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Multistage distribution network expansion planning considering the emerging energy storage systems

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ABSTRACT

This paper addresses multistage distribution network expansion planning (DNEP) incorporating energy storage systems (ESSs). The ESSs are utilized to shave the peak demand and to reduce the planning cost. Annual and daily load duration curves are considered to evaluate the impacts of the ESSs on the planning. The proposed planning is carried out based on the AC power flow including active power, reactive power, and network loss. The problem is formulated as a constrained, mixed-integer, and nonlinear programming (MINLP) and solved by using particle swarm optimization (PSO) algorithm. A 11 kV and 30-bus radial distribution network is considered as case study and the typical ESSs are also regarded to install on the network. Simulation results demonstrate the effectiveness and viability of the proposed method to consider the ESSs in DNEP. The results indicate that integrating the ESSs in DNEP reduces the planning cost significantly, as well improves the technical parameters of the network such as bus voltages and line loading.

1. Introduction

Energy storage is mainly defined as converting energy from the forms which are difficult to store (e.g. electrical energy) to more convenient storable forms. In electrical networks, the electrical energy storage is defined as the process of converting electricity into a more convenient storable form for converting back to the electricity when needed. This procedure enables the electrical energy to be stored at the times of low demand or low generation cost and to be used when needed. In recent years, electrical ESSs have been widely developed for a variety of reasons including deregulation of the electric power systems toward electricity market, power quality issues and growth of the renewable resources penetration. In this regard, many governments (e.g. USA, EU, Japan and Australia) have launched their national programs on the ESSs [1–5].

With respect to the function of the ESSs, electrical energy storage technologies are mainly designed for (i) power quality-reliability issues or (ii) energy management [1]. The technologies related to the power quality issues comprise low energy content ESSs including super-capacitors [4], superconducting magnetic energy storage (SMES) [6], flywheels, and batteries [7]. On the other hand, the technologies related to the energy management issues have large energy content ESSs comprising pumped hydro-electric storage (PHS) [8], compressed air energy storage system (CAES) [9,10], thermal energy storage (TES) [3,11], large-scale batteries [12], flow batteries [13] and fuel cells [1,2].

As well, storage technologies for electrical energy are classified by the form of storage. In this regard, following technologies are utilized [1–4]: electrical energy storage techniques [1], mechanical energy storage systems [4], electrochemical energy storage approaches [12], chemical energy storage methods [1], thermo-chemical energy storage systems [1] and thermal energy storage procedures [1,14,15].

The ESSs provide many applications in electric power systems including mitigating the renewable resources uncertainties [16–18], micro-grid applications [19,20], risk mitigation in electricity market [21], frequency-voltage control, stability enchantment, power quality-reliability improvement, congestion relief, peak load shaving, and load leveling [22]. Additionally, by installing large-scale electricity storage capacity, the network planners would need to build only sufficient generating capacity to meet the average electrical demand rather than the peak demand [23].

With respect to the rapid developments and applications of the ESSs in electric power systems, it is valuable to investigate the impacts of the ESSs on the power system studies such as distribution network expansion planning (DNEP). The DNEP is a problem which denotes where, when and how many new lines should be installed in the distribution network to serve the growing demand

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in the future [24]. The DNEP has been widely investigated through various objective functions, design variables and constraints [24,25], taking into account static [25] and dynamic [26] planning periods, modeling different loads (e.g. one load level, multi-load levels, probabilistic or fuzzy load levels) [24], and incorporating distributed generation (DG) [27]. Besides, DNEP is a constrained, nonlinear, and mixed integer optimization problem which has been successfully solved by several mathematical and Meta-heuristic methods [24]. The DNEP considering DGs and storage units has also been investigated by [28]. The objective function of [28] aims at minimizing the investment-operational costs of the DGs, storage units and lines. As well, the reliability cost is considered in the planning. The storage units have been modeled by a simple charging–discharging equation. It can be concluded that the main purpose of [28] is not to focus on the ESSs in DNEP and the paper only partially deals with the storage units.

Regarding the above mentioned issues and the conducted literature review, it is valuable to study DNEP with main focus on the ESSs. In this regard, this paper presents an advanced methodology for DNEP taking into account the ESSs. In the proposed method, the ESSs are used to shave the peak demand. The problem is mathematically formulated as a nonlinear, constrained, and mixed integer optimization problem and solved by using PSO. The AC power flow formulation considering active–active powers and network loss is proposed. Simulation results emphasize on the viability and flexibility of proposed DNEP including the ESSs through the proposed method.

