altered hence alternating the original crank-path and making the resultant off-line analysis inaccurate. Moreover, real-time operation may observe load distributions that are significantly different than the ones that were originally evaluated and will result in updated circuit-based network model in our approach. Therefore, even though our proposed methodology starts with a planned crank-path, its following step updates are further based on the real-time decision analysis, available measurement data and network topology.

III. OPTIMIZATION-BASED SUGAR-R FRAMEWORK

In order to ensure the feasible actuation of each crank path step while respecting voltage and frequency limits, the proposed network analysis is supplemented with a non-convex optimization framework defined by:

\[
\text{minimize} \quad \Delta P_G \quad \left\| \Delta P_G \right\|^2_2
\]

subject to

\[
g(X, \Delta P_G) = 0 \quad \text{(3a)}
\]

\[
\Delta f_i \leq \Delta f \leq \Delta f_{max}, i \in \text{islands} \quad \text{(3c)}
\]

\[
V_{m} \leq V_i \leq V_{max}, i \in \text{bus} \quad \text{(3d)}
\]

Given a set of non-linear equations representing the frequency dependent network equations (\( g(X, \Delta P_G) \)) and the state/primal variables, \( X \), an additional active power generation, \( \Delta P_G \) at each participating generator \( G \) is required to ensure feasibility of the network while respecting voltage and frequency bounds. The added generation, \( \Delta P_G \), represents the delta change of active generation \( G \) that is required to maintain the health of the system. By minimizing the square of necessary additional active power, the optimization formulation (3) is able to identify necessary change in generation set-points to satisfy network constraints while ensuring that the voltages at the buses, \( V_i \) and frequency at each island, \( \Delta f \) are within operational limits.

By embedding the circuit simulation techniques within the existing local constrained Primal-Dual Interior Point (PDIP) optimization algorithms [21], the Equivalent Circuit Programming (ECP) [22] approach for power grid optimization has been shown to robustly solve extremely large network problems. In this approach, the solution to an optimization problem is obtained by solving first-order
necessary KKT conditions, while ensuring the circuit passivity [22] to guarantee the local optimality of obtained operating point (solution).

The KKT conditions of an optimization problem from 3(a)-(d) can be obtained from the Lagrangian function:

\[
\nabla L - \nabla f(X, \Delta P_g) + \lambda (\Delta f - f_{\text{max}}) = 0
\]

where \( \lambda \) is a vector corresponding to the dual variables associated with the equality constraints, while \( \mu \) and \( \lambda \) represent the dual variables associated with upper and lower bounds from (3c)-(3d). Next, by differentiating (4) with respect to primal and dual variables and relaxing the complementary slackness constraints, the set of KKT conditions is given as:

\[
\nabla g(X, \Delta P_g) = 0
\]

To robustly solve the obtained set of KKT conditions while maintaining primal (primal variables within bounds) and dual (dual variables \( \mu \) and \( \lambda \geq 0 \)) feasibility of the Newton iterate we make use of homotopy and limiting methods. In this case, previously developed homotopy method [12]-[13] was able to ensure robust convergence for the non-linearities introduced by the equality constraints. Similarly, the diode limiting adapted from [22] and described below was able to ensure robust convergence for the inequality constraints while satisfying the primal and dual feasibility at each Newton iterate. Most importantly, in contrast to the existing state-of-art nonlinear optimization algorithms [21] that conservatively damp the complete NR-step vector with a single constant damping factor, in this approach we limit each of the variable step separately based on physical characteristics of the problem [22],[12].

