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Strategic maintenance scheduling in an islanded microgrid with distributed energy resources

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ABSTRACT

This paper addresses passive and active preventive maintenance scheduling in an islanded microgrid with storage and renewable energy sources. At first, under a centralized framework, a single-level cost-minimization formulation for passive maintenance scheduling is developed and used as a benchmark in the operation. An independent microgrid operator is responsible for the operation in this framework. Then, through a bi-level formulation, the active maintenance scheduling and operation is carried out with profit-maximization objective. These two developed frameworks provide the houses with opportunity to earn profit and the regulator and the operator to analyze the performance of the system. The bi-level formulation is transformed into a single-level problem through Karush–Kuhn–Tucker conditions. Furthermore, the proposed model provides the capability of incorporating condition monitoring data into the operation. The model is validated through a test system and the outcomes demonstrate the advantages, applicability and challenges of utilizing the proposed model.

1. Introduction

The conventional electric power system is changing its form due to efforts such as reducing the greenhouse gas emissions, future scarcity of fossil fuel, shun substantial investments in power generation, deregulation, increasing the integration of distributed energy resources (DERs) (e.g. solar, wind, storage) and large deployment of advanced metering infrastructure [1]. Such transition brings about several challenges from different perspectives (e.g. integration, operation, stability, protection). In particular, rapid growth in utilization of DERs in the electric power distribution systems is gaining attention as it provides the customers with more control and flexibility on their operation and opportunity to earn profit. Therefore, the connected topics should also try to follow with this quick development. One of these topics that helps the components keep their stable operational level and contribute to acceptable reliability constraints in a power system is preventive maintenance. As an example, avoiding significant investments in the electric grid by distributing the energy generation and high integration of DERs result in increased utilization of the equipment in microgrids (MGs) and thus, higher wear in the components [2]. Therefore, a MG requires optimum preventive maintenance planning and operation scheduling; otherwise, maloperation of DERs (e.g. due to abnormal condition or failure) can endanger the security of power delivery and reduce the reliability and satisfaction of the customers from the services. [3].

Preventive maintenance scheduling can be divided into two categories of passive and active. Passive maintenance scheduling considers the outages are planned without considering the electricity market and the prices while the active maintenance scheduling considers that the outages are planned considering the change in the electricity prices. With this classification, most of the research studies in the electric power systems have been focused on the passive maintenance scheduling [4–8]. Moreover, because of the complexity of the problem, several simplifications are always considered (e.g. forecasted electricity prices, neglecting renewable resources, disregarding storage systems, ignoring health condition information). Ref. [9] proposes a maintenance scheduling model in a distribution system with the objective of minimizing total operation cost of the system. The generation companies suggest their favorable maintenance time-window and the system operator verifies whether these plans fall withing distribution system's considerations (e.g. economic, security). There are also several similar works where the focus of the problem is solely on the grid [10,11].

MGs can be considered as entities that coordinate the operation of DERs [12]. This coordination can be performed by an independent MG operator (IMGO) in a centralized or decentralized manner

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Indices:

h	index for hour
g	index for houses and diesel generator
j	index for distributed energy resources
b	index for battery storage system

Sets:

$\Gamma(g)$	houses in the microgrid

Parameters

α_g	cost of operating diesel generator ($/kWh)
C_j	cost of maintenance action for DER j ($)
B	life-cycle cost factor for battery ($/kWh)
$T_{g,j}$	required maintenance time for DER j in house g (h)
N_h	number of hours
E_j	limit on the simultaneous maintenance actions of DER j
L	maximum number of DERs that can go under maintenance simultaneously
h'	maximum limit of time to have maintenance after the alarm
g'	the house that has received the alarm signal
j'	the DER system that has received the alarm signal
$D_{h,g}$	demand at house/generator g at hour h (kW)
$Q'_{h,g,j}$	maximum available power for DER j in house g at hour h (kW)
$Q''_{h,g}$	maximum available power in generator g at hour h (kW)
M_1, M_2, M_3	large enough numbers used in linearization

Variables:

