Emergency Electric Service Restoration in the Aftermath of a Natural Disaster

Moein Choobineh and Salman Mohagheghi
Electrical Engineering and Computer Science Department
Colorado School of Mines
Golden, CO

***Abstract*—The colossal amount of energy released by natural disaster events can devastate the critical infrastructure of affected cities and rural regions. Possible damages to the electric power grid can lead to large-scale interruption in electric service, which could greatly impede post-disaster relief efforts. To make communities resilient against natural hazards, the power grid must have post-disaster self-healing capability, allowing it to restore power to as many sections of the network as possible within a reasonably short timeframe. Traditionally, electric service restoration is performed by first identifying alternative substations and possible routes, followed by network reconfiguration, so that the outage area can be re-energized via these substations. However, this approach may not be possible in the aftermath of a natural disaster. This is because many parts of the network may already have become non-operational due to direct or indirect damages incurred by the event. Here, service restoration can be achieved through a decentralized approach where one or more Microgrids are formed in order to supply the loads locally. A Microgrid dispatch solution is proposed in this paper for emergency electric service restoration in the aftermath of a natural disaster event. A nonlinear mixed-integer optimization problem is formulated that finds the optimal dispatch of the energy resources within the Microgrid subject to capacity and fuel availability constraints. To demonstrate the applicability of the solution, a case study is provided using the IEEE 123-bus test distribution system.**

Keywords—Distributed energy resource, demand response, electric service restoration, Microgrid, natural disaster

I. NOMENCLATURE

A. Indices

i	Index used for generation units
j	Index used for demand responsive loads
k	Index used for battery energy storage systems
q	Index used for loads
t	Index used for time

B. Parameters

A_i	Area swept by the rotor of wind turbine i (m^2)
c^B_k	Price of using battery k over its lifetime; this value can be determined based on the total cost of purchasing and maintaining the battery and the maximum amount of A.h it can provide over its lifetime ($)
c_i^{fuel}	Price of fuel for DG i ($/$m^3$, $/l, $/kg)
$f_i^{DG,max}$	Maximum amount of fuel available for DG unit i (m^3, l, kg)
H_i^{fuel}	Net thermal value of the fuel for DG unit i (MWh/m^3, MWh/l, MWh/kg)
k^{PV}	Temperature coefficient of power for PV (℃$^{-1}$)
NB	Number of Batteries
NDG	Number of distributed generation units
NDR	Number of demand responsive loads
NL	Number of loads
NT	Number of operation time steps, representing the repair time during which the Microgrid needs to be dispatched
$P_k^{B,Total}$	Total capacity that battery k can deliver over its lifetime (MWh)
$P_k^{B,max}$	Maximum allowable power level for battery k (MW)
$P_k^{B,min}$	Minimum allowable power level for battery k (MW); battery is not allowed to be discharged below this level
$P_i^{DG,max}$	Maximum allowable production level for DG unit i (MW)
$P_i^{DG,min}$	Minimum allowable production level for DG unit i (MW); it is assumed not to be cost effective for the DG to generate power below this level
$P_j^{DR,max}$	Maximum allowable power reduction level for DR load j (MW)
$P_j^{DR,min}$	Minimum allowable power reduction level for DR load j (MW); it is assumed not to be cost effective for the DR load to provide demand reduction below this level
$P^L_{q,t}$	Active demand of load q during time period t (MW)
$P_{i,t}^{PV}$	Power output of PV panel i during time period t (MW)
$P_i^{PV,STC}$	Maximum power provided by PV panel i under standard test condition (STC) (MW)
$P_{i,t}^{W}$	Output power of wind turbine i during time period t (MW)
$SOC_k^{B,max}$	Maximum limit of battery k SOC
$SOC_k^{B,min}$	Minimum limit of battery k SOC; battery is not allowed to be discharged to lower than this level
$T_{i,t}^{C}$	PV cell temperature for panel i during time

	period t (℃)
T^R	PV reference temperature (℃)
$v_{i,t}$	Wind speed at turbine i during time period t (m/s)
α	Albert Betz constant
β_j^{DR}, γ_j^{DR}	Cost function coefficients for DR load j (\$/MW and \$/MW^2)
δ_k	Self-discharge rate of battery k
$\Phi_{i,t}$	Incident solar irradiance at PV panel i during time period t (W/m^2)
Φ^{STC}	Solar irradiance at STC (W/m^2)
$\eta^{B,c}{}_k$	Charging efficiency of battery k
$\eta^{B,d}{}_k$	Discharging efficiency of battery k
$\eta^{DG}{}_i$	Generation efficiency for DG unit i
ρ_a	Air density (kg/m^3)

