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Adaptive robust AC optimal power flow considering load and wind power uncertainties

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A R T I C L E I N F O

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A B S T R A C T

This paper proposes a tri-level adaptive robust AC optimal power flow (AR-ACOPF) model incorporating wind units. The uncertain wind power production as well as the system demand are characterized in terms of bounded intervals forming a polyhedral uncertainty set. The proposed model is robust against any realization of uncertain parameters (i.e. wind power production and system demand) within the uncertainty set. Also the robustness of the solutions is controlled through a parameter denominated budget of uncertainty. Since the proposed tri-level model is not solvable via an off-the-shelf optimization package, a decomposition strategy relying on primal and dual cuts is proposed to solve it. To reduce the computation burden of the proposed AR-ACOPF problem, an effective initialization process is also presented. The proposed AR-ACOPF model and solution approach are illustrated using the well-known IEEE 300-bus and Polish 2746-bus test systems.

1. Introduction

The optimal power flow (OPF) is a common and frequently used operational tool in power systems. Mainly, OPF aims at obtaining the optimal operating state of a power system based on a specific objective function (commonly minimum cost) while both units and system constraints are satisfied. The OPF problem is usually modeled as a mixed integer and nonlinear (MINLP) optimization problem which is hard to solve [1–3]. Recently, the increasing penetration of intermittent renewable energy sources, such as wind power, has made this problem even more challenging. As the OPF is a large-scale and complex optimization problem, some of the previous research works have neglected the uncertainty sources and developed deterministic models [1–5]. However, deterministic OPF results may be non-optimal or even insecure when the power system deviates from the forecasted conditions such as forecasted wind power production or system demand. Therefore, to ensure security while considering uncertainties in the OPF problem, stochastic programming (SP) has been widely used [4–11]. Note, however, that SP characterizes the uncertain parameters by means of scenarios. Accordingly, the optimal solution of a SP problem is only guaranteed to be feasible for the scenarios considered in the model. Moreover, the solution space of a SP problem depends on the number of uncertain parameters and the number of scenarios. Accordingly, SP faces two challenges: (1) becoming intractable for large-scale optimization problems, and (2) requiring a detailed distributional knowledge of uncertain parameters, information that is rarely available in practice [12].

To overcome SP difficulties, robust optimization [12] has recently attracted an increasing attention. However, previous robust OPF research works consider DC power flow equations instead of AC ones [13]. In a DC representation, voltage magnitudes and reactive powers as well as their constraints are neglected. As a result, the obtained solutions might be inaccurate or even insecure.

To overcome the aforementioned limitations, this paper proposes an adaptive robust OPF model with AC constraints (AR-ACOPF), characterizing the uncertainties pertaining to wind power productions and system demands in terms of bounded intervals rather than scenarios. Also, the effect of contingencies is considered in this work using a prespecified set of these contingencies. In comparison to the robust AC unit commitment (ACUC) presented in [14], the following differences can be mentioned:

(1) In the ACUC work in [14], the second level considers DC power flow equations. However, in this OPF work, a new linearization process is applied to the AC power flow equations to find the worst-case realization of the uncertain parameters. Unlike DC power flow equations, the linearized AC power flow equations consider reactive power and voltage magnitude, which increases the accuracy of the second level.
(2) In the ACUC work in [14], only the uncertainty of wind power is

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Nomenclature

Indices

n index of thermal units
i/k index of buses
s index of iterations
l index of branches
m index of break points
s' index of out-of-sample scenarios

Parameters

A_n, B_n, C_n the coefficients of the quadratic cost function pertaining to thermal unit n
PLC_n^m the production cost of power segment P_n^m
Cw_i the marginal cost of the wind unit at bus i
C^{Sh} cost of unserved load
C_n^U/C_n^D cost of the up/down deployed reserve of thermal unit n
G_{ik}/B_{ik} conductance/susceptance of line i-k
μ budget of uncertainty
$\Gamma_{ik}^{max}/\Gamma_{ik}^{min}$ maximum/minimum limits of Γ_{ik}
$\theta_{ik}^{phase\ max}/\theta_{ik}^{phase\ min}$ maximum/minimum limits of θ_{ik}^{phase}
$Q_i^{C\ max}/Q_i^{C\ min}$ maximum/minimum limits of Q_i^C
P_n^{max}/P_n^{min} maximum/minimum active power output of thermal unit n; $P_{n,m}^{max}/P_{n,m}^{min}$ are maximum/minimum limits for segment m of thermal unit n
Q_n^{max}/Q_n^{min} maximum/minimum reactive power output of thermal unit n
$R_n^{U,max}/R_n^{D,max}$ maximum up/down reserve capacity of thermal unit n
$\overline{Pw}_i$ forecasted wind power output of the wind unit at bus i
$\overline{Pd}_i$ forecasted load demand of bus i
$\widehat{Pw}_i/\widehat{Pd}_i$ deviation of $\widetilde{Pw}_i$ and $\widetilde{Pw}_i$ from $\overline{Pd}_i$ and $\overline{Pw}_i$, respectively
$\widetilde{Pw}_i^{\,s}/\widetilde{Pd}_i^{\,s}$ the worst case realization of Pw_i/Pd_i at iteration s
$\overline{Pw}_i^{\,s'}/\overline{Pd}_i^{\,s'}$ realizations of Pw_i/Pd_i at scenario s'
pf_k power factor of the demand at bus k
$\Delta V_k^{max}/\Delta V_k^{min}$ maximum/minimum value for ΔV_k
BF_l^{max} maximum capacity of branch l
$\mathbb{M}$ sufficiently large constant

