Optimal Operation for Resilient and Economic Modes in an Islanded Alaskan Grid

Preprint

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Optimal Operation for Resilient and Economic Modes in an Islanded Alaskan Grid

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***Abstract*—Legacy energy management systems for distribution system or microgrids are typically driven by economics. During extreme events, resiliency can be defined as ability of the system to keep supplying critical loads. Resilient operation during extreme events (e.g. avalanche in Alaska) may require decision variables to be different and conflicting with economic operation. Operational objectives are driven by a complex consideration of the economic, reliable and resilient operation of the system: economic and reliable in normal operating state and resilient during extreme events. Challenge is to move between economic and resilient operation in optimal manner and setting up problem formulation and constraints specially with Distributed Energy Resources (DERs). In this paper, we focus on prioritizing optimal economic and resilient operation driven by events using novel formulation and developed tool: Resiliency Enabled Energy System Operation Toolbox (RE-ESOT). Simulation results are provided for a real islanded grid in Alaska with battery energy systems.**

***Index Terms*—Resiliency, Economics, Optimization, Microgrids, DERs, islanded grid, battery.**

I. INTRODUCTION

Reliable and economic supply of electricity is one of the main objectives of the electric utilities. Efforts are being made towards the infrastructure, security automation, protection, and other factors critical to run the electric grid with changing energy landscape. Extreme events have posed a threat to the operation of the grid. This has led to an increased interest in microgrids, DERs and in making the grid more resilient. The concept of resilience is picking up pace among researchers, utilities, and governments. There are multiple definitions of resilience of the electric grid, with no consensus yet among researchers and industry experts. The U.S. Department of Defense Space Policy [1] defines resilience as the ability of an architecture to support the functions necessary for mission success with higher probability, shorter periods of reduced capability, and across a wider range of scenarios, conditions, and threats, in spite of hostile action or adverse conditions. The National Infrastructure Protection Plan of the U.S. Department of Homeland Security defines resilience as "the ability to resist, absorb, recover from, or successfully adapt to adversity or a change in conditions" [2]. For the electric grid-which is a complex system with mutual dependence on other infrastructures such as transportation, water supply, communication, controls, and instrumentation, the prioritization of certain loads that are critical to the minimum function of the electric grid and to minimize loss of essential services such as communications, finance, healthcare, and emergency services are important. We propose defining resilience as the ability of the system to serve critical loads during extreme events. In case of an extreme event, some generation, lines, and other infrastructure might be lost; however, with better planning and management, imparting resilience on the grid allows continuous service to critical loads.

It is anticipated that the frequency and impact of high-impact low-frequency events, especially extreme weather events, are going to increase soon, as indicated in [3]. There have been several incidents of unprecedented damage to the electric grid because of extreme weather events, such as Hurricane Sandy [4], Hurricane Katrina [5], Hurricane Irma and Hurricane Maria [6]. Apart from extreme weather events, a cyberattack can result in a blackout, as observed in the Ukraine attack in 2016 [7]. Microgrids, distributed generation, and energy storage have been presented as a viable solution to preventing large-scale blackouts that were observed in the examples mentioned above; however, microgrid formation and the implementation of DERs is a challenge to integrate and manage economically and reliably. Researchers have addressed the issue of economic operation in microgrids. In [8], the

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cost of microgrid operation was optimized using swarm optimization, where controllable loads and battery storage are considered. In [9], linear programming algorithms were used to minimize microgrid operation cost and optimize battery charge states. The authors of [10] considered an optimal participation strategy for a wind electric generator and a day-ahead unit commitment process using an energy storage device. All the energy optimization for economic microgrid operation used some underlying assumptions based on the system of operation. The drawback to these methods that they do not consider the resilient operation. Therefore, in this work, we propose a Resiliency Enabled Energy System Operation Toolbox (RE-ESOT), capable of operating in an economic and resilient mode. The proposed RE-ESOT toolbox uses an optimization engine to determine the optimal operation of various energy sources to achieve the specified objectives. Examples of possible objectives are the minimization of overall operational cost or system resilience for supplying power to the critical load. The proactive actions [11], ensure that the system resiliency during such events are high and maximum critical load is served.

