Electrical Power and Energy Systems 105 (2019) 500–513

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Optimal oversizing of utility-owned renewable DG inverter for voltage rise prevention in MV distribution systems

Abdelfatah Ali[a,b,*], David Raisz[b], Karar Mahmoud[c]

[a] Department of Electrical Engineering, South Valley University, 83523 Qena, Egypt
[b] Department of Electric Power Engineering, Budapest University of Technology and Economics, 1111 Budapest, Hungary
[c] Department of Electrical Engineering, Aswan University, 81542 Aswan, Egypt

ARTICLE INFO

Keywords:
Distribution systems
Distributed generation
Optimal inverter size
Voltage regulation
Active power curtailment
Reactive power capability

ABSTRACT

The penetration of renewable distributed generations (DG) is recently being increased in distribution systems. Due to the intermittent nature of these generation units, several technical problems are expected based on the environmental conditions and load profiles, such as voltage rise and increasing losses. A traditional way to alleviate these technical problems is to oversize their interfacing inverters for releasing their capacities to inject/absorb further reactive power. In the literature, the DG inverter is normally oversized by a certain percentage (e.g., 10%) for this purpose. In turn, an optimization-based method is proposed in this paper to calculate the optimal oversize of the interfaced inverter employed in various utility-owned DG types to regulate voltages and to reduce losses with minimum total costs. The proposed method considers the active power curtailment (APC) feature in the DG inverter and the transformer taps. Different control schemes of the interfaced inverter are considered and incorporated in the proposed optimization model. The simulation results demonstrate the effectiveness of the proposed method compared with existing methods.

1. Introduction

As the annual electric energy demand grows, the penetration of distributed generations (DG) in distribution systems has noticeably increased throughout the world to fulfill the massive demand for electricity. The integration of DG units with an existing distribution system has many benefits to several entities (e.g., owner, utility, and final user).

The optimal allocation of the DG has been deeply studied in the literature. In [1,2], the optimal size and location of DG are determined to minimize the system losses and maximize the system voltage stability. The simultaneous optimal placement of DG and optimal allocation of tie-switch based on maximization of system load-ability is addressed in [3]. The allocation of multiple DG units to minimize the system losses, increase load-ability, and improve system voltage stability has been addressed in [4–6].

High penetration of utility-owned DG into distribution system has positive and negative effects on the normal operation of the system. Improved voltage profile, high reliability of power supply to the consumers, power loss reduction, support voltage stability and support of ancillary services are major positive impacts [6–10], whereas negative ones include several technical, economic and regulatory challenges. These challenges have to be considered when deciding the DG penetration level. Voltage rise is one of the main concerns that can limit the allowed penetration of DG [11,12]. During high power generation of DG and light load periods (extreme state), there is a high possibility of reverse power flow, and therefore voltage rise, in the distribution feeder [13–15]. The conventional voltage regulation devices such as on-load tap changers (OLTCs) are not capable of treating these issues completely without a proper coordination with DG. Therefore, a supervisory control and data acquisition-based two-stage voltage control scheme for the coordination of the capacitor banks (CBs), OLTC transformer, and DG has been presented in [16].

Several forms of utility-owned DG such as photovoltaic (PV), wind turbine generation system (WTGS), microturbines, and fuel-cells are interfaced to the medium voltage (MV) distribution system through inverters. These power electronics devices are superior to the conventional interface machines due to their flexibility in operation and control. Inverters of DG have the capability to provide reactive power support to MV distribution systems locally at the point of common connection (PCC). The reactive power capability of DG inverters is an efficient way to compensate the fluctuating voltage, caused by the fluctuating DG output (active) power [17–22]. Furthermore, the smart voltage source inverters (VSI) of DG with reactive power compensation

* Corresponding author at: Department of Electric Power Engineering, Budapest University of Technology and Economics, 1111 Budapest, Hungary.
E-mail address: abdelfatah.mohamed@vet.bme.hu (A. Ali).

https://doi.org/10.1016/j.ijepes.2018.08.040
Received 19 December 2017; Received in revised form 18 June 2018; Accepted 23 August 2018

Nomenclature

Abbreviations

DG	distributed generation
APC	active power curtailment
OLTC	on-load tap-changer
CB	capacitor banks
PV	photovoltaic
WTGS	wind turbine generation system
MV	medium voltage
PCC	point of common coupling
VSI	voltage source inverter
MPPT	maximum power point tracking
KKT	Karush–Kuhn–Tucker
pdf	probability distribution function