C. Variables

$C^B{}_{k,t}$	Operation cost of battery k during time period t (\$)
$C^{DG}{}_{i,t}$	Operation cost of DG unit i during time period t (\$)
$C^{DR}{}_{j,t}$	Cost of demand responsive load j at time t (\$); DR is modeled as negative demand
$f_{i,t}{}^{DG}$	Amount of fuel consumed by DG unit i during time period t (m^3, l, kg)
$P^{B,c}{}_{k,t}$	Amount of charging power provided to battery k during time period t (MW)
$P^{B,d}{}_{k,t}$	Amount of power discharge provided by battery k during time period t (MW)
$P^{DG}{}_{i,t}$	Active power provided by DG unit i during time period t (MW)
$P^{DR}{}_{j,t}$	Active power reduction of demand responsive load j during time period t (MW)
$SOC^B{}_{k,t}$	State of charge of battery k during time period t (%)
$u^{B,c}{}_{k,t}$	Binary variable that indicates battery k is charging during time period t (1: being charged, 0: not being charged)
$u^{B,d}{}_{k,t}$	Binary variable that indicates battery k is discharging during time period t (1: being discharged, 0: not being discharged)
$v^{DR}{}_{j,t}$	Binary variable that specifies DR load j is being curtailed during time period t (1: being curtailed, 0: no curtailment)

II. Introduction

Natural disasters can cause temporary or permanent damages to the electric power infrastructure. In fact, natural hazards have been considered as one of the two main causes of the largest blackouts in North America (the other being cascading failures) [1]. This not only affects the supply of energy to residential, commercial and industrial customers, it may also impact the operation and availability of critical infrastructures such as water sanitation and sewage plants, telecommunication networks, transportation systems, and hospitals and emergency service facilities, whose services are essential for disaster recovery efforts. From the standpoint of resiliency to natural disasters, the power grid has to be able to withstand a major disruption with limited degradation, and to recover within a narrow timeframe with constricted costs [2]. Resilience itself may be further characterized by robustness, redundancy, resourcefulness and rapidity [3].

In general, power system resilience can be achieved by: (*a*) reducing the extent of damage incurred by natural disasters on power grid components, (*b*) limiting the consequence of power system partial failure on the society, especially during post-disaster recovery activities, and (*c*) speeding up service restoration to the outage areas affected by the disaster. As such, various mitigation techniques can be devised based on the timeline of interest. Kwasinski [4] proposed three timeframes for this purpose: during the event that lasts for a relatively short period of time, at most for a few days, immediate aftermath (response, recovery and restoration) that lasts from a few days to a few weeks until the system is fully repaired, and long-term aftermath that is related to the planning stage and grid reinforcement.

The focal point of this paper is on electric service restoration in the aftermath of a natural disaster. When the power grid is exposed to a large scale disturbance such as a natural disaster event, the protection system immediately reacts to isolate the faulty section(s) and prevent the disturbance from propagating through the rest of the grid. Depending on how reliable and selective the protection system is, some healthy sections of the grid may also be de-energized in the process. These circuits are referred to as the *outage area*. The objective of electric service restoration is to re-energize these sections as quickly as possible while the faulty sections are being repaired. Traditionally, this has been done by finding alternative routes (tie-lines) and alternative sources (substations) that are able to supply the load in the outage area in addition to their own usual load. If sufficient capacity is available for the expected duration of repair time for the faulty circuits, appropriate network reconfiguration is implemented to re-energize the outage area via the alternative sources.

While this approach works usually well during ordinary disturbances, it may prove to be too simplistic for the time when a natural disaster hits the power grid. The potential footprint of the event, in conjunction with the likely damages imposed on power grid components may make it impractical, if not infeasible, to continue supplying the grid via usual power sources. It may therefore be necessary to revert to decentralized supply of power where local Microgrids are formed in order to supply the critical loads. Under this condition, the available energy resources must be optimally dispatched in order to minimize the load lost. For each Microgrid, these resources would be the distributed energy resources (DER) such as distributed generation (DG) units and energy storage systems (ESS). Since the stability of the Microgrid is one of the key requirements for its operation, the available energy resources need to be properly dispatched in order to maintain the balance between the load and the available generation at all times. Availability of fuel for DG units is another constraint that needs to be taken into account. When balance between available generation and load cannot be maintained, which is foreseeable given the usually limited supply of fuel, load curtailment can be implemented in order to drop the less-critical loads for the benefit of more critical ones.

In this paper, a solution is proposed for energy management of a Microgrid formed in the aftermath of a natural disaster event. The objective here is to supply as many loads in the outage area as technically possible while taking into account the operational constraints of the Microgrid and its energy resources. It is assumed that the available fuel is limited. The problem therefore tries to optimize the usage of the available fuel in addition to minimizing the cost of operation of the whole system. The problem is formulated as a nonlinear mixed-integer optimization problem subject to the operational constraints of the system, and is solved over the time horizon for repairing the faulty circuits.