II. MICROGRID OPERATIONAL MODE

To study the economic and resilient impact of using the proposed tool on the operation of an isolated microgrid, we model the real-world system in a real-time environment. The chosen real-world system- vulnerable to extreme weather events such as a tsunami, avalanche or earthquake- provides an interesting test case and led to the conceptualization of RE-ESOT. The ability of the toolbox to switch between economic operation and resilient operation during extreme events has proved to be of value with the partner utility. The extreme weather events and their impacts on the grid- in particular, the topological changes during extreme events- are studied. The current mode of operation being used by the partner utility is based on response-based logic, where run-of-the-river hydropower units are used, followed by the battery, and if the generation does not meet the demand, high-cost diesel units are operated. The two major drawbacks of this style of operation are:

1) Economic operation not considering DERs
2) Resilience is not considered

The idea behind the current operation is to use the hydro units as much as available because they are a run-of-the-river plants. In cases where diesel unit needs to be started, however, they provide a certain fixed amount of power. This leads to spillage of the hydropower. For example, if there is a shortage of 200 kW of power and a diesel unit needs to be started, the minimum amount of power it will provide is 400 kW. This leads to spillage of 200 kW of a Hydro Unit. The cost of operation of different units is not considered, and the running cost of fuel is minimized by the rule-based logic. We propose to use the RE-ESOT for the operation of the microgrid. The economic mode of operation ensures that all the generating units are utilized to ensure a low cost of operation at any given system condition. Once a weather advisory is issued, the tool transitions to the resilience mode, and the objective functions are changed to ensure that the maximum critical loads are served during events.

A. Economic Mode of Operation

Fig. 1 shows the workflow of the RE-ESOT tool in a microgrid. RE-ESOT gets runtime information regarding various generation assets, including storage, from the Micro-Grid management system. Apart from such runtime data, RE-ESOT also utilizes static data such as - network configuration, rated values of generation and loads, priority category for each load, depth of discharge curve for battery storage, etc. RE-ESOT consists of an optimization engine driven by a Genetic Algorithm method. Based on the mode of operation, different input data, constraints, and objective function is used by the optimization engine.

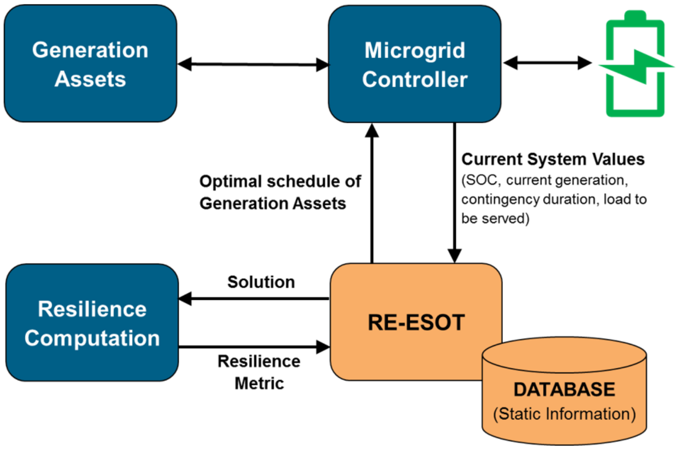

Fig. 1: Workflow of RE-ESOT in a Microgrid

During normal operation, i.e. before an event, in economic operation mode, RE-ESOT takes as input the various system information and determines the optimal schedule of various generation assets for the duration the microgrid is running in economic mode. This information includes current generation status and values for various assets, state of charge (SOC) for storage, status and values for various loads in the system, and time duration. The objective in this mode is to minimize the overall operational cost of the system. Overall duration is further divided into smaller time steps. The optimization engine determines the optimal schedule for the various generation assets such that the overall operation cost for the duration (T) is minimized. Mathematically, the optimization problem can be formulated as follows, assuming battery storage: (Note that detail formulation is not shown here.):

$$min\ C = \sum_{i=1}^{n} \sum_{t=1}^{T} C_i^t \tag{1}$$

Subject to:

$$\sum_{i=1}^{n} P_i - \sum_{j=1}^{m} L_j = 0 \tag{2}$$

B. Resilience Mode of Operation

In the event of a current or impending contingency, RE-ESOT will work in resilience operation mode. In this mode, the microgrid management system will provide the probable duration of the event, and a resilience computation program will provide the system resiliency metric as input. In this mode, the mathematical formulation of the optimization problem is similar (1) and (2), except that the constraint limits for the generation assets are modified to shore up the system resources to meet sudden unplanned events. So, for example, for the battery storage, the SOC constraint is modified as - $SOC^{'}_{min} < SOC < SOC_{max}$, where $SOC^{'}_{min} > SOC_{min}$.

