A Conceptual Framework for Determining the Economically Optimal Level of Microgrid Resilience

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Abstract. Microgrids are considered to be an effective measure for resilience due to their ability to operate in island mode during a power outage and to ensure continuity of supply. Current standard frameworks for microgrid resilience evaluation overlook the economic parameters, which are important for decision-making about investments in resilience enhancement. To bridge this gap, a new methodology is proposed in order to evaluate the economically optimal level of microgrid resilience. An availability-based resilience evaluation framework is used for quantification of the resilience using both a deterministic and a stochastic approach. The quantified resilience values are monetized using the economic indicator Value of Lost Load. The economically optimal resilience level is evaluated using the Net Present Value capital budgeting method.

Keywords: Resilience · Microgrid · Economic evaluation

1 Introduction

Storms, hurricanes, floods, wildfires, and other natural disasters may result in major disruptions to the power supply. The increased frequency and severity of natural disasters in recent years have necessitated the enhancement of the resilience of power grids. The losses due to electrical outages have a large negative economic impact. Hence it is important to mitigate these impacts in the future to a reasonable extent. In this context, the resilience of the power grid comes into the picture. The resilience of power grids is the ability of a grid to adapt and recover from extreme events.

Microgrids are considered to be one of the most effective measures to increase resilience during natural disasters because of their ability to isolate themselves

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from the main grid during the occurrence of an outage and to maintain continuity of supply to the local load [1]. Microgrids are a part of the power grid, having their own local distributed generation resources and being able to operate autonomously to supply local loads and thus reducing the impact of any disaster. While planning a microgrid for resilience purposes, it is important to quantify the level of resilience of the microgrid in order to evaluate its preparedness for extreme events. Since the enhancement of microgrid resilience involves significant capital investment, it is important to determine the economic value of the resilience in order to decide about the optimal level of resilience that a microgrid should possess. Currently, there is no standard to measure the economic value of microgrid resilience, which is one of the challenges when designing a microgrid for resilience enhancement purposes [2].

This study aims to propose a new methodology in order to evaluate the economically optimal level of resilience for a microgrid. First, the concept of availability-based resilience evaluation is discussed in Sect. 2. The quantification of microgrid resilience using a deterministic versus a Markov-chain-based stochastic approach is presented in Sect. 3. In Sect. 4, it is discussed how the measured resilience value can be translated into an economic metric using the Value of Lost Load (VoLL) [5]. A methodology is then proposed to evaluate the optimal resilience enhancement option which justifies the cost of resilience enhancement. In Sect. 5, the applicability of the proposed methodology is discussed, conclusions drawn, and some ideas for future research outlined.

The proposed methodology evaluates the resilience of a microgrid only during its islanded operation and not in grid-connected mode. But the suggested framework can easily be extended to include the grid-connected operation of the microgrid as well. Also, it is assumed that during a disaster, the microgrid is not physically damaged and that the microgrid resources are able to serve the load. Partial supply of load is not considered yet in the proposed approach.

2 Resilience Evaluation Framework

This work uses the so-called availability-based resilience measurement framework for measuring microgrid resilience, as proposed in [3]. US Presidential Policy Directive (2013) on Critical Infrastructure Security and Resilience defines Resilience as ‘the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions’. According to the proposed framework, the resilience of a microgrid can be measured as a quantity corresponding to the availability. Hence, the resilience level R of the microgrid can be calculated as

$$R = \frac{T_U}{T_D + T_U}, \tag{1}$$

where T_U is the uptime of the microgrid during the outage and T_D is the downtime. The sum of T_D and T_U denotes the total resilience evaluation time T. This equation gives a suitable measure of resilience within the context of the definition provided above. The downtime T_D is related to the recovery speed and is influenced by both the available infrastructure and to human-related activities such as repairs and maintenance policies. The uptime T_U is directly dependent on the withstanding capability of the microgrid to the given event. Its value is mostly related to infrastructure characteristics and grid design.

