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Reliability improvement in radial electrical distribution network by optimal planning of energy storage systems

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A B S T R A C T

This paper provides an optimal approach to denote the location and size of ESSs (energy storage systems) with the intention of reliability improvement in radial electrical distribution networks. The proposed optimal ESSs planning is addressed as a minimization problem which aims at minimizing the cost of ENS (energy not supplied) as well as ESSs costs at the same time, subject to safe operation of the network; where, the safe operation is guaranteed through satisfying security constraints such as voltage and line-flows limits. The minimization problem is mathematically formulated as a mixed-integer nonlinear programming and solved by PSO (particle swarm optimization) algorithm. A comprehensive sensitivity analysis is carried out on the results such as ESSs numbers, ESSs cost and reliability parameters. Simulation results demonstrate the viability of the proposed method in the real networks. Results also indicate the positive impact of ESSs on the network reliability. The proposed ESSs planning significantly reduces the ENS of the network and can be employed to deal with low reliability issues in the real networks.

1. Introduction

Radial electrical distribution networks are the most conventional configuration of distribution networks. In these systems, feeders are extended from the distribution substations to the lateral feeders and all consumers are supplied through these lateral feeders. This simple configuration provides some advantages such as low cost, simplicity of the network topology and the simple protection system [1]. On the other hand, low reliability issues due to the radial structure can be stated as the worst disadvantage of these networks. In such networks, each disconnection in a feeder leads to disconnecting all loads on the feeder. Thus, such networks are exposed to the highest rates of interruption [1].

Regarding the low reliability issues of radial electrical distribution networks, several methods have been reported to improve the reliability in such networks. Network reconfiguration is one of the main methods which has been proposed to increase the network reliability [2]. The approach addressed in Ref. [2] proposes the reconfiguration problem on three radial distribution networks of 33-bus, 69-bus, and 136-bus. Where, the reconfiguration problem minimizes the network loss as well as maximizes the network reliability subject to the network constraints of performance. It is indicated that network reconfiguration can successfully improve the network reliability in the radial distribution networks. Electrical distribution network planning can also be considered as a suitable method to improve the network reliability [3]. The Methodology presented in Ref. [3] expresses the distribution network expansion planning problem as a mixed integer linear programming and solves it using pseudo-dynamic planning approach. Where, simulation results are carried out on a 54-bus distribution network and demonstrate the effectiveness of the given reliable planning on the network reliability. Energy expansion planning has also been proposed to improve the network reliability [4]. In the approach given by Ref. [4], an expansion planning for electrical and thermal energy distribution systems is presented. Where, the problem aims at minimizing the investment and operational costs as well as improving the reliability of the network based on the reliability indexes of SAIFI (system average interruption frequency index), SAIDI (system average interruption duration index), and AENS (average energy not supplied). It is demonstrated that the contributed methodology can effectively improve the network reliability. Reference [5] proposes an optimal switch allocation in

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radially operated distribution networks for reliability enhancement. Where, sectionalizing and link switches with manual or automatic control strategies are well-thought-out in the solution methodology. The approach addressed by Ref. [5] minimizes the costs of switch allocation and reliability index of energy not supplied (ENS), at the same time. It is indicated that optimal switch allocation reduces the cost and improves the network reliability through significant ENS reduction. Advanced design of distribution automation devices (e.g., automatic re-closers) has also been addressed for reliability improvement in distribution networks [6]. The method addressed by Ref. [6] suggests contingency-load-loss-index for reliability assessment and improves the reliability though optimal allocation of automatic re-closers. Simulation results on two distribution networks 54-bus and 100-bus demonstrate that the advanced design of distribution automation devices can enhance the reliability of the network based on the contingency-load-loss-index. DG (distributed generation) has also be utilized to enhance the network reliability [7]. DGs provide numerous advantages in distribution networks such as reliability improvement [7]. DGs in distribution networks are mainly classified as intermittent and dispatchable DGs. The dispatchable based DGs can operate under islanding condition and therefore improve the network reliability [7]. Optimal allocation of dispatchable based DGs for reliability enhancement has been studied by Ref. [7]. The approach presented in Ref. [7] evaluates the network reliability through a reliability index which is defined as “customers' willingness to pay” to prevent power interruptions. In Ref. [7], DG planning is carried out to minimize the DG cost and improve the network reliability, at the same time. It is demonstrated that DGs can effectively enhance the network reliability based on the defined index.

