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A real-time optimal coordination scheme for the voltage regulation of a distribution network including an OLTC, capacitor banks, and multiple distributed energy resources

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ABSTRACT

The progression towards smarter grids, incorporating clean energy resources, has increased the integration of distributed generators (DGs) into power distribution networks. The DGs often cause a rise in voltage at their points of common coupling. Ordinary voltage regulation devices such as on-load tap changers (OLTCs) are not capable of addressing these issues adequately without careful coordination with DGs. In this paper, a new supervisory control and data acquisition-based two-stage voltage control scheme for the coordination of an OLTC transformer, capacitor banks (CBs) and the DGs is presented. The proposed scheme sets forth a new criterion for the selection of tap positions of an OLTC. In the first stage, tap positions of the OLTC are changed optimally using the micro genetic algorithm, whereas in the second stage, a recursive genetic algorithm is run to minimise the power losses in order to find the optimal reactive powers for the distribution network. Stochastic modelling of wind speed and solar irradiance data is also performed. The scheme is verified by studying it under four different test cases. An OLTC, CBs, photovoltaic panels, wind power DGs and dispatchable DGs are installed in the distribution network, and an IEEE 37-node test feeder is used for the verification of the proposed scheme. The simulation results show that the scheme achieves the objective of voltage regulation.

1. Introduction

1.1. Motivation

Widespread awareness of global warming has catalysed the integration of various eco-friendly, zero-emission distributed generators with power grids. A large number of DGs have already been integrated with distribution networks, and a significant increase in this number is expected until 2050 [1]. The DGs pose a number of challenges to the protection devices in the traditional distribution systems [2,3]. Active distribution networks, the distribution networks with DGs, often encounter the problem of voltage rise at the points of common coupling of the DGs [4,5]. The problem of voltage rise can be traced to high DG penetration. Conventional voltage regulation devices such as OLTCs are sometimes unable to resolve these issues without proper coordination of different power equipment. Without the proper coordination between an OLTC, CBs and various distributed energy resources, the number of switching operations in these devices rise significantly, thereby degrading the power quality. The absence of a rigorous coordination scheme suggests that the negative impacts of DG integration may outweigh the benefits.

IEEE Standard 1547 suggests that DGs cannot actively participate in the voltage regulation of the distribution network unless the distribution system operators (DSOs) require them to change their outputs based on the voltage control of a distribution system [6]. DGs should act as constant power resources to prevent the simultaneous interactions of various voltage control devices. With the integration of non-dispatchable DGs such as the wind and solar power DGs, optimal voltage regulation in real-time has become a challenging task. In the past, owing to long execution time of optimisation algorithms for large power systems, the schemes which were proposed as real-time voltage regulation schemes do not employ the optimisation algorithms. For the optimal operation of distribution networks, solutions in the form of day-ahead scheduling schemes were proposed. It has been mentioned in [7] that the severe errors of MW may occur in the forecasting due to

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Nomenclature

Acronyms

CB	capacitor bank
DG	distributed generator
DSPDG	dispatchable DGs
MAC	master controller
MCS	Monte Carlo simulations
MLE	maximum likelihood estimation
OLTC	on-load tap changer transformer
PF	power factor
PV	photovoltaic
RGA	recursive genetic algorithm
SAC	slave controller
SCADA	supervisory control and data acquisition
μ-GA	micro genetic algorithm

Indices

c	index of a CB
d	index of DSPDGs
i	index of system buses $\forall\, i \in N$
j	index of system buses $\forall\, j \in N$
s	index of PV panels
t	index of time
w	index of wind DGs