III. Electric Service Restoration And Microgrid Dispatch

In modern distribution networks, Microgrids can play a significant role in system restoration [5], [6]. Microgrids are typically comprised of distributed generation, distributed storage (DS), and demand-responsive loads (DR), and can operate in both grid-connected and islanded modes [7], [8]. By incorporating Microgrids into the system operation planning, utility operators can optimize the performance and economics of the power grid by efficiently dispatching their DG, DS and DR units [9], [10]. One of the important characteristics of a Microgrid lies in its ability to help the utility during a disturbance. This can be done either by providing local power to a portion of the network or by disconnecting from the grid completely and thereby partially relieving the capacity of the distribution circuit [11]. One such application arises during electric service restoration, where the objective is to provide as much capacity relief for the utility as possible. To do this, Microgrids can provide local support to some loads by utilizing their DG and DS units, or can reduce their demand by curtailing their DR loads.

The problem of electric service restoration in the presence of Microgrids can essentially be modeled as an operation optimization problem which tries to minimize the operational cost of the network subject to technical and capacity constraints. Modeling DER units (DG, DS, and DR) and considering their operational constraints make the problem nonlinear and add to its complexity level [10], [12]. Many researchers have tried to address this problem by focusing on one or more types of DERs. Table I summarizes some of the related recent studies in the literature.

TABLE I. Comparison of Recent Studies on Restoration and Optimal Dispatch of Distribution Networks with Microgrids

Ref	**Objective functions**							**Constraints**													**Solution Method**
	Min Operational Cost	Min Load Shedding	Min switching operation	Min emission cost	Min Loss	Min EENS	Other objectives	Power balance	DG power limit	Grid substation limit	DR power limit	DG ramp rate	DS operational limits	Reserve constraint	Islanded mode constraint	Line flow limit	Voltage limit	Emission constraints	Up/down time limits	Other constraints	
[13]		✓			✓											✓	✓			✓	BPSO
[14]		✓	✓													✓	✓			✓	HM
[9]	✓			✓			✓	✓	✓	✓		✓	✓				✓				FT
[11]	✓	✓						✓	✓		✓				✓	✓					MINLP
[15]	✓						✓	✓	✓						✓			✓	✓		SbA
[16]	✓			✓	✓			✓	✓	✓				✓		✓	✓				GA/PSO/AIS
[17]	✓							✓	✓	✓		✓	✓	✓							PSO/MC
[18]	✓							✓	✓					✓						✓	MDS
[19]		✓	✓													✓	✓			✓	GA
[20]	✓					✓	✓	✓	✓											✓	MINLP

*BPSO: Binary Particle Swarm Optimization, HM: Heuristic Method, FT: Fuzzy Theory, SbA: Subgradient-based Algorithm, PSO: Particle Swarm Optimization, GA: Genetic Algorithm, AIS: Artificial Immune Systems, MDS: Modified Direct Search method, MC: Monte Carlo simulation

¤The table is a modified version of the work presented in [11].

IV. Proposed Methodology

A. Preconditions and Objectives

It is assumed here that after the natural disaster event, the outage area is de-energized. It is further assumed that prior to restoring service to the outage area, the available capacities of the DER units and the forecasted localized demand are known. This is a reasonable assumption for most utilities. The objective is to restore power to this system while ensuring the balance between load and generation is maintained. The outcome of the proposed methodology would be a series of dispatch set-points that consists of the level at which the generation and storage systems need to inject power, given the demand forecast of the system. These set-points will be derived for a certain period of time, i.e. the repair time when the faulty sections due to the natural disaster event are being repaired and are expected to be redeployed. Once these set-points are determined and the balance between available generation and loads to be supplied is ensured, the Microgrid can be formed through black start and can supply the outage area (see Section VI for a discussion).

The problem of generation dispatch is formulated here based on the assumption that the supply of fuel is limited. This seems reasonable within the context of natural disasters where the road and transportation system may be affected, hence negatively impacting the fuel delivery system. With this assumption, it is desired to find an optimal dispatch strategy so that some (if not all) of the loads in the system can be supplied using the available DER and fuel capacity. For islanded operation of the grid, one of the most important requirements is to ensure that frequency is stable and as close to 60Hz as possible. This requires a balance between load and generation. However, it is fair to assume that in most cases, decentralized DER units are not sufficient for supplying the whole system. Hence, load curtailment approaches can be used as an alternative to relieve some of the capacity of the system. This can be voluntary in the form of demand response or involuntary in the form of load shedding. The former is considered in this paper (see Section VI for a discussion).

B. Mathematical Models for DER Units

In this section, the mathematical models for distributed energy resources (DER) are described. In the rest of this section, each time step of analysis is assumed to be one hour, which means the power levels (in MW) would be equivalent in value to the energy levels (in MWh). In the absence of this assumption, all power values would have to be multiplied by the duration of the time step in order to derive the corresponding energy level.

