EVALUATION AND ENHANCEMENT OF SOLAR PV HOSTING CAPACITY FOR MANAGEMENT OF VOLTAGE RISE IN LV NETWORKS

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Abstract

Proliferation of solar photovoltaics (PV) in low-voltage (LV) distribution networks is inciting technical challenges in network design and operation with regard to the quality of power. Violations of operational performance limits are increasingly evident at higher solar PV penetration levels, in particular, local voltage rise has become the major issue of concern in LV distribution networks. As the solar PV industry continues to grow, emerging challenges need to be addressed by adopting best policies and practices at a utility level. Thus, to comply with stipulated network operational limits, distribution network operators (DNOs) are compelled to develop comprehensive techniques to determine acceptable levels of solar PV hosting capacity (HC) and explore HC enhancement options.

Complexity of modelling distribution networks is a barrier for DNOs to decide levels of maximum solar PV penetration using stochastic approaches. Thus, there is a necessity to develop a systematic approach to assess solar PV HC, considering factors such as geographic layout of networks and their electrical characteristics.

This thesis extends the knowledge of managing of solar PV integration in LV networks by developing systematic approaches to evaluate solar PV HC subjected to over voltage curtailment. In this regard, a novel feeder based solar PV HC evaluation approach was developed to address the diverse network characteristics of multi feeder systems in LV distribution networks. To assess the voltage violations and critical factors affecting the solar PV HC, a comprehensive analysis of potential power quality issues was conducted on a practical LV distribution network in Sri Lanka.

The approach proposed in this thesis establishes a safe limit for solar PV HC for a given distribution feeder based on the locational and operational aspects of the solar PV units deployed on a LV network. The safe limit for HC was developed employing a number of sensitivity analyses considering factors influencing solar PV HC. Further, the proposed feeder based solar PV HC approach was extended to develop a generic method to quantify solar PV HC under different operating con-

ditions of PV inverters. Thus, it can be used as an approximate guide or a rule of thumb to evaluate solar PV HC at a given point on an LV feeder without using complex stochastic techniques.

With the increasing demand for solar PV systems, development of both solar PV HC assessment and enhancement techniques is essential in managing network voltage. DNOs have recognised the need for smart PV inverter technologies to maintain acceptable voltage levels in distribution networks. Smart PV inverters possess fast and flexible active and reactive power control functions such as; Volt-VAr and Volt-Watt control modes which can be used to manage over-voltage conditions that often limit the solar PV HC. At present, most of solar PV connection standards provide a set of rules and guidelines to mitigate voltage violations by enabling Volt-VAr and Volt-Watt control modes of the inverters. In particular, it is imperative to analyse the impact of such solar PV connection standards on HC assessment and its potential to enhance solar PV HC. Thus, a detailed analysis of smart solar PV inverter capabilities and a comparative evaluation of solar PV HC enhancement facilitated by different connection standards are presented in this thesis.

Electricity utilities around the world seek to develop strategies to increase solar PV integration while maintaining acceptable network performance. Hence, more generalised and straightforward tools are required to rapidly assess solar PV HC without complex and extensive network modelling and simulations. Extending the deterministic outcomes, a nomogram based solar PV HC assessment approach is proposed in this thesis to determine HC values specific to any location of a given conductor. Further, solar PV connection criteria is proposed which permits the electric utilities to approve new solar PV connections which facilitates reasonable modelling insights to assess HC. The proposed nomogram based solar PV HC assessment approach and solar PV connection criteria cover technical and regulatory aspects to manage PV integration in LV distribution networks.

For the continued development of solar PV as a distributed generation, accuracy of PV connection approval process is crucial to correctly and easily allow PV connections that will not cause issues. Therefore, grid codes, distribution codes or guidelines on interconnection of solar PV require to be refined or re-written in relation to solar PV HC assessment/enhancement and approval criteria for new PV connections in LV distribution networks. The solar PV HC assessment/enhancement and solar PV connection criteria proposed in this thesis shall be a contribution to further improvement of the available guidelines/standards on solar PV installation in LV networks.

All network modeling and simulations presented in this thesis were carried out in DIgSILENT PowerFactory platform.

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List of Principal Symbols and Abbreviations

PV	photovoltaic
HC	hosting capacity
LV	low voltage
MV	medium voltage
HV	high voltage
POC	point of connection
MCS	monte-carlo simulation
DNO	distribution network operator
GW	gigawatt
kW	kilowatt
MW	megawatt
kVAr	kilovar
kWh	kilo watt hour
ABC	aerial bundle cable
AAC	all aluminum conductor
SAM	system advisor model
AC	alternating current
DC	direct current
am	ante meridiem
pm	post meridiem
UVF	voltage unbalance factor (%)
V_n	neutral voltage
DNSP	distribution network service provider
HC_{min}	minimum hosting capacity
HC_{max}	maximum hosting capacity

