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A scenario-based voltage stability constrained planning model for integration of large-scale wind farms

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ABSTRACT

Recently, penetration of intermittent power sources has been increased in power systems due to an international drive for clean and sustainable energies; but these alternative sources could encounter power systems with some problems, which need planning and prevention. This paper proposes a two-stage scenario-based planning model for large-scale wind farms development, based on a project management approach. Considering a 10-year project of large wind farms development, the annual installation capacities of wind turbines are first optimally planned in order to minimize the Levelized Cost of Energy (LCOE) of wind farms. Second, as wind power penetration is consistently increasing in the grid, some stability concerns will come up such as voltage instability. To remedy this condition, the optimum dispatch of grid's conventional power sources and control variables is determined in such a way that not only in any state of operation (taking into account wind and load uncertainties) but also in post-contingency conditions, the prescribed security margin is ensured at the lowest possible cost. This study has been conducted on an actual power system of Iran's southeast grid, as well as IEEE 118-bus standard test system. Also, modified crow search algorithm (MCSA) is utilized to solve the developed optimization model. The numerical studies substantiate the effectiveness of the proposed method for long-term planning of wind farms.

1. Introduction

1.1. Background and motivations

Despite the fact that renewable energy sources and their integration into power grids are somewhat new, stability and control problems are not new issues in power industries. However, maintaining the voltage stability of power systems at the presence of renewable power sources is one of the new challenges faced by power system operators. While the growing penetration of wind energy in global power systems brings more green energy and less dependency on fossil fuels, risk assessment of this new type of power source is becoming more important. One of the most important issues is replacement of conventional power plants with uncertain wind farms and consequently reduction in dispatchable reactive power sources. This issue could be a source of voltage instability especially in high levels of wind power penetration or in weak grids [1]. The other issue is wind farm output power fluctuations that can degrade the grid voltage stability, due to the surplus or shortage of injected power [2]. Therefore, Preventive control is needed to be applied not only to restore the system from an unsecure to a secure state (i.e. from a negative to a zero margin) but also to maintain adequate security margins.

1.2. Literature review

In recent years, several research studies have been conducted worldwide, which have addressed different aspects of wind power impact on voltage stability of power systems. For example in [1], the voltage stability margin (VSM) of power system is enhanced by optimal allocation of wind capacity, or in [2] an optimization-based method is developed for optimal usage of energy storage equipment to smooth out the output power of wind farms in order to enhance the grid voltage stability.

Ref. [3] studies the steady state voltage stability of a power system with a high penetration of wind power and analyzes the impact of high penetration of wind power on the voltage stability of a power system. The authors in [4] studied the feasibility of injecting reactive power of variable-speed wind turbine generators into the grid in order to support

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Nomenclature

Sets

NB	set of buses
NG	set of generators
NL	set of branches
NT	set of transformers
NG_b	set of generators connected to bus b

Indices

T	index of year
S	index of load-wind dependent scenarios
i, j	counters
q, b, l	indices of transformers, buses and lines
$iter$	CSA optimization iteration counter

Parameters

N	number of wind turbine operation year
N	number of wind farms construction year
P_D/Q_D	active and reactive load demand (MW/MVar)
P_G/Q_G	active and reactive output power of generator (MW/MVar)
Q_G^{min}/Q_G^{max}	reactive power limits of each generator (MVar)
P_G^{min}/P_G^{max}	active power limits of each generator (MW)
V_b^{min}/V_b^{max}	voltage limits of bus b
S_l	power transfer capacity of line l
$E_{g\text{-}2024}$	energy demand of grid at year 2024 (MWh)
$E_{wf\text{-}2024}$	wind farm produced energy at year 2024 (MWh)
$P_{wf\text{-}r}$	rated output power of wind farms (MW)
$P_{wt\text{-}r}$	rated output power of wind turbines (MW)
$v_{\mathrm{cut.in}}/v_{cut.out}$	cut-in/out speed of wind turbine (m/s)
v_{rated}	rated wind speed of wind turbine (m/s)
$v_{w,min}/v_{w,max}$	lower and upper limits of wind scenarios (m/s)
v_w	wind speed in w-th independent wind scenario (m/s)
$L_{d,min}/L_{d,max}$	lower and upper limits of load scenarios (MW)
L_d	load value in d-th independent load scenario (MW)
π_w/π_d	probability of independent wind/load scenario
π_s	probability of dependent wind-load scenario s
a, b, c	coefficients of generator cost function
C/K	scale/shape parameter of Weibull distribution
$\gamma, \delta, \sigma, \zeta$	parameters of Johnson-SB distribution
λ_{des}	desired loading margin
Fl	flight length of crow i at iteration *iter* in crow search algorithm
AP	awareness probability of crow j at iteration *iter* in crow search algorithm
A	flight length decrement coefficient in modified crow search algorithm
r/e	nominal discount rate/inflation rate
C_{ins}	wind turbines installation cost per MW (USD/MW)
$C_{o\&m}$	wind turbines O&M cost per MWh energy (USD/MWh)