Sets

ω^{DC} set of dual cuts generated by the third-level problem
ω^{PC} set of primal cuts generated by the second-level problem
ω^{ACOPF} set of ACOPF constraints for continuous decision variables
ω^{LACOPF} set of linear ACOPF (LACOPF) constraints for continuous decision variables
$\omega^{\mathrm{I-OPF}}$ set of OPF constraints for integer decision variables
ω^I set of buses
ω^w set of wind units
ω^{NG} set of thermal units
ω^{NG_k} set of thermal units connected to node k
ω^L set of lines
ω_n^{BP} set of break points for thermal unit n
$\omega^{s'}$ set of out-of-sample scenarios
ω^{US} uncertainty set

Variables

Γ_{ik} tap setting of the tap-changing transformer i-k; Γ_{ik}^s indicates Γ_{ik} at iteration s
θ_{ik}^{phase} setting of the phase shifter i-k; $\theta_{ik}^{phase^s}$ indicates θ_{ik}^{phase} at iteration s
Q_i^C setting of the shunt capacitor/reactor of bus i; $Q_i^{C^s}$ indicates Q_i^C at iteration s
P_n / Q_n active/reactive power of thermal unit n; P_{ns}/Q_{ns} indicate P_n/Q_n at iteration s
P_n^m active power output of thermal unit n in segment m of the piece-wise linear approximation of its cost function; P_{ns}^m indicates P_n^m at iteration s
$Pr_{ns'}^U/Pr_{ns'}^D$ up/down deployed reserve of thermal unit n in scenario s' of the out-of-sample analysis
P_i^{sp} spillage of the wind unit at bus i; P_{is}^{sp} indicates P_i^{sp} at iteration s; $P_{is'}^{sp}$ indicates P_i^{sp} in scenario s' of the out-of-sample analysis
P_i^{Sh} unserved load at bus i; P_{is}^{Sh} indicates P_i^{Sh} at iteration s; $P_{is'}^{Sh}$ indicates P_i^{Sh} in scenario s' of the out-of-sample analysis
ΔV_k deviation of voltage magnitude from 1 p.u. at bus k;ΔV_{ks} indicates ΔV_k at iteration s
V_k voltage magnitude of bus k
θ_k voltage angle at bus k; θ_{ks} indicates θ_k at iteration s
BF_l apparent power flow of branch l; BF_{ls} indicates BF_l at iteration s
lBF_l linear approximation of the apparent power flow of branch l; lBF_{ls} indicates lBF_l at iteration s
LB^{ACOPF} lower bound of the objective function of the ACOPF problem
LB^{LACOPF} lower bound of the objective function of the LACOPF problem
UB^{ACOPF} upper bound of the objective function of the ACOPF problem
UB^{LACOPF} upper bound of the objective function of the LACOPF problem
ρ,τ,φ auxiliary continuous variable
$\lambda_{ik}^{\mathrm{I}}$, $\lambda_{ik}^{\mathrm{II}}$, $\lambda_{ik}^{\mathrm{III}}$ dual variables
Ψ_{I} objective function of the first-level problem
Ψ_{II} objective function of the second-level problem
Ψ_{III} objective function of the third-level problem, where Ψ_{III}^s indicates Ψ_{III} at iteration s
$\Psi_{OS}^{s'}$ objective function of scenario s' pertaining to the out-of-sample analysis

Uncertain parameters

$\widetilde{Pw}_i$ uncertain wind power of the wind unit at bus i
$\widetilde{Pd}_i$ uncertain load demand of bus i

Vectors

$\boldsymbol{E}$, $\boldsymbol{F}$ vector of operation costs
$\boldsymbol{U}$ vector of uncertain parameters
$\boldsymbol{M}$ vector of integer decision variables
$\boldsymbol{N}$ vector of continuous decision variables

considered. However, in this OPF work both the uncertainties of load and wind power are taken into account, which makes the OPF solution immune against load forecast errors in addition to wind power forecast errors.

(3) The ACUC work in [14] considers linear approximation of the quadratic cost function of units. However, as OPF is closer to power delivery, a more accurate cost function is usually required. For this reason, we consider piece-wise linear approximation of the quadratic cost function in the second level and the exact quadratic cost function in the third level of the proposed OPF model.

(4) Since the results obtained from a linearized AC power flow are close to the results of a nonlinear AC power flow, we have used an