DG	distributed generation
p.u.	per unit
R	resistance
X	inductance
Z	impedance
P_{LOAD}	active power of the load
S_{LOAD}	apparent power of the load in p.u.
S_{inv}	rating of the PV inverter
$Q_{Volt/VAr}$	required reactive power of VAr priority Volt-VAr control
Q_{avail}	available reactive power of Watt priority Volt-VAr control
OLTC	on-load tap changer
BESS	battery energy storage system
P_{DG}	total solar PV capacity
P_{tr}	MV/LV transformer rating
$P_{thermal\_line}$	thermal limit of the feeders,
$HC_{Feeder,Min}$	minimum hosting capacity of a given feeder
$HC_{Feeder,Max}$	maximum hosting capacity of a given feeder
HC_{min_LV}	minimum hosting capacity of a given distribution network
HC_{max_LV}	maximum hosting capacity of a given distribution network
HC_{Fn_End}	maximum connectable solar PV capacity at the feeder end of n^{th} feeder
HC_{Fn_Front}	maximum connectable solar PV capacity at the feeder front of n^{th} feeder
HC^{*}	solar PV hosting capacity obtained from the nomogram
P_{PV}	active power of PV system
Q_{PV}	reactive power of PV system
P_L	active power of the load
Q_L	reactive power of the load
P	active power
Q	reactive power
V_{PV}	voltage at the point of connection
V_S	voltage at the supply end
I_S	net current

I_L	load current
I_{PV}	net PV current
I_{p1}	active current component of net current when solar PV system operating at unity power factor
I_{q1}	reactive current component of net current when solar PV system operating at unity power factor
I_{p2}	active current component of net current when solar PV system operating at lagging power factor
I_{q2}	reactive current component of net current when solar PV system operating at lagging power factor
I_{p3}	active current component of net current when solar PV system operating at leading power factor
I_{q3}	reactive current component of net current when solar PV system operating at leading power factor
I_{pl}	active current component of load current
I_{ql}	reactive current component of load current
V_{PV1}	voltage at the point of connection when solar PV system operating at unity power factor
V_{PV2}	voltage at the point of connection when solar PV system operating at lagging power factor
V_{PV3}	voltage at the point of connection when solar PV system operating at leading power factor
I_{PVp}	active current component of PV system
I_{PVq}	reactive current component of PV system
DV_l	total voltage drop at the feeder end
l	feeder length
V_b	nominal line-line voltage
P_S	real power component of the total load
Q_S	reactive power component of the total load
d	distance to the POC from the distribution transformer
P_d	active power flow at a distance d from the distribution transformer

Q_d	reactive power flow at a distance d from the distribution transformer
$d^{'}$	zero crossing point of active power
$Q^{'}$	reactive power flow at a distance $d^{'}$ from the distribution transformer
λ	ratio between the distance to POC and feeder length
VD_l^{re}	real component of voltage drop
VD_l^{im}	reactive component of voltage drop
ΔV	total voltage drop made by the load across the feeder
$d^{''}$	zero crossing point of reactive power
pf_{pv}	inverter operating power factor
θ	voltage angle deviation
$HC_{calculated}$	HC obtained from the proposed analytical approach
$HC_{simulated}$	HC obtained from the DIgSILENT PowerFactory simulations
CIGRE	International Council on Large Electric Systems
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
EPRI	Electric Power Research Institute
MPP	maximum power point
V_{array}	voltage of PV array
I_{array}	current of PV array
$V_{mmp-array}$	voltage in the maximum power point
P_{conv}	active power signal from power measurement device
E	irradiance
V_{dc}	DC output voltage of PV system
I_{cap}	differential current in DC capacitor
C	capacitance
V_{dcin}	output DC voltage from DC bus-bar and capacitor link
V_{dcref}	reference DC voltage
V_{ac}	measured AC voltage at the output of PV inverter
V_{ref}	reference AC voltage
Id_ref	reference active power current
Iq_ref	reference reactive power current

cos_{ref}	d-axis reference angle
sin_{ref}	q-axis reference angle
id	d-axis current
iq	q-axis current
id_{min}	d-axis minimum current
id_{max}	d-axis maximum current
iq_{min}	q-axis minimum current
iq_{max}	q-axis maximum current
db	dead-band
ab	active-band
ib	ideal-band
K_{iq}	reactive current droop gain
K_{id}	active current droop gain
V_0	input voltage
P_{max}	maximum real power output of PV inverter
P_{min}	minimum real power output of PV inverter
I_{rated}	rated current of PV inverter
VVC	volt-var control
VWC	volt-watt control
VUL	upper voltage limit
AS	Australian Standard
NZS	New Zealand Standard
HR14	Hawaii Rule 14
CR21	California Rule 21
LECO	Lanka Electricity Company
STC	standards test condition

Publications Arising from the Thesis

Book Chapters

1. D. Chathurangi, U. Jayatunga, S. Perera and A. Agalgaonkar, "A Generalised Deterministic Approach to Evaluate PV Hosting Capacity of LV Distribution Networks Under Different Operating Conditions," In: Zobaa A., Abdel Aleem S., Ismael S., Ribeiro P. (eds) Hosting Capacity for Smart Power Grids. Springer Cham, 2020.

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