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Energy management system for enhanced resiliency of microgrids during islanded operation

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ABSTRACT

This paper proposes a method to enhance resiliency of microgrids through survivability. Survivability in this context is to minimize load shed for the duration the microgrid is in islanded mode following a disturbance event. During islanded operation, microgrid loads are prioritized as critical and non-critical loads. The key decision is to ascertain whether to provide energy to non-critical loads after supplying the critical loads or to store excess energy for future dispatches. This task is formulated as a non-linear programming problem. The objective is to minimize the amount of critical load shed while maximizing the amount of non-critical load served for a projected restoration time while adhering to relevant operational and physical constraints. For this extended time-scale problem, uncertainty of renewable generation and load forecast is quantified with probability distribution and confidence levels are used to establish likelihood of forecast error. Distributed generation such as solar and wind farm along with battery energy storage system are modeled. Demand response is implemented through adjustable loads and a fleet of plug in hybrid electric vehicles that can be operated in both grid to vehicle and vehicle to grid mode. Test cases are studied on a modified CIGRE microgrid benchmark test system and results are compared with a temporal decomposition scheme based energy management system.

1. Introduction

Resiliency represents the ability of power systems to withstand high-impact, low-probability events with least possible interruption of electric supply while enabling quick recovery and restoration to normal operating state [1]. According to electric power research institute (EPRI), three key aspects of enhancing grid resiliency are prevention, recovery and survivability [2]. While prevention and recovery require infrastructural and operational changes, survivability can be accommodated into existing framework. Hence, the focus of this work is on survivability of microgrids under islanded mode of operation following a high-impact disturbance event. Survivability in this context is to minimize the amount of load shed following a disturbance.

Microgrids have been an area of active research in power systems community [3–5]. Microgrids are well suited to the concept of survivability of power grid by having the means to operate in islanded mode during a large disturbance. However, depending on the restoration time and the amount of distributed generation available within the microgrid, serving all of the load might be infeasible. In addition, not all loads are equally important and can be prioritized as critical and non-critical loads.

This work is aimed at development of mathematical framework for resiliency based microgrid energy management system (EMS), specifically designed for islanded mode of operation. Relevant operational constraints such as generator operational limits, voltage constraints, reactive power requirement are imposed in the problem formulation. Storage units are modeled with a variable efficiency curve that depends on state of charge (SOC) of battery. The concept of demand response is modeled through adjustable loads and PHEVs.

The ensuing problem is modeled as a non-linear programming (NLP) problem. The developed resiliency based EMS schedules dispatches in such a way that total amount of critical load unserved during the time the microgrid is in islanded mode of operation is minimal and at the same time tries to maximize the amount of non-critical load served.

1.1. Literature review

A mathematical framework for microgrid resilient operation is developed in [1]. Both grid connected and islanded mode of

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Nomenclature

Adjustable load variables

$E_{i,a}$	energy consumed by adjustable load at *i*th node
$P_{i,a}$	power consumption of adjustable load at *i*th node

Battery variables

E_B	energy stored in BESS
E_{rating}, P_{rating}	energy and power rating of BESS
P_B^C, P_B^D	rate of charge and discharge of BESS

Generator variables

$\Delta P_{i,g}$	ramp rate of *i*th generator
$P_{i,g}$, $Q_{i,g}$	*i*th generator real and reactive power
$P_{i,var}$	variable generation/load at *i*th node

Network variables

θ_i	voltage angle of *i*th node
$P_{i,c}$, $P_{i,nc}$	critical and non-critical real power supplied at *i*th node
$P_{i,inj}$	real power injection at *i*th node
P_{ik}	real power flow between nodes *i* and *k*
$Q_{i,c}$	critical reactive power supplied at *i*th node
$Q_{i,inj}$	reactive power injection at *i*th node
$Q_{i,nc}$	non-critical reactive power supplied at *i*th node
V_i	voltage magnitude of *i*th node

