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Optimum electricity purchase scheduling for aggregator storage in a reliability framework for rural distribution networks

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ABSTRACT

The inclusion of Renewable Energy Resources (RER) and Electric Energy Storage (EES) can significantly improve the reliability of rural feeder customers with no cross connect switches to alternative supply. In such setups, there can be a financial incentive for aggregators to facilitate bulk storage to deal electricity with energy supplier and customers by using optimal scheduling strategy. Within this context, this paper proposes a framework for network reliability assessment to include bulk storage scheduling strategy in the evaluation. In this technique, seasonal effects on load demand and RER output, electricity market price, islanding provisions and EES state of charge (SOC) are taken into consideration. Finally, a case study is presented to illustrate the application of this approach and to evaluate the results.

1. Introduction

In rural networks with long feeders, cross connect switches to alternative supply feeders may not be economically viable, or even be practically possible. In such cases often poor reliability is reported, for instance; as noted in a utility Distribution Annual Planning Report (DAPR) [1]. Inclusion of EES facilities in these networks not only reduces energy and peak network costs for the customer, it can significantly improve customers' reliability by making some islanding operation possible. Generally, customers are reluctant to invest and manage such expensive devices, therefore aggregator owned bulk storage is recommended in literature [2–6]. But, in addition to EES, the inclusion of customers' RER in rural distribution networks can also complement financial benefits to both aggregators and customers. Nonetheless, such network arrangements can introduce complications in terms of reliability assessment. Commonly, reliability evaluation methods are categorized into two main techniques; simulation and analytical methods. Both techniques are based on failure mode and effect analysis (FMEA) for evaluating load points and system reliability indices [7]. With the integration of Photovoltaic (PV) resources and EES into the distribution system new evaluation approaches are required to assess the reliability, with different modes of operation. As part of maximizing the cost benefit operation of storage, an economic charge/discharge scheduling strategy is required for bulk storage devices to take advantage of market price changes. This scheme needs to be coupled with probabilistic network outage events for long term economic viability and network planning purposes.

The reliability assessment methods and various storage scheduling strategies cited in the literature are briefly discussed in the following. In [8] the reliability improvement of a distribution system which incorporates energy storage and renewable energy generation is investigated. A Model Predictive Control (MPC) based operation strategy for the energy storage considering wind turbine as the renewable energy source, and a framework for reliability assessment has also been proposed. In [3] an intelligent operation strategy for energy storage that can improve reliability and be integrated with renewable energy is presented. This approach uses smart grid communication and centralized network control to implement the proposed energy storage operation. A sequential Monte Carlo method has been used for reliability evaluation. This requires a long convergence time and uses a type of data which may not easily be available.

Researches on strategies to evaluate smart grid reliability have also been proposed in the literature. In [9] a scenario based technique has been proposed to assess distribution system reliability with renewable distributed generators. Related analytical methods are taken into account including islanding operation, load shedding and curtailment policies in this approach. The proposed procedures for reliability evaluation in the foregoing research work can notably be reduced by using a segmentation based strategy proposed in [10]. Normally, a long rural feeder with its radial branches can be formed into segments. A segment is part of distribution network that starts with a protective device such as an automatic