Symbols

R	solar irradiance (kW/m^2)
α, β	parameters of Beta pdf
$f_b(R)$	beta distribution function of R
$prob_R(G_s)$	probability of the solar irradiance being in state s
R_{s1}, R_{s2}	solar irradiance limits of state s
P_{PV_s}	output power of the PV module during state s
T_{Cells}	cell temperature during state s (°C)
T_A	ambient temperature (°C)
K_v	voltage temperature coefficient (V/°C)
N_{OT}	nominal operating temperature of cell (°C)
I_{sc}	short circuit current (A)
V_{oc}	open circuit voltage (V)
I_{MPP}	current at maximum power point (A)
V_{MPP}	voltage at maximum power point (V)
R_{avs}	average solar irradiance of state s
I_{cells}	cell current (A)
V_{cells}	cell voltage (V)
$f_w(v)$	weibull distribution function of v
v	wind speed (m/s)
$f_r(v)$	Rayleigh pdf
$prob_{WT}(G_w)$	probability of the wind speed being in state w
v_{w1}, v_{w2}	wind speed limits of state w
P_{WTw}	output power of the wind turbine during state w (MW)
v_{ci}	cut-in speed (m/s)
v_r	rated speed (m/s)
v_{co}	cut off speed (m/s)
v_{avw}	average wind speed of state w
P_{rated}	rated power (MW)
Ψ	complete annual generation-load model
C	a matrix that includes all possible combinations of the PV/WTGS output power state and the load states
$prob(C_g)$	one-column matrix that represents the probability corresponding to matrix C
Ns	total number of states in modelΨ
P_{grid}	grid active power (MW)
Q_{grid}	grid reactive power (Mvar)
P_{inv}	active power output from the inverter (MW)
Q_{inv}	reactive power output from the inverter (Mvar)
P_{inv}^{max}	maximum active power of the inverter (MW)
Q_{inv}^{max}	maximum reactive power of the inverter (Mvar)
P_{PV}	dc power output from PV farm (MW)
T_{ij}	period between hours i and j (h)
T_{km}	period between hours k and m (h)
T_s	time duration of the worst-case period (h)
T_p	time duration of the planning period (h)
V_N	nominal voltage (pu)
V^{max}	upper limit of the voltage (pu)
V^{min}	lower limit of the voltage (pu)
V_{PCC}	voltage magnitude at PCC (pu)
$V_{i,g}$	voltage magnitude at bus i during state g
S_{rated}	rated size of the inverter (kVA)
$S_{os,k,g}$	inverter oversize at bus k during state g (kVA)
S_{os}^{max}	maximum inverter oversize (kVA)
$S_{os,k,o}$	inverter oversize without considering OLTC (kVA)
$S_{os,k,N}$	inverter oversize with considering OLTC (kVA)
P_{curt}	APC (MW)
$P_{curt,k,g}$	APC at bus k during state g (MW)
$P_{curt,k,g}^{min}$	minimum APC at bus k during state g (MW)
$P_{curt,k,g}^{max}$	maximum APC at bus k during state g (MW)
P_{MPPT}	maximum power point tracking power (MW)
C_{total}	total cost ($)
C_{g1}	cost of energy losses in the distribution system during state g ($)
C_{g2}	cost of energy losses in the inverter during state g ($)
C_{g3}	cost of inverter oversize during state g ($)
C_{g4}	cost of curtailing active power during state g ($)
a_s, b_s, c_s	cost coefficients of inverter oversize
a_p, b_p, c_p	cost coefficients of active power curtailment
a_{inv},	inverter's stand by losses
b_{inv}	voltage dependent losses
c_{inv}	ohmic losses
$C_{total,k,o}$	total costs without considering OLTC ($)
$C_{total,k,N}$	total costs with considering OLTC ($)
C_L	cost rate of energy losses in the distribution system ($/kWh)
$C_{inv,k}$	cost rate of energy losses in kth inverter ($/kWh)
$\varnothing_{dg}$	set of inverters-based DG locations
$\varnothing_b$	set of buses of the system
$\varnothing_r$	set of branches of the system
$PL_{ds,g}$	active power losses of a distribution system during state g (MW)
$PL_{inv,g}$	active power losses of Kth inverter during state g (MW)
$tap_{ij,g}$	tap position of OLTC in the line i-j during state g
tap^{min}	minimum tap position of OLTC
tap^{max}	maximum tap position of OLTC
G_{ij}	conductance of the line i-j (Ω^{-1})
B_{ij}	susceptance of the line i-j (Ω^{-1})
x,y	binary variables
$P_{DG,i}$	rated power of the PV/WTGS connected at bus i (MW)
$P_{d,i}$	active power demand at bus i (MW)
$Q_{d,i}$	reactive power demand at bus i (Mvar)
NB	number of buses
CR_k	cost reduction at DG location k (%)
OSR_k	oversize reduction at DG location k (%)

capability can mitigate the voltage rise problem [23]. For instance, at the occasions of high PV generation, i.e., sunny moments, and low consumption (extreme state), the spare capacity of the interfaced inverter can be employed to absorb reactive power, thereby regulating the voltage at PCC. However, during such extreme state, the DG inverter is often fully loaded. For the purpose of allowing further reactive power capability, many studies suggested to oversize the interfaced inverter. For example, in [19,24], it is established that 10% inverter oversize provides a sufficient release of the inverter capacity for loss reduction and voltage improvement, while 60% is considered in [25]. Oversizing the inverter of DG with a certain level (e.g., 10% or 60%) for preventing voltage rise is not an optimal approach. Oversized inverters