A. Diode Limiting

Inequalities of (3) are modeled with relaxed complementary slackness [21]. In case of modeling upper bounds, these can be represented with a barrier function of the form:

\[
\nabla g(X, \Delta P_g) = 0
\]

where \( \mu \) is the dual variable associated to the variable \( x \) being bounded by \( x_{\text{max}} \). In addition, \( \epsilon \) is a small scalar (approximately 1e-6) that ensures a continuous behavior. During Newton Raphson (NR), each iteration will update the dual variable and primal variable by:

\[
\mu^{k+1} = \mu^k + \tau_u \Delta \mu
\]

and

\[
x^{k+1} = x^k + \tau_x \Delta x
\]

where \( \Delta \mu \) and \( \Delta x \) are the updates found after each NR, and \( \tau_u \) and \( \tau_x \) are their respective damping factors. \( \tau_u \) and \( \tau_x \) are chosen to ensure that the slack dual and primal variable are within the limits defined by (19) and (20).

\[
\tau_u = \min (1, -\gamma_u \frac{\mu^k}{\Delta \mu})
\]

\[
\tau_x = \min (1, x_{\text{max}} - \gamma_x \frac{x^k}{\Delta x})
\]

where \( \gamma_u, \gamma_x \) are constants (usually a value of 0.95) to restrict the variables \( x \) and \( \mu \) from oscillating around their limits. By selecting a damping factor that ensures the dual variables and primal variables are bounded, given there exists a feasible solution, the optimization framework will have robust convergence.

B. Minimizing Excess Active Power

To make feasibility of each crankpath, we introduce a delta active power variable, \( \Delta P_g \) for generators \( G \in PV \) that are participating in blackstart. This controllable \( \Delta P_g \) is required to satisfy the network constraints and preserve system feasibility through adjustment of pre-defined generator setpoints. This is integrated within the current-voltage formulation [13], by modifying the current produced by a generator as:

\[
l_R = \frac{(P_G + \Delta P_g) + Q_{vR}}{V_R^2 + V_I^2}
\]

\[
l_I = \frac{(P_G + \Delta P_g) V_I - Q_{vR}}{V_R^2 + V_I^2}
\]

where \( l_R \) and \( l_I \) are the real and imaginary currents produced by the generator and \( V_{vR} \) and \( V_I \) are the real and imaginary voltages. The added first-order optimality constraints corresponding to \( \Delta P_g \) can be then written as:

\[
\nabla \Delta P_g = 2 \Delta P_g + \lambda \frac{d l_R}{d \Delta P_g} \frac{d l_I}{d \Delta P_g}
\]

C. Synchronizing Multiple Islands

While the optimization-based SUGAR-R framework can ensure proper re-energization of individual islands, there is still the added intricacy of properly synchronizing the two islands. In real operations, synchronizations are done using synchronizers to ensure that the complex voltage magnitude, phase and frequencies at the interconnection points are identical. To ensure that the voltages and frequencies at the two islands are matched, the synchronization is often performed near a generating station where the operator can control both the voltage and frequency [23]. A voltage mismatch at the interconnection nodes predominantly causes a flow of reactive power between the interconnections, where as a frequency...
mismatch causes a flow of active power. Therefore, to ensure proper synchronization, operators adjust the reactive power and active power of the participating generators to ensure matching of frequency and complex voltages. On the other hand, the operator would prefer not to make a large change in the existing frequency and voltage setpoints as it may cause system instability. Hence, to minimize the operator adjustment during synchronization, we recommend the active and reactive power setpoints for the generating station based on the SUGAR-R simulation and will result in matched complex voltages and frequency at two interconnecting points.

To do that, we connect the two network models with a high impedance line between the interconnection points (as shown in Figure 4), thereby ensuring identical reference buses for the two islands. The single slack bus also provides a single frequency term throughout the network. To mimic the adjustments the operator would have to make, we add infeasibility active power to two participating generators, thereby suggesting the needed active power change in order to maintain identical frequencies between the islands. In addition, we add a constraint to the optimization framework that sets the voltages at either ends of the interconnection to have identical magnitudes and angles, as shown by (24)-(25) and allow operators to adjust their reactive power settings in order to ensure that the voltages are identical, similar to the analysis done by the operators [23].

\[ V_{R1} = V_{R2} \]  \hspace{1cm} (24) \n\[ V_{I1} = V_{I2} \]  \hspace{1cm} (25)