1) Dispatchable DG Units

The mathematical model of the operational cost of a DG unit can be expressed as a function of the fuel price as well as its thermal value [9], [17]. Equation (1) represents the general mathematical relationship that can be adapted for a diesel generator, a microturbine, or a fuel cell unit.

$$C_{i,t}^{\mathrm{DG}} = \frac{c_i^{\mathrm{fuel}}}{H_i^{\mathrm{fuel}}} \times \frac{P_{i,t}^{\mathrm{DG}}}{\eta_i^{\mathrm{DG}}} \tag{1}$$

Hence, the amount of fuel consumed by the DG unit can be expressed as a function of its output power. A linear function is adopted here for proof-of-concept purposes. Naturally, a higher order nonlinear function may be used for more accurate modeling.

$$f_{i,t}^{\mathrm{DG}} = \frac{P_{i,t}^{\mathrm{DG}}}{\eta_i^{\mathrm{DG}} H_i^{\mathrm{fuel}}} \tag{2}$$

2) Non-dispatchable DG Units

Two types of non-dispatchable DG units have been considered in this paper: wind power and solar power. The output power of wind energy conversion system can be determined as a function of the wind speed and the swept area of the turbine rotor, among other things [21]:

$$P_{i,t}^{\mathrm{W}} = 0.5\alpha\rho_a A_i \cdot v_{i,t}^3 \tag{3}$$

The output power of a PV generator i at time t can be modeled based on the generation level under standard test condition (STC) [16]:

$$P_{i,t}^{\mathrm{PV}} = P_i^{\mathrm{PV,STC}} \frac{\Phi_{i,t}}{\Phi^{\mathrm{STC}}}[1 + k^{\mathrm{PV}}.(T_{i,t}^C - T^R)] \tag{4}$$

3) Battery Energy Storage System

The capacity of battery k at time t can be determined based on its capacity at the previous time step, and the consideration of whether or not it has been charged or discharged during this time period. Therefore, the state of charge (SOC) of the battery is modeled according to (5) [12], [17].

$$\begin{aligned} \mathrm{SOC}_{k,t}^B &= (1-\delta_k)\cdot \mathrm{SOC}_{k,t-1}^B \\ &+ u_{k,t}^{B,c} \cdot \left(\frac{P_{k,t}^{B,c}\eta_k^{B,c}}{P_k^{B,\max}}\right) - u_{k,t}^{B,d} \cdot \left(\frac{P_{k,t}^{B,d}}{\eta_k^{B,d} P_k^{B,\max}}\right) \end{aligned} \tag{5}$$

C. Problem Formulation

To formulate the problem, it is assumed that as a result of the natural disaster event, supply of power from the utility's distribution substation is lost, causing an outage across the entire system. It is desired for the system to operate as a Microgrid so that distributed resources of energy can continue supplying the more critical loads, while the less critical ones may be voluntarily or involuntarily curtailed. Hence, the objective is to minimize the total operational cost of the Microgrid, subject to the available fuel and available energy capacity, while ensuring the demand on the circuit is maintained as much as technically possible. It is assumed that operational costs incur due to usage of any DG, DR or ESS units, with the exception of non-dispatchable units that operate at Maximum Power Point Tracking (MPPT) mode. Renewable units are therefore not incorporated into the cost function; however, they are considered in the generation-load balance equation. Curtailment of the DR loads can be modeled as a quadratic cost function [10]. Finally, because the lifetime of batteries depends on the total ampere hour (Ah) they provide, their cost functions are modeled based on their working Ah [12].

The objective function is therefore defined as follows:

$$\min \sum_{t=1}^{\mathrm{NT}} \left\{ \sum_{i=1}^{\mathrm{NDG}} C_{i,t}^{\mathrm{DG}} + \sum_{k=1}^{\mathrm{NB}} u_{k,t}^{B,d} \cdot C_{k,t}^{B} + \sum_{j=1}^{\mathrm{NDR}} v_{j,t}^{\mathrm{DR}} C_{j,t}^{\mathrm{DR}} \right\} \tag{6}$$

where:

$$C_{j,t}^{\mathrm{DR}} = \beta_j^{\mathrm{DR}} P_{j,t}^{\mathrm{DR}} + \gamma_j^{\mathrm{DR}} (P_{j,t}^{\mathrm{DR}})^2 \tag{7}$$

$$C_{k,t}^{B} = c_k^B \frac{P_{k,t}^{\mathrm{B},d}}{P_k^{B,\mathrm{Total}}} \tag{8}$$