Variables

$V_{b,s,t}/\theta_{b,s,t}$	voltage/angle of bus b at scenario s, year t (pu)
$P_{D\ b,s,t}/Q_{D\ b,s,t}$	active/reactive demand of bus b in normal operating point at scenario s, year t (pu)
$P_{G\ b,s,t}/Q_{G\ b,s,t}$	active/reactive generation of bus b in normal operating point at scenario s, year t (pu)
$P_{wf\ b,s,t}/Q_{wf\ b,s,t}$	active/reactive generation of wind farms in normal point at scenario s, year t (pu)
$S_{l,s,t}$	transfer capacity of line l in normal operating point at scenario s, year t (pu)
$\hat{V}_{b,s,t}/\widehat{\theta}_{b,s,t}$	voltage/angle of bus b in collapse point at scenario s, year t (pu)
$\hat{P}_{D\ b,s,t}/\hat{Q}_{D\ b,s,t}$	active/reactive demand of bus b in collapse point at scenario s, year t (pu)
$\hat{P}_{G\ b,s,t}/\hat{Q}_{G\ b,s,t}$	active/reactive generation of bus b in collapse point at scenario s, year t (pu)
$\hat{P}_{wf\ b,s,t}/\hat{Q}_{wf\ b,s,t}$	active/reactive generation of wind farms in collapse point at scenario s, year t (pu)
$\hat{S}_{l,s,t}$	transfer capacity of line l in collapse point at scenario s, year t (pu)
P_{wt}	wind turbine output power (MW)
$P_{wf(t)}$	available capacity of wind turbines in wind farm at year t (MW)
P_t	annual installation capacity of wind turbines (MW)
$TC(t)$	total cost of energy production by conventional units in year t (USD)
I_t	investment cost of wind turbines in year t (USD)
M_t	operation and Maintenance cost of wind turbines in year t (USD)
E_t	wind generated electrical energy in year t (MWh)
X	control variables in optimization problem
x	search positions in crow search algorithm
λ	loading margin index

Abbreviations

VSM	Voltage Stability Margin
ORPD	Optimal Reactive Power Dispatch
FACTS	Flexible AC Transmission Systems
HVDC	High Voltage DC
DFIG	Doubly-Fed Induction Generator
PDF	Probability Distribution Function
GEP	Generation Expansion Planning
TEP	Transmission Expansion Planning
LDC	Load Duration Curve
WECC	Western Electricity Coordination Council
STR	Single Turbine Representation
O&M	Operation and Maintenance
LCOE	Levelized Cost of Energy
CSA	Crow Search Algorithm
MCSA	Modified Crow Search Algorithm
PSO	Particle Swarm Optimization
NPV	Net Present Value
TSR	Tip Speed Ratio

and improve the VSM in steady state operation. The impact of large wind farms on voltage and angle stability is also studied in [5] and the impact of FACTS devices on grid stability is investigated. It is worth mentioning that due to increasing demand of power systems and also lack of financial resources, the expansion of power grid and especially transmission lines, has been severely limited. As a result, some transmission lines are operated near their maximum power transfer limit. FACTS devices have been used widely to cope with these stability problems [6], but it should be noted that high degree of compensation can even reduce the security limits under some conditions. Although in remedies such as [2,5,6], some equipment are used to increase the VSM of wind penetrated power systems, but it should be mentioned that such devices are expensive with high maintenance costs. Therefore, these methods are not always the best choices for a developing country with a large geographical area such as Iran. Hence, in this paper it is tried to cope with the problem of voltage stability economically via available