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Factor analysis based optimal storage planning in active distribution network considering different battery technologies

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HIGHLIGHTS

- A novel four-layer approach for optimal battery planning is presented.
- Factor analysis is used for wind power data mining.
- Different battery technologies are compared.
- The technical and economic uncertainties are taken into account.

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ABSTRACT

Today's batteries are commercially developed technologies and are commonly used for energy storage in active distribution grids. In spite of their numerous advantages, batteries are expensive; consequentially, they should be installed and managed in an optimal manner. Furthermore, every battery technology has particular technical and economic characteristics that may be particularly well- or poorly-suited to certain applications. This paper represents a comparison based optimal planning of several battery technologies to find the best choice in distribution grid applications. The proposed planning methodology is a novel four-layer procedure that considers the uncertainty of battery characteristics as well as load and wind power. The long-term planning layer optimizes the location, capacity and power rating of batteries. The short-term scheduling layer includes the probabilistic optimal power flow with respect to technical constraints. In the uncertainty modeling layer, the technical and economic characteristics of battery technologies and load demands are modeled using fuzzy values. Moreover, in order to consider the correlations and independencies of the wind power profiles, they are classified to several categories using factor analysis technique in the classifying layer. The numerical results show that Zn-Br technology is the most suitable option in deterministic studies, however, the Na-S technology can be an alternative in uncertain conditions. Several sensitivity analyses are carried out to generalize and extend the results. Finally, it is found that more storage capacity is required in realistic conditions thanks to using factor analysis technique.

1. Introduction

Nowadays, energy storage units are used in Active Distribution Networks (ADNs) due to several advantages such as dispatching the renewable-based Distributed Generation (DG) resources, peak shaving, reliability enhancement and voltage regulation [1]. In [2], an optimal scheduling is proposed for storage units aiming at energy management and reliability enhancement of an AND, handling the uncertainty of wind energy, load and plug-in electric vehicles using point estimate method. Optimal load shifting by storage scheduling is discussed in [3], and a comparison study is presented for two different retail tariffs, i.e. a time-of-use tariff and a real-time-pricing tariff. Moreover, the project benefits are investigated from both economic and environmental pollution points of view. Reducing the voltage violations by using a coordinated control strategy based on Photovoltaic (PV) and battery energy storage, a methodology is proposed in [4] for improvement of the voltage profile. In [5], a comprehensive review on different types of energy storage systems including pumped hydro, compressed air, super capacitors, superconducting magnetic, flywheels, batteries, and fuel cells is presented for wind power integration support. A dynamic programming method is proposed in [6], where compressed air energy storage is considered to accommodate intermittency of

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Nomenclature

Abbreviations
ADN Active Distribution Network
DG Distributed Generation
PV Photovoltaic
PSO Particle Swarm Optimization
FLF Fuzzy Load Flow
FA Factor Analysis
POPF Probabilistic Optimal Power Flow
O&M operation and maintenance
HV/MV high voltage/medium voltage
ENS Energy Not Supplied
SOC State of Charge
SA Simulated Annealing
GA Genetic Algorithm
LCA life cycle assessment

Variables
OF objective function
IC investment cost
OC operation cost
RC reliability cost
PEN penalty factor
C_{ST}^{INSC} installation cost function considering the storage capacity
C_{ST}^{INSP} installation cost function considering the storage power rating
C_{ST}^{REPC} replacement cost function considering the storage capacity
C_{ST}^{REPP} replacement cost function considering the storage power rating
CAP_k^{ST} capacity of the k-th storage
PR_k^{ST} power rating of the k-th storage
OC_{yr} annual operation cost
$Infr$ inflation rate
$Intr$ interest rate
T period of the project
C_{ST}^{OM} O&M cost function of battery
$C_{s,t}^{SS}$ cost of purchased energy at s-th HV/MV substation in t-th hour
$AILR$ annual increment load rate
λ_e rate of e-th failure event
CO outage cost function
P_e^{OT} interrupted load due to e-th failure event
r_e outage duration due to e-th failure event
P_t^u active power of equipment u at time t
$P_{\max}^u$ maximum allowed active power of equipment u
Q_t^u reactive power of equipment u at time t
$Q_{\max}^u$ maximum allowed reactive power of equipment u
$SOC_{k,t}$ SOC of the k-th battery at time t
$SOC_{k,\min}$ minimum allowed SOC of the k-th battery
$SOC_{k,\max}$ maximum allowed SOC of the k-th battery
η efficiency of storage unit
$P_{k,t}^{ch}$ charge power of the k-th battery at time t
$P_{k,t}^{disch}$ discharge power of the k-th battery at time t
$V_{l,t}$ voltage magnitude in l-th load node at time t
$V_{\min}$ minimum allowed voltage magnitude
$V_{\max}$ maximum allowed voltage magnitude
$S_{s,t}^{SS}$ power of s-th HV/MV substation at time t
$S_{d,t}^{DG}$ power of d-th DG unit at time t
$S_{k,t}^{ST}$ charge/discharge power of k-th storage unit at time t
$S_{l,t}^{LD}$ load demand of l-th node at time t
S_t^{LOSS} total power loss in distribution network at time t
$n_{V,t}^{VIO}$ number of nodes in which the voltage magnitude constraint is violated (at time t)
$n_{S,t}^{VIO}$ number of devices in which the capacity constraint is violated (at time t)
$\tilde{A}$ a fuzzy number
$\tilde{B}$ a fuzzy number
$\tilde{F}$ a fuzzy number
F defuzzified form of $\tilde{F}$
X_i the i-th measured variable
F_i the i-th factor
a_i factor scores for variable i
d_i part of variable X_i which cannot be explained by the factors
ω_i the i-th eigenvector
$|\gamma_i|$ the i-th eigenvalue
φ rotation angle
FF final objective function
OF_g objective function considering the g-th group of wind profiles
w_g number of wind samples in g-th group
PF price factor
Pc_{peak} electricity price in peak load
Pc_{normal} electricity price normal load
Pc_{light} electricity price in light load
FRF failure rate factor

Matrices
R rotation matrix
Λ_{m} loading matrix

Indices
n_{ST} number of all installed storage units
n_{SS} number of all HV/MV substations
n_{EV} number of all possible failure events in distribution network
n_{EQ} number of all devices
n_{LD} number of all load nodes
n_{DG} number of all DG units
n_{GR} number of all groups
k storages
s HV/MV substations
yr years
t hours
e events
u equipment
l loads
d distributed generations
g groups

wind and PV energy. In [7], an energy management strategy based on flywheel energy storage is presented. The wind power smoothing is considered in the objective function, and GAMS software is used to solve the problem.

Among the energy storage technologies, the batteries have been widely considered to be utilized in power distribution networks [8]. Although the batteries bring important advantages to the distribution grids, they are expensive technologies because of