Equation (8) assumes that there will be a cost associated with the battery if it is being discharged. The cost is normalized based on the total energy that the battery can deliver over its lifetime. The first and second terms in (6) indicate the operational costs of dispatching the DG units and the battery systems, while the third term denotes the costs associated with utilizing demand responsive loads. The objective function in (6) would be solved subject to the following constraints:

$$\forall t: \sum_{i=1}^{\mathrm{NDG}} P_{i,t}^{\mathrm{DG}} + \sum_{j=1}^{\mathrm{NDR}} v_{j,t}^{\mathrm{DR}} P_{j,t}^{\mathrm{DR}} + \sum_{k=1}^{\mathrm{NB}} (u_{k,t}^{B,d} P_{k,t}^{B,d} - u_{k,t}^{B,c} P_{k,t}^{B,c}) = \sum_{q=1}^{\mathrm{NL}} P_{q,t}^{\mathrm{L}} \quad (9)$$

$$\forall i, \forall t: P_i^{\mathrm{DG,min}} \le P_{i,t}^{DG} \le P_i^{\mathrm{DG,max}} \quad (10)$$

$$\forall j, \forall t: P_j^{\mathrm{DR,min}} v_{j,t}^{DR} \le P_{j,t}^{\mathrm{DR}} \le P_j^{\mathrm{DR,max}} v_{j,t}^{DR} \quad (11)$$

$$\forall i: \sum_{t=1}^{\mathrm{NT}} f_{i,t}^{\mathrm{DG}} \le f_i^{\mathrm{DG,max}} \quad (12)$$

$$\forall k, \forall t: \mathrm{SOC}_k^{B,\min} \le \mathrm{SOC}_{k,t}^{B} \le \mathrm{SOC}_k^{B,\max} \quad (13)$$

$$\forall k, \forall t: P_k^{B,\min} u_{k,t}^{B,d} \le P_{k,t}^{B,d} \le P_k^{B,\max} u_{k,t}^{B,d} \quad (14)$$

$$\forall k, \forall t: u_{k,t}^{B,c} + u_{k,t}^{B,d} \le 1 \quad (15)$$

Constraint (9) indicates the requirement that generation and load have to be balanced at all times. Demand response has been modeled as virtual generation on the left hand side of (9). Equations (10) and (11) represent the lower and upper limits for capacity available through DG and DR, respectively. Equation (12) denotes the constraint on the maximum fuel available for each dispatchable DG unit over the entire dispatch period. This reflects a practical situation where the total amount of fuel that can be consumed during the repair period (here, NT hours) is limited. Equations (13) and (14) demonstrate the operational constraints of the battery. Finally, equation (15) indicates that during each time step, a battery system can be either in charging mode or discharging mode, but not both.

V. Case Study

A. Test System

The IEEE 123-bus test distribution system [22] has been used for the simulation studies (Fig. 1). This system has been expanded to include DER units, i.e. DG and batteries. The cost coefficients and other characteristics of the DER units are provided in the Appendix (see Tables A.1 and A.2). The network is an unbalanced one; therefore, different phases may have different loading levels. In addition, loads are assumed to change over the course of simulation, representing common distribution load profiles. Some of the loads are assumed to be demand responsive (see Table A.3 in the Appendix). Finally, the amount of fuel available for each DG and the fuel characteristics are presented in Table A.4 in the Appendix [23], [24]. It should be noted that the numeric values of available fuel for each DG are used here for demonstration purposes and do not alter the nature of the problem. Adopting higher or lower values would change the output of the problem, but not the methodology.

Different Microgrids can be formed based on the needs of the utility, the nature of the disturbance, and the availability of the components. In this paper, without loss of generality, it has been assumed that due to the natural disaster event, access to the main distribution substation (bus 150 in Fig. 1) is lost, and hence, a substation island [25] has been formed. Here, the utility wishes to reenergize as many loads in the system in Fig. 1 as technically possible using the available distributed energy resources in the system. The objective function (6) is therefore solved subject to constraints (9)-(15) using the GAMS/LINDO solver. The problem has been solved for 10 hours, assuming it will take the utility that long to repair the distribution substation.

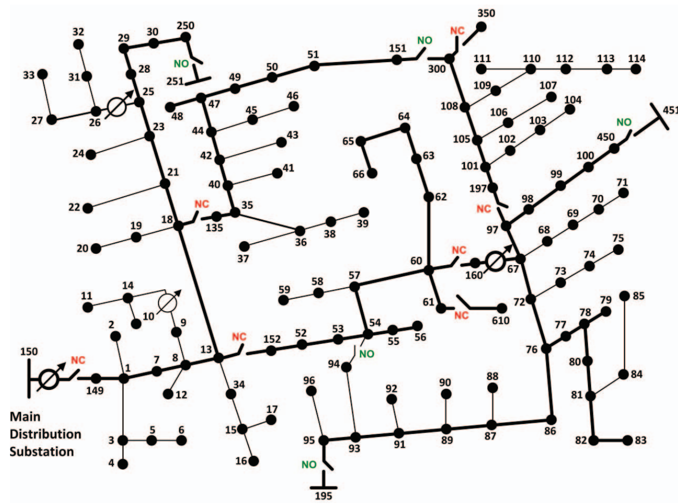

Fig. 1. IEEE 123-bus test distribution system. The entire system represents the outage area, as it has been assumed that the service from the main distribution substation is lost due to the natural disaster event.

