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Impacts of optimal energy storage deployment and network reconfiguration on renewable integration level in distribution systems

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HIGHLIGHTS

- A dynamic and multi-objective stochastic mixed integer linear programming model is developed.
- A new mechanism to quantify the impacts of network flexibility and ESS deployments on RES integration is presented.
- Optimal integration of ESSs dramatically increases the level and the optimal exploitation of renewable DGs.
- As high as 90% of RES integration level may be possible in distribution network systems.
- Joint DG and ESS installations along with optimal network reconfiguration greatly contribute to voltage stability.

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ABSTRACT

Nowadays, there is a wide consensus about integrating more renewable energy sources-RESs to solve a multitude of global concerns such as meeting an increasing demand for electricity, reducing energy security and heavy dependence on fossil fuels for energy production, and reducing the overall carbon footprint of power production. Framed in this context, the coordination of RES integration with energy storage systems (ESSs), along with the network's switching capability and/or reinforcement, is expected to significantly improve system flexibility, thereby increasing the capability of the system in accommodating large-scale RES power. Hence, this paper presents a novel mechanism to quantify the impacts of network switching and/or reinforcement as well as deployment of ESSs on the level of renewable power integrated in the system. To carry out this analysis, a dynamic and multi-objective stochastic mixed integer linear programming (S-MILP) model is developed, which jointly takes the optimal deployment of RES-based DGs and ESSs into account in coordination with distribution network reinforcement and/or reconfiguration. The IEEE 119-bus test system is used as a case study. Numerical results clearly show the capability of ESS deployment in dramatically increasing the level of renewable DGs integrated in the system. Although case-dependent, the impact of network reconfiguration on RES power integration is not significant.

1. Introduction

1.1. Background and motivations

Driven by a number of technical, economic and structural factors, the integration of renewable energy sources (RESs) is gaining an unprecedented momentum in many countries all over the world. In other words, the level of RESs integrated in power systems is increasing worldwide. Some of the main reasons that explain the massive integration of RESs are the continuous growth of energy consumption worldwide, the environmental issues associated with energy production (pollutant and inefficient production practices) and the climate change concerns [1,2]. Policy makers in many states across the globe are setting forth ambitious RES integration targets [3]. This is expected to reduce the energy production from conventional sources such as oil, gas and coal, which currently provide about 80% of primary energy worldwide according to the report in [4]. Despite the increasing trend of RES

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Nomenclature

Sets/indices

$g/\Omega^g/\Omega^{DG}$ index/set of generators/DGs
k/Ω^k index/set of branches
s/Ω^s index/set of scenarios
t/Ω^t index/set of time stages
w/Ω^w index/set of snapshots
$\varsigma/\Omega^\varsigma$ index/set of substations

Parameters

$ER_g^E, ER_g^N, ER_\varsigma^{SS}$ emission rates of existing and new DGs, and energy purchased, respectively (tCO_2e/MW h)
$IC_{g,i}$, IC_k, IC_{tr}, $IC_{es,i}$ investment cost of DG, line, transformer and energy storage, respectively (M€)
$LT_{es}, LT_g, LT_k, LT_{tr}$ lifetimes of energy storage, DG, distribution line, and transformer system, respectively (years)
MC_{es}^E, MC_{es}^N maintenance cost of existing/new storage per year (M€)
MC_g^E, MC_g^N maintenance costs of existing and new DGs (M€/yr)
MC_k^N, MC_k^E maintenance cost of new and existing line (M€/yr)
MC_{tr}^N, MC_{tr}^E maintenance cost of new/existing transformer per year (M€)
$OC_{g,i,s,w,t}^E, OC_{g,i,s,w,t}^N$ operation cost of unit energy production by existing and new DGs (€/MW h)
$\eta_{ch,es}, \eta_{dch,es}$ charging/discharging efficiency
$\lambda_{s,w,t}^{CO_2e}$ price of emissions (€/tons of CO_2 equivalent)
$\lambda_{s,w,t}^{es}$ variable cost of energy storage (€/MW h)
$\lambda_{s,w,t}^{\varsigma}$ price of electricity purchased (€/MW h)
μ_{es} scaling factor
ρ_s, π_w probability of scenario s and weight (in hours) of snapshot group w
$\upsilon_{s,w,t}$ penalty for unserved power (€/MW)