Although preparation/planning capacity and adaptation capability are not directly reflected in the resilience measurement, they influence the resilience metric indirectly. For example, they will be reflected in the resilience values of two different scenarios. Scenarios may differ in the available generation capacity or storage capacity of the microgrid and will give two different values for resilience. This difference will indicate a change in resilience when adopting different technological or infrastructure improvements in the microgrid. A comparison between the two resilience values will represent the planning capacity and adaptability of scenarios. This quantifiable difference can be used in conjunction with a cost analysis and a probabilistic evaluation to decide the priority, based on the resilience level and the costs of implementing different scenarios.

3 Resilience Quantification

The uptime for the microgrid is considered to be the time when the microgrid can satisfy the load demand by using its own resources. The downtime is the rest of the time when the microgrid is not able to serve the loads. Let $G[t]$ be the fitness function indicating the ability of the microgrid to serve the loads. At every time instance t, $G[t]$ measures the total difference between the capacity of the microgrid resources available (energy supply + energy storage) and the load demand, i.e.

$$G[t] = X[t] + B[t] - L[t], \tag{2}$$

where $X[t]$ is the energy supplied by the source in time interval t, $L[t]$ is the energy load during time interval t, and $B[t]$ is the energy in the battery storage at time interval t. Function $G[t]$ indicates the ability of the energy source and the battery to serve the load at time interval t. Function $G[t] > 0$ indicates that there is surplus energy in the grid, whereas $G[t] < 0$ indicates that there is an energy deficiency. If $f_X[t]$ is the probability distribution of $X[t]$, $f_L[t]$ is the probability distribution of $L[t]$, and $f_B[t]$ is the probability distribution of $B[t]$ at time t, then the probability distribution of $G[t]$, i.e. $f_G[t]$, can be calculated using Eq. (2). The resilience of the microgrid $R[t]$ at time t is given as

$$R[t] = Pr(G[t] \geq 0) = \sum_{g \geq 0} f_{G[t]}, \tag{3}$$

i.e. the resilience $R[t]$ is equal to the probability that the microgrid resources can satisfy the load demand at time instance t (probability of $G[t] \geq 0$). To find the probability distribution of $G[t]$, i.e. $f_G[t]$, the probability distributions of $f_X[t]$, $f_L[t]$ and $f_B[t]$ are required. The probability distribution of battery storage $f_B[t]$ depends upon the probability distributions of the energy source and the load, i.e. $f_X[t]$ and $f_L[t]$.

Deterministic Computational Approach: The deterministic approach evaluates resilience by calculating the availability of the microgrid. This method can be used to analyze the best- and the worst-case scenario. Figure 1 shows the algorithm developed for an example microgrid having a PV system and Li-ion battery storage as its only resources. This algorithm takes into account bidirectional energy flows and maintains a minimum state of charge in the battery during normal operation. The battery is allowed to discharge fully in the case of an outage. Since the deterministic approach provides a range of resilience values possessed by the microgrid (based on the best- and the worst-case scenario), it has limitations and does not provide any generalized value that can be used directly for resilience planning and investment decisions.