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Nomenclature

b	number of segments
c	case index
c_{ch}	price of extra PV energy to charge EES (\$/kWh)
c_t	tariff price (\$/kWh)
c_g	electricity locational marginal price (\$/kWh)
CB	circuit breaker
d	number of load points in the network
d_{MPP}	DC power output drop above STC temperature (25°)
E_{ch1}	energy to charge EES from utility (kWh)
E_{ch2}	energy to charge EES from PV surplus generation (kWh)
E_{chmax}	maximum charging power limit (kW)
E_{dis}	energy discharged from EES (kWh)
E_{dismax}	maximum discharging power limit (kW)
E_g	total purchased energy from utility (kWh)
E_{pv}	total generated RER (PV) energy (kWh)
E_L	total load energy demand (kWh)
η_c	charging efficiency including inverter losses
η_d	discharging efficiency including inverter losses
η_{inv}	inverter efficiency
h	number of load points inside the segment
i	segment index where fault occurs
j	segment index where the load points locate
k	line index
LS	lower shoulder price (\$)
$L_{soiling}$	soiling loss
LMP	locational marginal price (\$)
LP	load point
$\lambda_k^{s,i}$	failure rate of kth line inside segment i
λ^s	segment failure rate matrix
$\lambda^{LP,s}$	load point failure rate affecting by fault in other segments
λ^{LP}	load point failure rate affecting by fault in the same segment
λ_k	failure rate of line k inside a segment
m	number of lines in network
$M1$	segments' interconnection relationship matrix
$M2$	segments and CBs' interconnection relationship matrix
MP	mean price (\$)
N	number of time periods (e.g. 24 for one day)
n	number of lines inside the segment
nc	number of cases
$NOTC$	nominal operation cell temperature (manufacturer)
p	load point index
P_{ac}	AC power output
P_{dc}	DC power output
$P_{PVarray}$	nominal cell output power
ρ	probability of available cases
S	insolation in mW/cm^2
SOC	state of charge of EES at the end of period t
S^p	segment number that includes load point p
SSE	sum of squared errors
t	time period
T_{amb}	ambient temperature
T_{cell}	cell temperature
t_{sr}	alternative supply restoration time
t_{sw1}	island formation time for a fault outside the segment
t_{sw2}	fault isolation time for a fault inside the segment
t_r^k	repair time of line k
U^{LP}	load point outage time affecting by fault in the same segment
$U^{LP,s}$	load point outage time affecting by fault in other segments
U^s	segment outage time matrix
US	upper shoulder price (\$)

switch/recloser, as the only protective switch in this segment [8]. In such modeling [11] if a failure occurs downstream of a switch in the segment, all the customers in that segment and the downstream segments will be disconnected from the grid supply [8]. In such events, even with possible islanding operation, some loads in the affected segments may still experience a limited outage immediately after a fault. The reliability evaluation method based on segmentation, proposed in [10], considers distributed generators, where the reliability has been evaluated considering load curtailment for some of the islanding situations.

With the emerging distribution networks and the corresponding solutions offered as discussed above, an opportunity is recognized for aggregators to invest and manage segment based bulk storage. This opportunity occurs as a result of hourly (as modeled in this paper) or half-hourly change in grid electricity market price, customers' load demand, and surplus PV generation. In this context, an aggregator can buy and store customers' surplus PV generation and/or grid electricity during daily low price periods and sell it in the peak load demand period. This dealing arrangement can benefit both customers and aggregator.

The research work in this paper proposes an optimum economic strategy for purchase of electric energy in a framework where an aggregator operates existing bulk storage in dealing with both retailer and customers. In this context, a systematic approach is developed to evaluate network reliability while considering the planned scheduled storage. The main contribution of this paper is establishing a systematic reliability evaluation method suitable for large and complex networks as in this method a large network is broken into a number of small networks for simplifying the reliability assessment. Moreover, scheduled EESs and hourly PV generation in normal and islanding situations are considered in the reliability assessment. This approach can also include power exchange between electrically linked island segments with different levels of PV and EES. In fact, this work provides a systematic link between long term assessment and short term operation in order to minimize energy cost and improve system reliability. This work also contributes aggregators and retailers to manage their storage to get financial benefit while improving the reliability of their customers.

The remaining sections of the paper are organized as follows. Section 2 provides problem formulation and methodology. Section 3 presents a case study following with the conclusions in Section 4.

2. Problem formulation and methodology

In a distribution network, aggregator is responsible to provide power to its customers. It also operates EESs in the distribution network. The aggregator aims to minimize the energy costs of the network by using flexible operation of EESs to store low cost energy and dispatch in peak load hours. The other objective of aggregator is to use EESs as an alternative supply in islanding operation mode to supply loads independently and improve the reliability of the system. In this section a scheduling strategy for the aggregator to minimize the energy costs using k-means clustering