$x_{h,g,j}$	binary variable for maintenance status of DER j, in house g at hour h
$q_{h,g}$	the produced power by diesel generator g at hour h (kW)
$q'_{h,g,j}$	the produced power by DER j in house g at hour h (battery status for $j=b$) (kW)
$y_{h,g}$	charge of battery in house g at hour h (kW)
$z_{h,g}$	discharge of battery in house g at hour h (kW)
λ_{1_h}	Lagrange multiplier of demand balance
$\lambda_{2_{h,g,j}}$	Lagrange multiplier of maximum capacity limit for houses
$\lambda_{3_{h,g}}$	Lagrange multiplier of maximum capacity limit for diesel generator
$\lambda_{4_{h,g,j}}$	Lagrange multiplier of battery charge/discharge connection
$\lambda_{5_{h,g,j}}$	Lagrange multiplier of battery maximum charge
$\lambda_{6_{h,g,j}}$	Lagrange multiplier of battery maximum discharge
$\lambda_{7_{h,g,j}}$	Lagrange multiplier of battery charge link
$\lambda_{8_{h,g,j}}$	Lagrange multiplier of battery discharge link
$\lambda_{9_{h,g}}$	Lagrange multiplier of battery charging positivity
$\lambda_{10_{h,g}}$	Lagrange multiplier of battery discharging positivity
$\lambda_{11_{h,g,j}}$	Lagrange multiplier of power positivity for houses
$\lambda_{12_{h,g}}$	Lagrange multiplier of power positivity for diesel generatorv
$\lambda_{13_{h,g,j}}$	Lagrange multiplier of battery initial/final condition
$\mu_{1_{h,g,j}}$	variable for linearization of $\lambda_{2_{h,g,j}}$
$\mu_{2_{h,g,j}}$	variable for linearization of $\lambda_{5_{h,g,j}}$
$\mu_{3_{h,g,j}}$	variable for linearization of $\lambda_{6_{h,g,j}}$

[13,14]. MGs have become extremely popular due to their positive role in speeding up the transformation of the power system because of the mentioned challenges. As a result, there have been many studies on their operations and many MG projects have been developed [15–17]. For instance, Ref. [18] surveys trends for integration of wind and solar power generators from power electronics point of view and concludes that modern power electronic technologies can assist in achieving high efficiency and reliability at low costs for MGs. Ref. [19] optimizes operation of a grid-connected MG by minimizing operation and maintenance related costs of the DERs through economic dispatch formulation. It shows that when all types of sources are considered, the operation and maintenance costs are high, thus, emphasizing on importance of analyzing this topic. However, although storage can alleviate the intermittent problem of solar and wind by introducing time-shift in the energy consumption [20–22], it requires additional investments and increased operational costs. For instance, [20] shows that different types of storage systems (which can be classified based on the number of charge/discharge cycles) can have different influence on the costs and profit as the profit they bring about may not be financially better than the costs they impose. Ref. [23] minimizes the net present cost of a MG where they take into account capital, replacement, and operation and maintenance costs. It demonstrated that as the amount of interruptible load increases (e.g. load shedding due to failures or abnormal condition of equipment), the total cost of the MG decreases. However, this also reduces the satisfaction of the customers and preventive maintenance can help to overcome such shortcomings by assisting in maintaining the condition of the equipment at an acceptable level. Ref. [24] proposes a three-layer architecture for operation of MG. The proposed energy management system that schedules the operation receives the maintenance outages as inputs to the model. The maintenance is planned if the forecast results in excess power in the MG. Ref. [25] proposes a two-stage optimization model for dispatch in order to maximize the profit of a MG including storage, wind and solar. In a theoretical approach, Ref. [26] introduces a bi-level control scheme to increase reliability in a grid by taking advantage of bulk generation units. All these models neglect the mutual impact of the maintenance scheduling on the actual operation and the electricity prices.

Integrating electricity market into the operation of MG is gaining attention [27]. Performing operation of a MG through a cost-minimization framework has become very popular as it results in the least cost operation [28,16]. Ref. [29] considers a balancing market in a grid-connected MG where the users act independently and an energy manager sets the price for energy by considering the intersection of the generation and demand. The simulation model considered three consumers and DERs and set an upper limit on the price during the operation. It shows how the operation of DERs can directly affect the electricity prices while connected or in islanded mode. Ref. [30] proposes an optimization model for optimal operation of a MG with the objective of running with the least operational costs. The load curtailment is introduced as a penalty factor that displays the importance of considering the outages, which may be avoided if an efficient condition monitoring and preventive maintenance planning strategy is applied. Ref. [31] evaluates sustainability and reliability of MGs in an electricity market. It discusses how the reliability can be impacted by introducing MGs and the importance of studying other aspect of reliability such as outages which can be planned or unexpected. Ref. [32] analyzes interactions among agents in MGs through a cooperative game theoretic approach and shows how forming a MG can influence different agents in the system. It demonstrates that regulating price based on service cost can bring about market failures (i.e. misalignment between maximization of social welfare and maximization of objectives of other agents). This shows the importance of analysis of strategic behavior