B. Simulation Results

It is assumed that the power available through the wind and PV resources can be forecasted with relative accuracy. Figure 2 illustrates the projections used in this study.

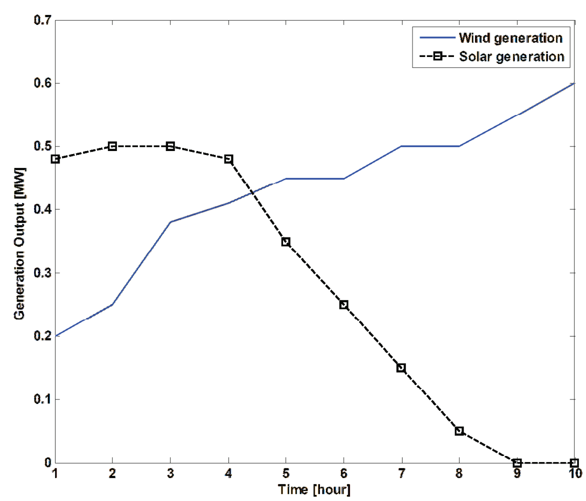

Fig. 2. Power trajectories for wind and solar.

Figure 3 illustrates how much each dispatchable DG unit will be injecting subject to the available fuel. Figures 4 and 5 depict the number of demand responsive loads activated during this period as well as the total power made available through DR. It can be seen that this resource becomes a noticeable one compared to the power made available via DG units.

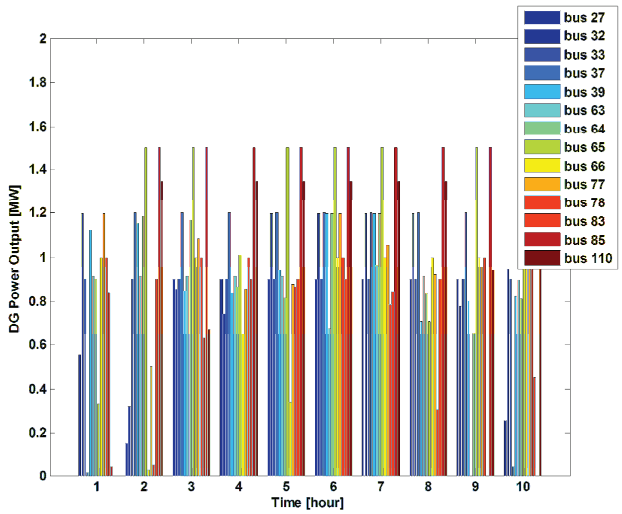

Fig. 3. Power injections by the DG units at different nodes.

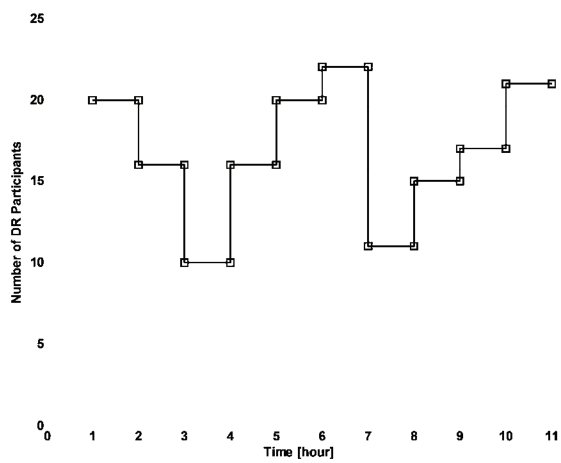

Fig. 4. Number of loads curtailed through demand response.

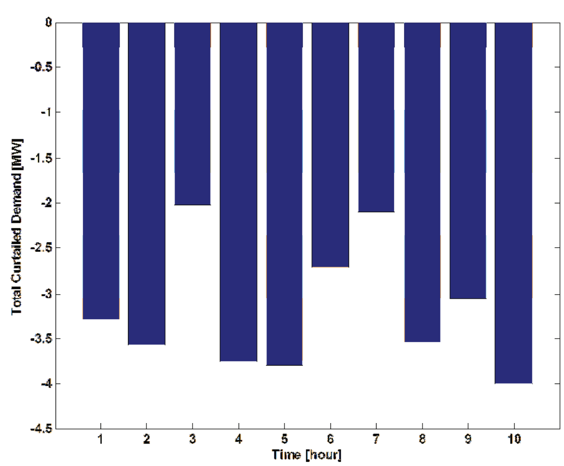

Fig. 5. Capacity relief provided through demand response.