The objective of the resilience mode is the maximization of the number of critical loads served during the event. The tool calls for the computation of the resilience metric where the system operating states are extracted and the impact of the event is analyzed; however, resilience is a multidimensional problem that requires the analysis of different resilience indicators of the system, and a resilience metric that captures the different dimensions of resilience is required. The resilience metric employs the Multi-criteria Decision Making technique called the analytical hierarchical process (AHP) to compare resilience indicators of the different operating scenarios presented. The formulation of a composite resilience score based on the variables of the system is described in [12]. For each scenario that is analyzed, the resilience metric engine creates a vector $\mathfrak{R}_w$ that captures the system performance with respect to resilience, as shown in (3). The vector is generated for each hour in the resilience calculation and contains the scenario-specific values for the resilience indicators as described in Table I:

$$\vec{\mathfrak{R}_w} = [G, D, TIF, CLNL, SOC] \tag{3}$$

In the AHP, a pairwise comparison matrix is created, which is a matrix of qualitative ranks for each factor compared against other factors, as shown in (4) where $c_{i,j}$ is the relative priority of each element of $\vec{\mathfrak{R}_w}$:

$$M_{pc} = \begin{bmatrix} c_{1,1} & \cdots & c_{n,1} \\ \vdots & \ddots & \vdots \\ c_{1,m} & \cdots & c_{n,m} \end{bmatrix} \tag{4}$$

$$c_{i,j} = c_{j,i}^{-1} \text{ for } i \neq j \tag{5}$$

$$c_{i,i} = 1 \tag{6}$$

Linear transformation of the elements is based on the positive or negative impact of the factor on the resilience of the system and is represented as $\rho_{i,j}$. The weights represent the impact of the factors on the resilience of the system. The sum of the product of the weights with the linear transformation element gives the composite score. The linear transformation is given by:

$$\rho_{i,j} = \frac{c_{i,j} - \min_{i=1}^{n}(c_{i,j})}{\max_{i=1}^{n}(c_{i,j}) - \min_{i=1}^{n}(c_{i,j})} \tag{7}$$

for improvement in resilience for a higher value of $c_{i,j}$:

$$\rho_{i,j} = \frac{\max_{i=1}^{n}(c_{i,j}) - c_{i,j}}{\max_{i=1}^{n}(c_{i,j}) - \min_{i=1}^{n}(c_{i,j})} \tag{8}$$

for reduction in resilience for a higher value of $c_{i,j}$.

TABLE I: Factors in resilience analysis

Factor	Description	Impact	Weights
Critical Load Not Lost (CLNL)	Fraction of critical loads online to total critical loads in the system	↑	0.3897
Generation (G)	Total generation available for dispatch for the BESS, it is the SOC*rating	↑	0.2330
Critical Load Demand (D)	Operating demand of the connected critical loads	↓	0.1494
Threat Impact Factor (TIF)	Integer value that accounts for further degradation of the system during the event progression	↓	0.0785
State of Charge (SOC)	Battery State of Charge	↑	0.1494

When the RE-ESOT tool operates in resilience mode, it uses the resilience score computed from the AHP by comparing the scores for the degraded system against the system in normal operating mode. The scenario generated for the event is shown in Table II and Section IV.

III. REAL TIME TEST BED FOR VALIDATION

Online testing of the RE-ESOT tool was done using the test-bed architecture depicted in Fig. 2. A real-time model of the isolated remote microgrid was modeled in HYPERSIM modeling software. With the help of the utility and historical data, events were modeled and their impact on the system was analyzed. Different events have different topological (electrical) effects on the power system depending on the location and the magnitude of the event. A Python Application Programming Interface (API) was used to run the real-time simulation based on the user's input to implement and study different operating scenarios. The operational changes- such as available generation, loads, and different events- were communicated to the HYPERSIM model and the RE-ESOT tool using the Python API. RE-ESOT tool, based on the input, uses the desired objective function and chooses the mode of operation. The solution is implemented back in the real-time mode using the Python API.

Fig. 3, shows the schematic of the real-world system as modeled in the real-time environment. It consists of two run-of-the-river hydropower generation plants. Hydro Generation 1 has three small hydro units with a capacity of 200 kW each. Hydro Generation 2- has two run-of-the-river hydro unit with a rating of 3.2 MW each. The diesel plant has five diesel units with different costs of operation and ratings varying from 1.2 MW to 5 MW. A 1-MW battery is installed at the substation providing load to the five feeders in this isolated microgrid. Depending on the geographic location of different power system infrastructures, they are exposed to extreme events, such as tsunamis and avalanches. The total system load is 6,000 kW, and 50% of the loads were considered to be critical, i.e., 3,000 kW. The critical load here, consists of Priority 1 and Priority 2 types of loads as identified by the utility.