Parameters

η	efficiency of BESS
$\overline{\theta_i}$, $\underline{\theta_i}$	upper and lower limit for voltage angle of *i*th node
$\overline{\Delta P_{i,g}}$	maximum ramp up rate of *i*th generator
$\overline{P_{i,a}}$	maximum power consumption of adjustable load at *i*th node
$\overline{P_{i,g}}$	upper limit for *i*th generator real power
$\overline{P_{ik}}$	real power flow limit between nodes i and k
$\overline{Q_{i,g}}$	upper limit for *i*th generator reactive power
$\overline{V_i}$	upper limit for Voltage magnitude of *i*th node
Δt	dispatch interval
$\underline{\Delta P_{i,g}}$	maximum ramp down rate of *i*th generator
$\underline{P_{i,a}}$	minimum power consumption of adjustable load at *i*th node
$\underline{P_{i,g}}$	lower limit for *i*th generator real power
$\underline{Q_{i,g}}$	lower limit for *i*th generator reactive power
$\underline{V_i}$	lower limit for Voltage magnitude of *i*th node
a, b	linear regression parameters
$E_{i,a}^d$	energy demand of adjustable load at *i*th node
G_{ik}, B_{ik}	conductance and Susceptance between nodes *i* and *k*
K_c, K_{nc}	weights for critical and non-critical load
$P_{i,d}$	real power demand at *i*th node
$Q_{i,d}$	reactive power demand at *i*th node
$t_{i,a}^{end}$	end time of adjustable load at *i*th node

Set

A	set of all adjustable loads
B	set of all buses
G	set of all generator buses
$T_{i,a}$	set of dispatches where adjustable load at *i*th node is operational
T	set of dispatches where microgrid operates in islanded mode

operation are considered. The aim is to improve the resiliency of the system by lowering the possibility of load shedding. Normal operation problem is formulated as a mixed integer linear programming (MILP) problem as this formulation includes binary variables associated with unit commitment. Resilient operation is modeled as a linear programming problem. Load modeling used in [1] includes adjustable loads with a pre-defined start and end time. Uncertainty in load and renewable sources is considered. The paper also takes into account the forecast errors of renewable sources by using a robust optimization strategy.

Ref. [6] discusses the impact of demand side bidding on microgrid operation taking into account variation in market prices, renewable energy generation and load. The paper presents two scenarios. Scenario one pertains to normal economic operation of microgrid. Second scenario is based on applying an adequacy constraint when a specific section of the microgrid has to be operated in islanded mode in the event of an upstream fault. Load shedding of both critical and non-critical loads are controlled using demand side bidding. Network constraints are not considered in this work.

The authors in [7] discuss reliability and vulnerability of microgrid operation in addition to economic considerations. A vulnerability index in terms of loss of load has been formulated to show the impact of potential outages on a system. The aim is to study the impact of undesired outages on microgrid and vulnerability index is used as a measure to determine resiliency of the system. Ref. [8] studies the impact of extreme weather on power grid resilience.

Coordination of energy storage systems to maintain frequency and voltage of microgrid during islanded mode of operation is studied in [9]. The authors demonstrate how microgrid can be resilient in the moments subsequent to islanding by maintaining its frequency and voltage within limits using storage devices. The focus of the work in [9] is limited to restoring stable operation in the moments immediately following an islanding event and not for the entire duration the microgrid remains in islanded mode.

Ref. [10] proposes a method to operate microgrids with minimum cost. Additional constraints on power exchange with the grid, generator operating limits and load curtailment of critical and non-critical loads are also considered in this work. However, network and reactive power constraints are not considered.

A multi-agent based self-healing of microgrids is proposed in [11]. A priority hierarchical controller based on a set of predefined rules is used. This work relies on agent cooperation through negotiation and the resulting self-ordering scheme enables transition from emergency to stable operating state. Phase-angle droop control scheme for microgrid is designed in [12] in order to mitigate system vulnerability to storms and hurricanes.

As noted by [1], although the use of microgrid for resiliency is well known, the mathematical modeling of microgrids based on resiliency considerations is limited. The mathematical model developed in this paper adds to the existing body of work on resiliency of power systems by including network constraints in the problem formulation while using non-linear, non-convex power injection formulation. Thus, the coupling between real and reactive power is maintained. This enables modeling voltage and reactive power constraints of the system. In addition, the problem is solved as a single large NLP optimization problem spanning multiple dispatches instead of a decomposed problem such as first solving a unit commitment (UC) problem and then solving optimal power flow (OPF) at each dispatch.

The problem studied in this paper is fundamentally different from UC and OPF decomposition. It is assumed that the total generation capacity of the microgrid is not adequate at all times to cater to microgrid loads. If not for this assumption, the problem is not much different from economic operation problem of bulk power system. With the given assumption, the need to find schedule for the available generators is not-required as it is expected that all the