Figures 6 and 7 illustrate the power charge and discharge associated with the batteries, as well as their states of charge. It can be seen that the SOCs for all batteries remain within bounds during the analysis timeframe. During emergency conditions such as natural disasters, the availability of fuel would be the main concern, and operational costs of resources such as batteries would be of secondary importance. It can be seen that due to the lower rates adopted here for the batteries, the dispatch solution ends up using most of their capacity first, and charging them only to ensure the minimum required SOC levels for individual batteries are not violated.

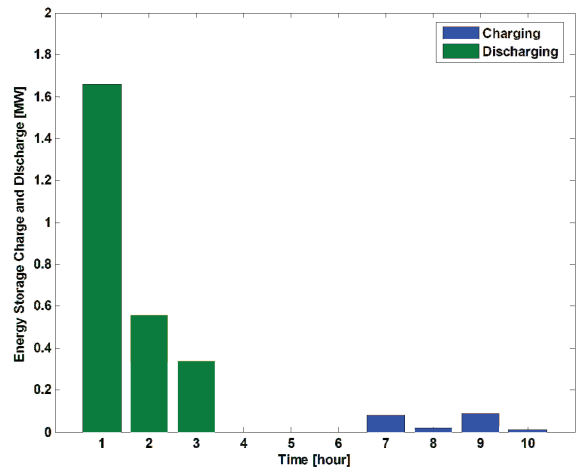

Fig. 6. Power charge and discharge of the batteries.

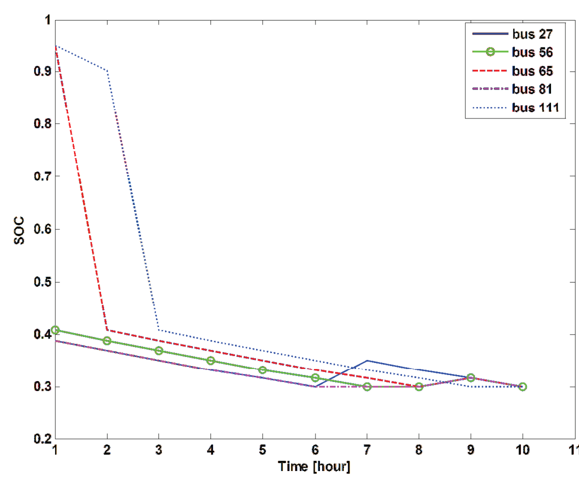

Fig. 7. SOC of individual batteries.

Clearly, the availability of fuel affects the way the energy resources will be dispatched. Lower fuel levels prompt DR loads to be utilized as much as possible, whereas higher fuel levels would typically result in more DG generation. This is illustrated in Figs. 8 and 9.

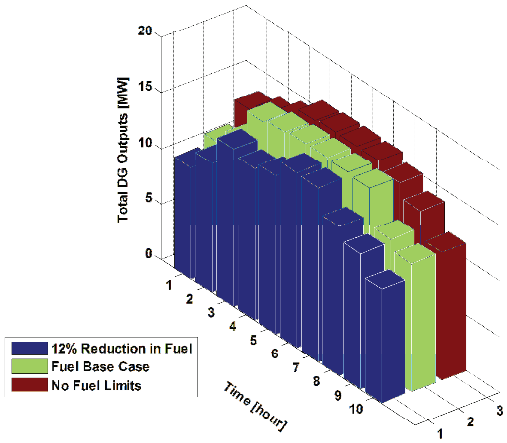

Fig. 8. Variations in DG generation based on availability of fuel.

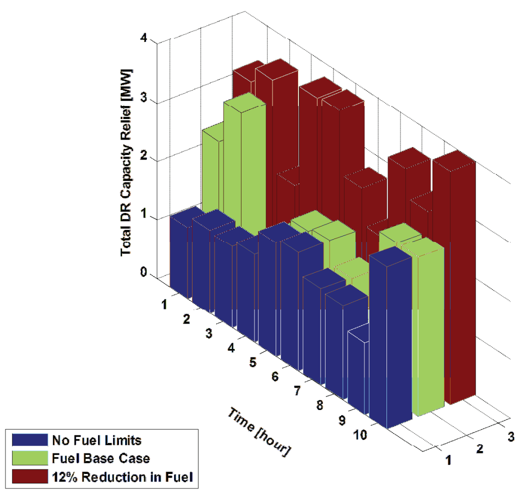

Fig. 9. Variations in DR utilization based on availability of fuel.

VI. Assumptions and Practical Considerations

Some assumptions are made in the formulation of the problem, which are briefly discussed here. First and foremost, the current paper assumes that all DER units are either owned by the utility or can be operated by it. However, if one or more units are autonomous, then the maximum capacity of those units that the utility can exploit would be limited by the bilateral contracts between the owner(s) and the utility. This would require modeling a deregulated energy market that falls outside the main scope of the paper.