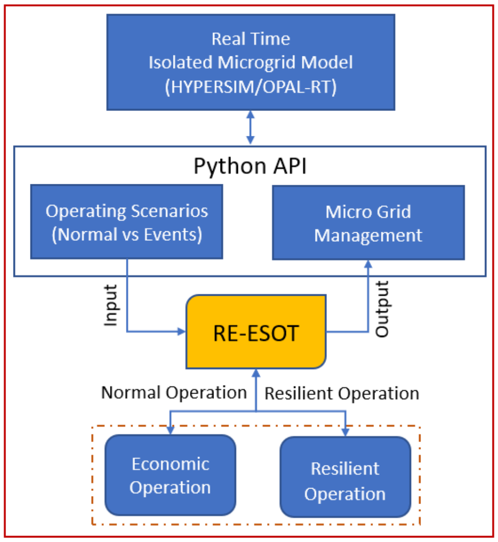

Fig. 2: Online test bed architecture

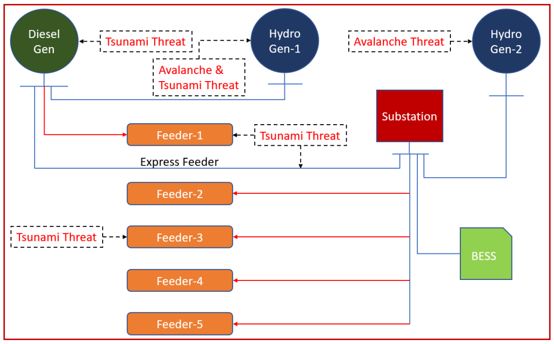

Fig. 3: Simplified Model of the real-world system

IV. TSUNAMI SCENARIO AND RESULTS

The system shown in Fig. 4 was modeled to be hit by a tsunami. The scenario is described in Table II, where the diesel plant that is near the seashore was hit by a tsunami and was unable to supply power to the grid. The RE-ESOT tool's ability to run in resilience and economic mode produces two ways of operating the grid. In the economic mode of operation, the threat was not considered and the battery was used to supply cheap and economic power. Because of this, when the tsunami hit the area, there was not enough generation to supply all the loads and some critical loads were dropped.

Fig. 5, shows that cheaper battery power was used to supply the load over the costly diesel generation in the first 3 hours. When the tsunami hit the grid, diesel was not available and the battery was subsequently drained. Some fraction of critical load was not supplied along with other non-critical load because of lack of generation. The battery was reduced to 20%, which is the advised minimum limit of its operation.

Fig. 6 shows the hourly resilience score computation for the economic (E-mode) and resilient (R-mode) modes of operation. In the economic operation, the scores, shown in blue, shows depreciation as a result of the dispatch of cheaper battery power through the progression of the tsunami. At Hour 3, when the tsunami hits, the battery has already discharged to 20%. Because the battery controls prevent discharging to less than 20% to conserve health, and there is no diesel generation available to charge it, the battery is taken out of service; therefore, critical and non-critical loads are lost over hours 4, 5, and 6. There is considerable loss of resilience, as indicated by the lower resilience score.

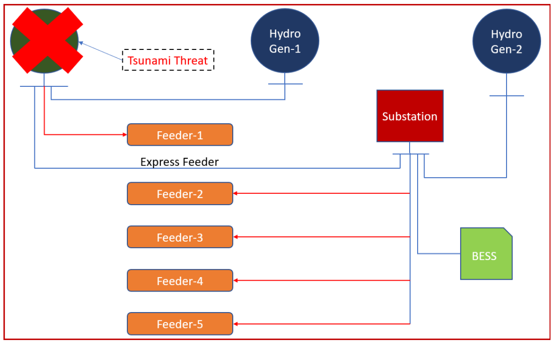

Fig. 4: Tsunami Scenario for Operation

TABLE II: MW Generation and Loads for Tsunami Scenario

Components	Hour Before Event (kW)	Last Event Hour(kW)
BESS	Depends on mode of operation	200 kW
Diesel 1	3200	0
Diesel 2	3200	0
Diesel 3	1200	0
Diesel 4	5000	0
Diesel 5	5000	0
Hydro 1	500	500
Hydro 2	2000	2000
Total Load	6000	6000
Critical Load	3000	3000

In the resilience mode of operation, the operator considered the tsunami warning and the RE-ESOT tool preferred resilience of the system over the economics. The constraints were changed so that the ability to supply the critical load during the extreme event was maximized. Fig. 7, that pre-event the battery was charged using the more expensive diesel generation. When the actual event started, the ability to serve critical load as a result of the resilient operation was maximized.