Regarding the above issues, it can be concluded that many approaches have been addressed to improve the network reliability. Furthermore, with respect to the reliability concept, it seems that ESSs (energy storage systems) can also impact on the network reliability. But, ESSs have not been adequately studied to improve the reliability in distribution networks. Therefore, this paper addresses the reliability improvement in radial electrical distribution networks by optimal planning of energy storage systems. Next subsection introduces the applications of ESSs in the electrical networks. Then, the functions and technologies of ESSs are discussed and eventually, the orientation of the paper is presented.

1.1. ESSs applications in electrical networks

ESSs mainly convert electrical energy into a more convenience storable form for converting back to the electricity when required. ESSs have been widely developed in electrical networks. Mitigating the uncertainties related to the renewable energy resources is one the main applications of ESSs [5–8]. Nowadays, wind farms are increasing their part of the energy production in electrical networks in the world. The incapability of wind farms to match demand power profiles increases the requirement for large ESSs. The ESSs are capable to balance the instability of wind farms and shifting the generated power during low demand to peak periods [5,8]. Furthermore, ESSs have been successfully utilized in cooperation with solar power plants [6,7] and photovoltaic systems [9]. The ESSs have also been widely utilized in microgrids networks. Microgrids are mainly equipped with renewable energy resources such as photovoltaic systems, solar-thermal systems, geothermal heat pump, and wind units [10,11]. In such systems, ESSs play a fundamental role in the management of the microgrids demand and produced energy by renewable energy resources. Where, ESSs collect renewable energy during day-time to release it during night-time, or store renewable energy during low demand to release it during high demand and effectively shave the peak of the demand [10,11]. The ESSs are also utilized in electricity market to mitigate the risk of the private participants [12,13]. The methodology specified in Ref. [12] addresses an optimal allocation of ESSs for risk mitigation of DISCO (distribution company) with high renewable penetrations. Where, the risk of price volatility in electricity market is mitigated through optimal sizing and siting of ESSs based on the cost-benefit analysis approach. The planning given by Ref. [13] also utilizes ESSs together with wind power plants in deregulated electricity market. The other ESSs applications in electric power systems can be summarized as frequency control [14], stability improvement [15], power quality enhancement [16,17], increasing transmission line capacity [15,18], reliability improvement in generating systems [19], peak load shaving and load leveling [20,21]. Furthermore, by installing large-scale ESSs, network planners would need to build only sufficient generating capacity to meet average electrical demand rather than peak demands [22].

1.2. Functions and technologies of ESSs

Regarding the function of ESSs, electrical energy storage technologies are usually intended for energy management or power quality-reliability issues [23]. The technologies related to the power quality issues include low energy content ESSs such as supercapacitors [24], SMES (superconducting magnetic energy storage) [25], flywheels [26], and batteries [27]. On the other hand, the energy management technologies comprise large energy content ESSs such as PHS (pumped hydroelectric storage) [28], CAES (compressed air energy storage system) [29], TES (thermal energy storage) [30], large-scale batteries [31], flow batteries [32], and fuel cells [23,33].

Additionally, electrical storage technologies are classified based on the form of storage. In this respect, subsequent technologies are utilized [23,24,33,34]; (i) Electrical energy storage techniques including electrical field storage (super capacitors), and magnetic field storage (SMES) [23]; (ii) Mechanical energy storage systems containing kinetic energy storage (flywheels), and potential energy storage (PHS and CAES) [24]; (iii) Electrochemical energy storage approaches comprising conventional batteries (e.g., lead-acid, nickel metal hydride, lithium ion), and flow batteries (e.g., zinc bromine and vanadium redox) [31]; (iv) Chemical energy storage methods consist of fuel cells, molten-carbonate fuel cells-MCFCs, and Metal–air batteries [23]; (v) Thermochemical energy storage approaches involving solar hydrogen, solar metal, solar ammonia dissociation–recombination, and solar methane dissociation–recombination [23]; (vi) Thermal energy storage systems including low temperature energy storage (e.g., aquifer cold energy storage, cryogenic energy storage), high temperature energy storage (e.g., steam or hot water accumulators, graphite, hot rocks, and concrete), and latent heat systems (e.g., phase change materials) [23,35,36].

1.3. Orientation of this paper

This paper addresses an optimal ESSs planning to denote the place and size of ESSs in radial electrical distribution networks. The proposed planning aims at improving the network reliability by minimizing ENS (energy not supplied). The problem is expressed as a mixed-integer nonlinear programming and solved by PSO (particle swarm optimization). It is shown that ESSs can successfully improve the network reliability through reducing ENS index.

It is worth remarking that ESSs planning can also be considered together with other devices expansion such as transformers and distribution lines. But, expansion of transformers and distribution