The problem addressed here is an operation problem. It is assumed that the generation and storage resources are already deployed in the system, and need to be dispatched to restore electric service to the outage area. As such, the investment costs for the DER units are not included in the cost function.

It should also be noted that to operate a Microgrid, a grid-forming DER unit is needed that is able to maintain the frequency and voltage magnitude across the system. This unit must have black start capabilities in order to form the Microgrid. Once the Microgrid is formed, this unit acts as a coordinator. All other energy resources would operate in a grid-following mode, and would inject active and reactive power into the system based on the set-points assigned to them. This aspect of Microgrid formation is considered outside the scope of the operation timeframe analysis of the current paper. Here, it is assumed that the Microgrid has been formed through an appropriate black start procedure and now needs to be properly dispatched.

In addition, the current paper only focuses on the active power dispatch across the Microgrid. As such, reactive power dispatch and voltage control have not been considered. This approach has been adopted to simplify the presentation of the equations. Furthermore, this approach is often used for contingency studies such as the one presented here. However, if desired, reactive power equations and constraints can be presented the same way active power is modeled here.

Also, power losses and operational constraints on the flow of the lines have not been incorporated into the problem formulation. Although these are critical aspects of system operation during normal conditions, under emergency situations, such as the aftermath of a natural disaster event, some of these constraints may be temporarily relaxed in order to maximize the supply of power during post-disaster relief efforts. Many utilities define short-term and long-term emergency ratings for the overhead lines to be able to handle such situations [26].

Lastly, the proposed formulation allows the utility operator to reduce the load on the system by exercising demand response. DR is a voluntary form of load curtailment where the customer is reimbursed for loss of power. If DR is not available, the utility can perform load shedding. This would be an involuntary form of load curtailment. Although there are no financial reimbursements paid to the customers affected by load shedding, the utility would still be hesitant to shed load since it adversely affects its reliability indices. In case load shedding is desired instead of demand response, the third term in (6) could be replaced with a penalty term proportional to the amount of load being shed.

VII. Concluding Remarks

A solution was proposed in this paper for electric service restoration in the aftermath of a natural disaster event using decentralized supply of power. It was assumed that a widespread outage is caused by the disaster event, and connection to the main grid is lost. As a result, it is now desired to restore power to the outage area by forming a Microgrid and dispatching the distributed energy resources inside it. A nonlinear mixed-integer optimization problem was formulated and solved subject to constraints on the capacity of the energy resources and the availability of fuel. It was shown that demand response can be used to relieve some of the system capacity in order to ensure the balance between load and generation is maintained. Restoring service to the outage area in the aftermath of a natural disaster can tremendously help the first responders in relief efforts.

APPENDIX

TABLE A.1. LOCATIONS AND PARAMETERS OF DG UNITS

DG Type	No. of Phases	Bus Number	$P_i^{DG,min}$ (MW)	$P_i^{DG,max}$ (MW)	η^{DG}_i
Diesel	3	85, 65	0	1.5	0.55
	1	32, 39, 64, 77	0	1.2	0.55
Microturbine	3	110	0	1.35	0.65
	1	63, 66, 78	0	1	0.65
Fuel cell	3	37	0	1.2	0.6
	1	27, 33, 83	0	0.9	0.6
PV	3	111	N/A	N/A	N/A
Wind Gen.	3	114	N/A	N/A	N/A

TABLE A.2. LOCATIONS AND CHARACTERISTICS OF BATTERIES

Bus Number	$P_k^{B,min}$ (MW)	$P_k^{B,max}$ (MW)	Min. SOC	Max. SOC	$\eta^{B,c}_k$, $\eta^{B,d}_k$	δ_k	c^B_k ($/MW)
27,56,65	0	0.9	30%	100%	0.8	0.05	40
81,111	0	0.6	30%	100%	0.8	0.05	40

TABLE A.3. LOCATIONS AND CHARACTERISTICS OF DR LOADS

Bus Number	$P_j^{DR,min}$ (MW)	$P_j^{DR,max}$ (MW)	β_j	γ_j
27, 31, 32, 45-50, 63-66, 76-79 80-82, 84, 85, 110-114	0	0.08–0.42	160	0.1

TABLE A.4. FUEL DATA FOR DG UNITS

DG Type	No. of Phases	Fuel cost ($/fuel unit)	H_i (kWh/fuel unit)	$f_i^{DG,max}$ (fuel unit)
Diesel	3	0.8	10.53	2080
	1	0.8	10.53	1664
Microturbine	3	0.6	10.55	1576
	1	0.6	10.55	1168
Fuel cell	3	0.7	13.88	1160
	1	0.7	13.88	872

[a] Units of fuel considered in this paper are liter for diesel, m^3 for natural gas, and kg for FC fuel.

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