Variables

$D_{s,w,t}^i$ active power demand at node i (MW)
$E_{es,i,s,w,t}$ reservoir level of ESS (MW h)
$I_{es,i,s,w,t}^{ch}, I_{es,i,s,w,t}^{dch}$ charging/discharging indicator variables
$P_{es,i,s,w,t}^{ch}, P_{es,i,s,w,t}^{dch}$ charged/discharged power (MW)
$P_{g,i,s,w,t}^E, P_{g,i,s,w,t}^N$ active power produced by existing and new DGs (MW)
$P_{k,s,w,t}$ power flow through branch k (MW)
$P_{\varsigma,s,w,t}^{SS}$ active power imported from grid (MW)
$u_{g,i,t}$, $u_{k,t}$ utilization variables of existing DG and lines
$x_{g,i,t}, x_{es,i,t}, x_{k,t}, x_{tr,ss,t}$ investment variables for DG, storage systems, transformer and distribution lines, respectively
$\delta_{i,s,w,t}$ unserved power at node i (MW)
$\varphi_{k,s,w,t}$ losses associated to each feeder (MW)

Functions

EC_t^{DG} expected cost of energy from DGs (M€)
EC_t^{ES} expected cost of energy from energy storage (M€)
EC_t^{SS} expected cost of energy purchased from upstream (M€)
$EmiC_t^{DG}$ expected emission cost of DG power production (M€)
$EmiC_t^N, EmiC_t^E$ expected emission cost of power production using new and existing DGs, respectively (M€)
$EmiC_t^{SS}$ expected emission cost of purchased power (M€)
$ENSC_t$ expected cost of unserved power (M€)
$InvC_t^{DNS}$, $MntC_t^{DNS}$ NPV investment/maintenance cost of DNS components (M€)

developments, mainly wind, solar and geothermal, their share in the primary energy is still very low, standing at 0.5% according to [4]. Generally, increasing RES integration and reducing heavy dependence on fossil fuels for energy production has been at the forefront of the goals set by several countries, resulting in a significant increase of RES in the recent years [5]. This urgency comes mainly from the need to reduce greenhouse gases, a large portion of which comes from conventional energy sources [6]. In the long term, the energy production share of RESs is expected to increase between 30 and 80% by 2100 [7]. Such wide range estimation comes from the present uncertainty surrounding the efforts of decommissioning nuclear power plants. In this regard, only a few countries such as Germany have so far shown determination to scale down or even permanently abolish using nuclear sources for energy production [8].

The transition from conventional to "clean" energy power generation paradigm involves a significant number of social, economic, environmental, political and technological factors [9]. With these changes, the creation of a standard set for renewable and environmental policies, which lead to the direct creation of a new chain of value, is required. The development of such strategies will cause geopolitical changes in the energy area [10].

Among the vast non-conventional generation sources, solar and wind power sources have been especially attracting large-scale investments in recent years. In particular, the level of RES-based distribution generation (DG) has been steadily increasing in many electrical distribution systems. However, the integration of RESs has certain challenges [11]. The most prominent challenge emanates from the nature of such resources. These resources are subject to natural variation and partial unpredictability (uncertainty), both of which make the operation, control and planning of power systems very complicated. In addition, the integration of RESs (if not properly planned and managed) may pose technical challenges such as uncertain current flows and voltage violations, network congestion and increasing losses among others. These challenges are especially critical at distribution levels as the reliability, power quality and system stability could be undermined. To overcome or alleviate the negative consequences of RES integration in the distribution systems, a number of smart-grid related technologies and concepts are available which can be rolled out in coordination with the variable energy sources. Among these technologies, energy storage systems (ESSs) have been poised to be viable solutions to increase the level of penetration of RES-based distributed generations while minimizing their side effects [12]. The use of ESS "levels" the gap between renewable generation and demand by storing energy in periods of low electricity demand or high production from renewable energy sources, and releasing the stored energy in periods of higher demand [13]. Such a practice brings about several technical and economic benefits especially in terms of cost reduction as well as reliability, power quality and stability improvements in the system. In addition, distribution reconfiguration can increase the flexibility of the network system, possibly paving the way to an increased penetration level of variable energy sources.

Given the background, this paper develops a new joint optimization model that maximizes the RES integration in distribution network systems. The model simultaneously determines the optimal allocation, sizing and timing of DGs as well as ESSs. In addition,