IV. SUGAR-R FRAMEWORK

Figure 5 shows the SUGAR-R algorithm for restoring the localized grid under a collapsed scenario. It begins by streaming any measurements and sensor output to update the localized grid model. Upon updating the model, the tool initiates with the first step of the crank path and analyzes its feasibility while ensuring that the voltages and frequency are within bounds. If the system is found to be infeasible, then corrective actions are suggested for the updating of the crank path step based on real-power infeasibility information. If feasible, the crank path step is actuated on the localized grid. Upon which, the localized model is updated again with the measurements, and the procedure is repeated for the next crank path step. This is performed until the last steps of crank-path are performed and the localized grid is restored. In case where the multiple islanded sections are energized in parallel; as a final step, the tool assists in synchronizing the islands by recommending the control setpoints such that the real and imaginary voltages at the ends of the synchronizing branch are similar with same frequency.

![Image](Image 101x377 to 249x425)

**Figure 4:** Setup for simulating synchronization of two islands.

\[ V_{R1} = V_{R2} \]  \hspace{1cm} (24) \n\[ V_{I1} = V_{I2} \]  \hspace{1cm} (25)

V. RESULTS

To highlight the capability of the proposed SUGAR-R framework, we assume a collapse of 39-bus network [8] and we run online-simulations to effectively energize this network starting from a pre-defined crank-path. The crank-path for this network has 10 stages (modified from [8]) as shown in Table 1 and it sequentially energizes generators to bring up parts of the network, with a reference generator at bus 30.

**TABLE 1: CRANKPATH FOR IEEE 39 BUS TEST CASE.**

| Seq. No. | Energized Buses | Energized Gen. |
|---------|-----------------|----------------|
| 1       | 30, 2, 25, 37   | Gen. 8         |
| 2       | 1, 39           | Gen. 1         |
| 3       | 3, 4, 5, 6, 31  | Gen. 2         |
| 4       | 25, 26, 28, 29, 38 | Gen. 9 |
| 5       | 10, 13, 14, 32  | Gen. 3         |
| 6       | 16, 17, 18, 19, 20, 34 | Gen. 5 |
| 7       | 21, 22, 35      | Gen. 6         |
| 8       | 23, 36          | Gen. 7         |
| 9       | 33              |                |
| 10      | 7, 8, 9, 11, 12, 15, 24, 27 | NA |

Note: Red highlighted bus number represents the generator bus.

In Section II, we have demonstrated how an online network model can be maintained using grid measurements in equivalent circuit framework. Therefore, for the rest of this experiment we assume access to the online network model with certain pre-defined control set-points. We recommend changes to those set-points based on SUGAR-R output in case we observe an infeasible (past the nose curve) network state or find the system states that are out of bounds. Finally, once the network has been energized, we assist in synchronization of two islanded networks. However, first, we demonstrate that existing power flow simulators are unable to realistically assist in energizing of the collapsed network.

A. Restoration through Power Flow Tool

In this experiment, we solve for each step of the crankpath using a standard power flow tool and document the voltages

![Image](Image 298x53 to 316x72)

**Figure 5:** Flowchart for SUGAR-R methodology for restoring grid.
and slack generator power as shown in Table 2. Here it is seen that the obtained solution is impractical for assisting in grid blackstart as the slack generator is consuming power (negative), well below its active power minimum of 0 MW in many of the crankpath steps. By not simulating the change in frequency due to over-generation, the slack generator is required to consume active power rather than inject. Therefore, this approach is unlikely to assist in robust energization of the grid as it is not able to mimic the reality. Moreover, this platform does not provide awareness about network feasibility or the frequency state and hence is unlikely to prevent actuation of protective devices due to out of bound state variables. Therefore, next we use SUGAR based governor power flow [20] platform.