With respect to the discussed issues, the contributions of the current paper can be stated as follows; this paper considers a dynamic (multistate) DNEP comprising several stages which is similar to the real problems. In this study, the ESSs are included in DNEP, and this issue has been rarely addressed by the previous studies. This coordinated ESS-DNEP significantly impacts on the problem and provides suitable financial-technical results. This paper uses AC power flow which comprises active–reactive powers and network loss; while, most of the studies perform DC power flow without considering reactive power and loss. A large number of the options are considered as the candidate places and the candidate capacities to install the ESSs. This issue expressively increases the flexibility of the problem. An ill-conditioned radial distribution network is regarded as test system for taking into account the real world distribution networks.

Apart from this introductory, the rest of this paper is organized as follows; the energy storage systems are described in section two. Section three provides the mathematical formulation of the problem. The details of the proposed method are completely described in section four. Illustrative test case and system data are given in section five and the simulation results are presented in section six. Eventually, section seven is devoted to the discussions and conclusions.

2. Energy storage systems

Fig. 1 shows a typical ESS. The ESSs mainly produce a DC voltage by using an energy storage device such as battery. This DC voltage is converted to a controllable AC voltage by using DC–AC converter and the AC voltage is increased by step-up transformer and sent to the AC network. The output AC voltage of the converter (voltage on AC terminal in Fig. 1) is characterized by three parameters of magnitude, phase angle and frequency. These three parameters can be regulated through controlling pulse width modulation (PWM) signal of the converter [29]. In Fig. 1, the active (P) and reactive (Q) powers between the AC terminal and the AC network can be controllably exchanged through controlling the magnitude and phase angle of the voltage on the AC terminal, and afterward, the ESS can absorb or supply P or Q [29]. In this regard, four possible cases can be derived as Table 1. Therefore, the ESSs can be considered as the

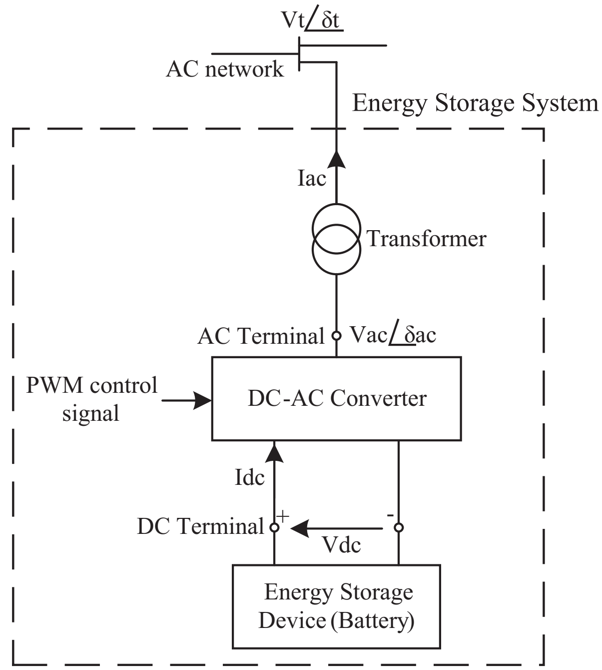

Fig. 1. Typical ESS installed on the AC system through DC–AC converter.

controllable loads or the generators. These controllable devices can store energy for the duration of charging state and supply it to the network for the period of discharging state. Basically, charging and discharging states are specified by the network operator subject to the load levels. The ESSs are charged when the demand is low (or the generated power is more than the demand). Then, at the time of high demand, the ESSs are discharged to supply the demand. During mid-load levels, the ESSs can be disconnected from the network to reduce the unnecessary loss [1].

3. Problem formulation

The proposed planning aims at minimizing the investment and operational costs over the planning horizon. The planning objectives are defined in the following.

3.1. Investment cost of the new lines

Before providing mathematical formulation, it can be stated that, in finance, each cost is often discounted back to its present value and then, the net present value is described as the sum of the present values of costs over the planning horizon [30]. Regarding this issue, the investment cost of the lines at each stage can be given as (1) and the last term of (1) is used to convert the investment cost to the present value. Where, of_1 shows the investment cost of the new installed lines at stage t ($/stage t), the vector Lt indicates number of the new installed lines at stage t, vector ILt specifies the cost of the lines at stage t, T represents the stages of the planning horizon and, r specifies the discount rate. It should be remarked that Lt is one of the design variables of the problem.

$$of_1 = L_t \times IL_t \times \frac{1}{(1+r)^{t-1}} \quad \forall t \in T \quad (\$/\text{stage } t) \qquad (1)$$

Table 1
Possible cases to exchange power through the ESSs.

$\delta_{ac} > \delta_t$	ESS supplies P
$\delta_{ac} < \delta_t$	ESS absorbs P
$V_{ac} > V_t$	ESS supplies Q
$V_{ac} < V_t$	ESS absorbs Q