Variables

$\alpha_{n,n+1,\ldots,N}$	samples generated from uniform distribution
$\gamma_s, \gamma_w, \gamma_d$	PV panels, wind DGs and DSPDGs, respectively
λ	tap position
$\lambda_{min}, \lambda_{max}$	minimum and maximum value of the tap positions
Λ	fill factor
$\phi_{(i,t)}$	PF of the i-th DG at time t
ϕ_{min}, ϕ_{max}	minimum and maximum value for a PF
ϕ_w, ϕ_s, ϕ_d	PFs of a wind DG, PV panel and DSPDG
$\veebar$	exclusive or operation
C, D, S, W	total number of CBs, dispatchable, solar and wind DGs, respectively
$CB^{(min)}_{(c)}, CB^{(max)}_{(c)}$	minimum and maximum number of capacitors in a CB
$CB^{(ON)}_{(c,t)}$	number of capacitors switched-on in a CB at time t
f	probability distribution functions
f_1, f_2	objective functions to be minimised
$I_{(i,j)}$	current flowing between buses i and j
I_{maxp}	current at maximum power point
I_{sc}	short circuit current
K_i	temperature coefficient value for current
K_v	temperature coefficient value for voltage
N	total number of buses
n_R, n_L	right and left data points, respectively
N_{total}	total number of PV modules
$P_{(i,t)}, Q_{(i,t)}$	active and reactive loads connected to the bus i at time t
P_r	rated capacity of a Wind turbine
P_s	power generated from a PV panel
s_{ird}	solar irradiance
$s_w,\ s_{ci},\ s_{co},\ s_r$	current wind speed, cut-in wind speed, cut-out wind speed and rated wind speed, respectively
T_{amb}	ambient temperature
T_{cell}	temperature of a cell
T_{not}	nominal operating temperature of a solar cell
$TSCB$	total number of switching operations of CBs
TSO	total number of switching operations of an OLTC
$V_{(i,t)}$	voltage of the i-th DG bus at time t
V_{maxp}	voltage at maximum power point
V_{min}, V_{max}	minimum and maximum value of voltage
V_{oc}	open circuit voltage
V_{ref}	reference voltage for an OLTC

uncertainties in the wind and solar power outputs. Therefore, it is essential to implement an optimal voltage regulation scheme which operates in real-time. The implementation of a voltage regulation scheme in real-time can eliminate scheduling errors. In addition, it is the intrinsic nature of several DGs to, at times, have low output power. For the accurate modelling of non-dispatchable DGs, the stochastic modelling of wind speed data and solar irradiance data should also be performed.

In this study, a rigorous real-time optimal SCADA-based two stage coordination algorithm for the voltage regulation of active distribution networks is proposed. This scheme sets out a new criterion for the selection of tap positions using the optimisation algorithm in real-time. The new tap position of an OLTC is found using the μ-GA. Both DSPDGs and non-dispatchable DGs are taken into account. DGs are classified into two groups. Some DGs are not permitted to change their active powers, whereas some can also alter their active powers for the voltage regulation. In the first stage, an OLTC changes its tap position, whereas in the second stage, an RGA is applied to find the optimal power factors of DGs and the number of capacitors to be switched on/off. As the variations in wind speed and solar irradiance increase the complexity of voltage regulation process, the intermittent nature of the DGs is also taken into account for evaluating the performance of the proposed scheme, and the real world wind speed and solar irradiance data are modelled for the simulations.

The significant contributions made by this study can be summarised as follows:

(1) *Real-time optimal coordination scheme:* The study proposes a rigorous optimisation-based coordination scheme for an OLTC, DGs and capacitor banks, which operates in real time.
(2) *New tap position:* A new μ-GA-based methodology for the selection of the OLTC-tap is presented. The methodology considers the voltage violations for all the buses simultaneously.
(3) *Dispatchable and non-dispatchable DGs:* The proposed scheme considers not only the DSPDGs, but also performs efficiently with the non-dispatchable DGs.
(4) *Optimal parameters:* An RGA is used for the calculation of optimal parameters such as power factors, active powers of DGs and the number of switched on/off capacitors. The use of the RGA reduces the execution time of the simulations.
(5) *Intermittent DG outputs:* The real world data of wind speed and solar irradiance are modelled for wind DGs and PV panels. Intermittent DG outputs do not affect the performance of the proposed real-time voltage control algorithm. The scheme can tolerate the worst cases of high peak hours and small DG output powers.

1.2. Related work

An extensive body of literature on the subject of voltage regulation of DG-integrated distribution networks already exists. In [8–10], optimisation based algorithms were used for calculating