**TABLE 2: SIMULATED RESULTS FOR EACH CRANKPATH STEP IN STANDARD POWER FLOW TOOL.**

| Crank-path step | \( V_{\text{max}} \) [pu] | \( V_{\text{min}} \) [pu] | Slack set active power \( P \) [pu] |
|-----------------|----------------|----------------|------------------|
| 1               | 1.06           | 1.028          | -3.07            |
| 2               | 1.064          | 1.028          | -2.027           |
| 3               | 1.051          | 0.982          | 0.849            |
| 4               | 1.06           | 0.982          | 2.5              |
| 5               | 1.072          | 0.982          | -7.31            |
| 6               | 1.075          | 0.982          | 2.01             |
| 7               | 1.076          | 0.982          | -1.78            |
| 8               | 1.074          | 0.978          | -4.5             |
| 9               | 1.067          | 0.982          | -10.65           |
| 10              | 1.076          | 0.982          | -0.182           |

B. Restoration through Governor Power Flow SUGAR

Governor power flow platform can capture frequency deviation and therefore can avoid unrealistic system state due to slack bus model by modeling implicit primary frequency control within the framework as shown in Figure 3. Table 2 documents maximum and minimum voltage values and the frequency deviation from nominal for each crankpath step. Although, SUGAR governor power flow-based framework provides realistic situational awareness, in the results we still observe that the frequency state is out of allowable bounds of +/- 1.2 Hz and hence can result in actuation of under/over frequency load shedding. Specifically, in the crank path stages 1, 2, 5 and 9, the large frequency deviation is a cause for concern.

**TABLE 3: SIMULATED RESULTS FOR EACH CRANKPATH STEP IN GOVERNOR BASED POWER FLOW TOOL.**

| Crank-path stage | \( V_{\text{max}} \) [pu] | \( V_{\text{min}} \) [pu] | Slack set active power \( P \) [pu] | Freq. change \( \Delta f \) [Hz] |
|------------------|----------------|----------------|------------------|------------------|
| 1                | 1.065          | 1.028          | 2.5              | 3.98             |
| 2                | 1.062          | 1.028          | 2.5              | 1.40             |
| 3                | 1.061          | 0.982          | 2.5              | 0.395            |
| 4                | 1.08           | 0.982          | 2.5              | 0.623            |
| 5                | 1.072          | 0.982          | 2.5              | 1.462            |
| 6                | 1.075          | 0.982          | 2.5              | 0.0639           |
| 7                | 1.079          | 0.982          | 2.5              | 0.503            |
| 8                | 1.079          | 0.978          | 2.5              | 0.724            |
| 9                | 1.08           | 0.982          | 2.5              | 1.223            |
| 10               | 1.08           | 0.982          | 2.5              | 0.002            |

This is because of primary droop control due to which, the network settles to a steady state with a positive frequency change, indicating excess power generation in the system. This may result in likely actuation of protective device tripping during energization and therefore may result in system collapse. Improved situational awareness in this framework suggests a likely issue in the crankpath; however, it does not provide feedback on how best to rectify this over frequency problem while ensuring that the other system states are bounded, and the feasibility of the state is maintained. Therefore, next we demonstrate system restoration through an optimization-based SUGAR-R framework.

**C. Restoration through Optimization-Based SUGAR-R Framework.**

To ensure proper steady state values for each crank path stage while re-energizing the island, SUGAR-R introduces frequency and voltage bounds, as well as a measure of active power infeasibility, \( \Delta P_G \) into the formulation. The limits on frequency and voltages used in this experiment are:

\[
\begin{align*}
\Delta f_{\text{max}} \quad \Delta f_{\text{min}} \quad V_{\text{max}} \quad V_{\text{min}} \\
1.2 & \quad -1.2 & \quad 1.1 & \quad 0.9
\end{align*}
\]

Using the optimization framework given in Section III, the bounds ensure stable energization of the network as shown in each stage of the crank path. The necessary correction to generator active power setpoint to ensure such operation is reflected by \( \Delta P_G \) in Table 4.