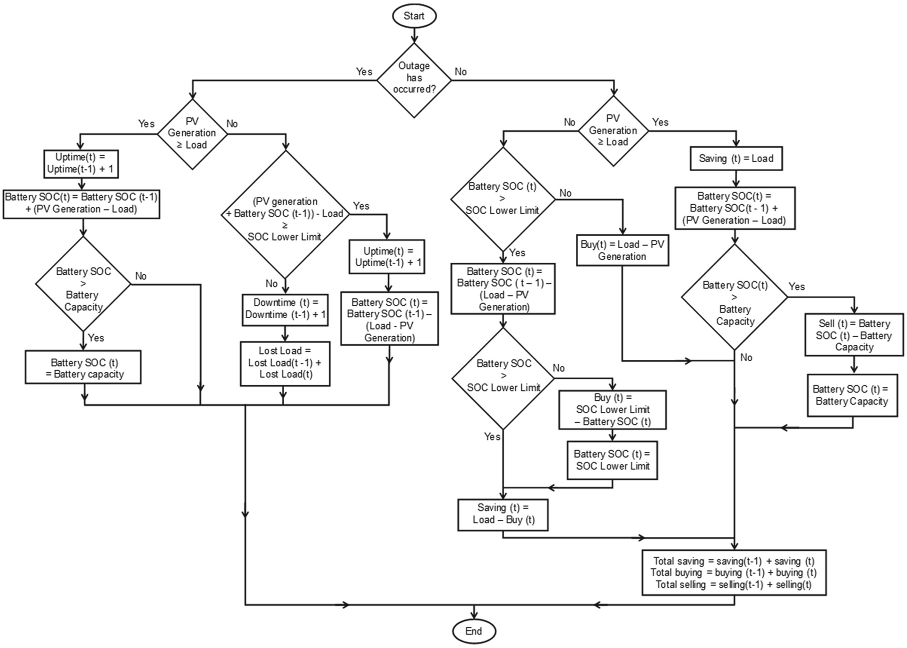

Fig. 1. Flowchart of the computational method adopted

Markov-Chain-Based Approach: The Markov-chain-based approach provides generalized value for resilience of the microgrid by calculating the probability of a microgrid being available to supply the load demand considering a large amount of possible values of load and generation. The stochastic data is generated using the Monte Carlo method to acquire more accurate availability results. The Markov chain model is designed according to the model proposed in [4]. The Markov chain model for microgrid resilience quantification is summarized in a flowchart in Fig. 2. Once π_E is known, the availability A and resilience

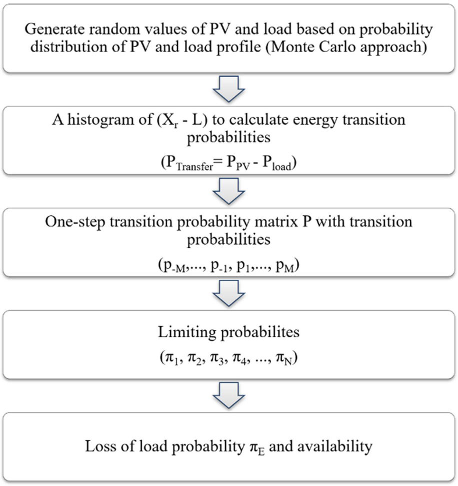

Fig. 2. Summary of Markov-chain-based method

R can be calculated as

$$R = A = 1 - \pi_E \tag{4}$$

4 Economically Optimal Level of Resilience

The methodology for finding the optimal level of resilience considers the economically optimal investment in resilience. To analyze the optimum investment in resilience, it is important to figure out how much the resilience value is from the consumer's perspective. VoLL is a monetary indicator expressing the costs associated with the interruption of electrical supply in $€/kWh$ [5]. The resilience values obtained can be translated into economic values using the VoLL specification in Eq. (5), where h denotes the average duration of the outage.

$$VoLL_{Total} = h \times (1 - R) \times (VoLL_{PerUnit} \times Avg.Load) \tag{5}$$

VoLL, as an economic metric to monetize resilience, is complementary to the availability-based resilience measurement framework. The greater the availability of the system, the less the economic impact due to the lost load is. The most resilient case is the one resulting in the least $VoLL_{Total}$.

The investment needed to obtain a certain level of resilience and the economic benefits due to resilience are compared with each other in order to find the economically optimal level of resilience by using the Net Present Value approach. The benefits G obtained from resilience are calculated as follows.

$$G_{Resilience} = VoLL_{Total(BaseCase)} - VoLL_{Total(ResilientCase)} \tag{6}$$

The methodology is further detailed in [9] for the case of a stylized microgrid (incl. results).

5 Conclusion and Outlook

In this paper, we have presented a new methodology for evaluating the economically optimal level of resilience in a microgrid using an availability-based resilience framework. Deterministic and stochastic approaches for resilience measurement are explained. The main aim of this work is to introduce an economic evaluation framework which monetizes the resilience value in order to facilitate the decision-makding process involved in the identification of optimum technologies for enhanced resilience.

The methodology proposed is also useful to evaluate different economic and policy instruments, such as feed-in tariffs and subsidies, and to observe the change in economic performance due to these interventions. In future research, the methodology can be extended to take into account the stochastic nature of the duration of an outage and change in load demand. This methodology can also be used in conjunction with more sophisticated optimization techniques with the objective of minimizing the total Value of Lost Load.

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