The resilience score and the Battery Energy Storage System's (BESS) State of Charge (SOC) in Fig. 6, show that, in the resilient mode the performance is better than the economic mode. The results show that the resilience performance of the system is increased by 40%. The loss of critical load at Hour 5 is prevented by the BESS being sufficiently charged by the diesel generators to serve the critical load.

CONCLUSIONS

A new energy optimization tool has been proposed for managing energy resources with battery energy system for economic and resilient mode of operation to maximize the ability of the system to serve critical loads under extreme

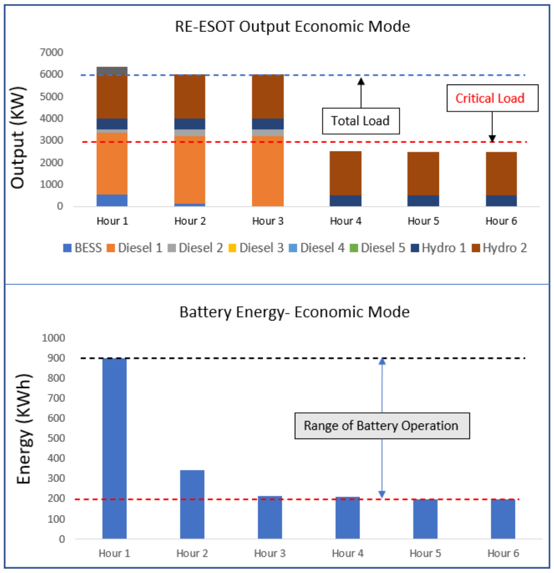

Fig. 5: Economic mode of operation

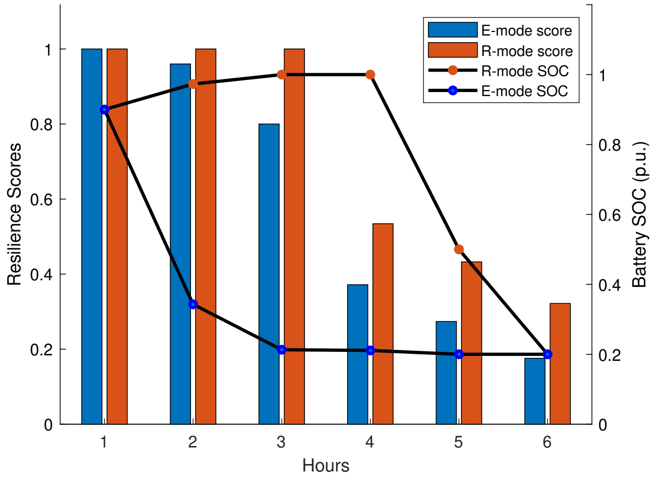

Fig. 6: Resilience analysis of RE-ESOT operations

weather events. An Analytic Hierarchical Programming (AHP) based resilience metric was formulated to be used by the optimization tool to quantify resilience. Two different modes of operation were used: economic mode to minimize operational cost in normal operation, and resilience mode to maximize critical load in expected extreme events. The Alaskan system model was developed in HYPERSIM and the threat scenarios were modeled as an explicit threat that affects diesel generation. The simulation results show that by operating the system in resilient mode, critical loads can be served for the longer duration of the extreme event, while cost can be minimized in normal operation.

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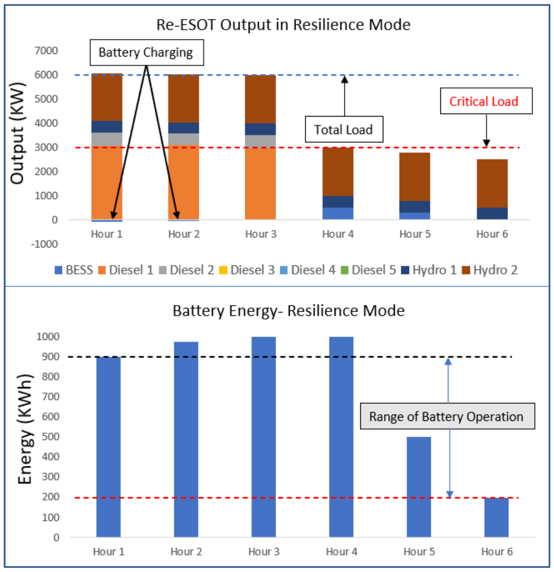

Fig. 7: Resilience mode of operation

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