**TABLE 4: SIMULATED RESULTS FOR EACH CRANKPATH STEP IN SUGAR-R FRAMEWORK.**

| Crank-path step | \( V_{\text{max}} \) [pu] | \( V_{\text{min}} \) [pu] | Slack P set point [pu] | Freq. change \( \Delta f \) [Hz] | Max \( \Delta P_G \) [pu] | Max \( \Delta P_G \) Bus |
|-----------------|----------------|----------------|---------------------|------------------|------------------|------------------|
| 1               | 1.063          | 1.028          | 0.553               | 1.200            | -1.96            | 37               |
| 2               | 1.063          | 1.028          | 2.283               | 1.200            | -2.53            | 39               |
| 3               | 1.061          | 0.982          | 2.500               | 0.395            | 0                | -                |
| 4               | 1.080          | 0.982          | 2.500               | 0.623            | 0                | -                |
| 5               | 1.081          | 0.982          | 2.500               | 1.200            | -0.92            | 32               |
| 6               | 1.075          | 0.982          | 2.500               | 0.064            | 0                | -                |
| 7               | 1.079          | 0.982          | 2.500               | 0.503            | 0                | -                |
| 8               | 1.079          | 0.978          | 2.500               | 0.724            | 0                | -                |
| 9               | 1.080          | 0.982          | 2.500               | 1.200            | -0.13            | 33               |
| 10              | 1.080          | 0.982          | 2.500               | 0.002            | 0                | -                |

As seen in stages 1, 2, 5 and 7 (also seen in Figure 6), the generator active powers are re-adjusted to control the frequency such that the ramping constraints are not violated.

*Figure 6: Generator ramp-up during network energization.*
D. Synchronizing Islands

In the final part of this experiment, we consider two 39-bus islanded networks that have been fully restored and require synchronization. To simulate proper synchronization at the interconnection nodes between bus 29 (of island 1) and bus 28 of island 2, we introduce a high impedance line of resistance $R_{pu} = 1\,\text{pu}$, thereby ensuring identical reference buses and frequencies across the entire system. In addition, we introduce two equality constraints given by (24)-(25) to result in a solution with identical complex voltages and frequency of:

$$|V_{29}| = |V_{28}| = 1.067\,\text{pu}$$  \hspace{1cm} (26)

$$\theta_{29} = \theta_{28} = 0.0803\,\text{degrees}$$  \hspace{1cm} (27)

$$\Delta f = -0.023\,\text{Hz}$$  \hspace{1cm} (28)

where $V_{29}, \theta_{29}$ are the voltage magnitude and angle of bus 29 on island 1, and $V_{28}, \theta_{28}$ are the voltage magnitude and angle of bus 29 of island 2. In addition, only one generator on each island (on bus 38 on island 1 and bus 38 on island 2) was actively participating in aiding the synchronizing of two networks. Recommended real and reactive power set-points for the generators to achieve similar complex voltages at the interconnection points are given below in Table 5.

| Generator | $P_v$ [pu] | $Q_v$ [pu] |
|-----------|------------|------------|
| 38 (island 1) | 8.04 | 0.543 |
| 38 (island 2) | 8.69 | 0.265 |

TABLE 5: GENERATOR SETPOINTS FOR SYNCHRONIZATION.

VI. CONCLUSION

In this paper, we developed a framework for assisting grid restoration under the loss of or unavailability of SCADA system. Unlike grid restoration through central SCADA based control, this approach works to energize critical components of the localized grid via maintaining an online network model that is continuously updated using real-time measurements. To assist in restoration, the framework simulates the online network model to ensure that each crackpath step is likely to result in a feasible grid state and is actuated such that the voltage and frequency remain within bounds. To achieve this goal, the framework recommends adjustments to the generator control setpoints. After energizing individual islands, the framework also assists in synchronization of islands through recommending generator setpoints that will result in identical complex voltages and frequency at the interconnection points. We demonstrated the efficacy of the framework by simulating the restoration and synchronization of two 39-bus systems.

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