Electric Power Systems Research 152 (2017) 105–121

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Grid capacity released analysis and incremental addition computation for distribution system planning

Michael Emmanuel*, Ramesh Rayudu, Ian Welch

Smart Power & Renewable Energy Systems Group, School of Engineering and Computer Science, Victoria University of Wellington, Wellington 6140, New Zealand

ARTICLE INFO

Article history:
Received 19 April 2017
Received in revised form 13 June 2017
Accepted 17 June 2017

Keywords:
Photovoltaic
Energy exceeding normal
Unserved energy
Incremental capacity
Planning

ABSTRACT

This paper presents a released capacity analysis for the power delivery system of the distribution grid, and the computation of the incremental capacity addition provided by an optimally deployed photovoltaic (PV) system in the IEEE 13 and 34 test feeders. The intrinsic strong correlation that exists between network capacity and reliability gives the inclusion of renewable distribution generation (DG) and the evaluation of their additional load serving capacity a prime place in the emerging active distribution system planning (ADSP). Also, this article presents a method capable of measuring risk and upgrade deferral in the evolving ADSP using two energy quantities referred to as the energy exceeding normal (EEN) and unserved energy (UE). The evaluation of these metrics is used to assess system capacity usage, and as a planning tool to identify required system upgrade and measure the effectiveness of the applied DG incremental solution. This analysis is pivotal as the load growth continues to outpace new feeder construction and network expansion becomes difficult and costly. Therefore, utilizing DG to provide peak load relief and incremental capacity solution is developing into a viable alternative. In addition, results presented in this article show that apart from optimal positioning and sizing, maximizing the value attributes of PV-DG also, depends on its ability to produce power at proper times and levels. Also, since energy is the quantity being sold, this article further presents a simple economic analysis based on EEN and loss savings which can be used to compare alternative power generation sources.

1. Introduction

The global quest for a sustainable energy production and downtrend of greenhouse gas emissions from the conventional fossil fuel power stations has become imminent. Global warming threats, inevitable load growth, frequent power outages and proposed legislation to increase taxation of GHG emissions are major drivers for the gradual shift from non-renewable to renewable energy sources such as wind and photovoltaic (PV) systems [1–3,57]. Over the years, the growing trend of PV systems continues to generate a global interest from various stakeholders such as the power utility, prosumers, policy makers and the research community. Moreover, with the global PV installed capacity at 227 GW and about 50 GW of additional capacity in 2015 [4], calls for a careful approach in the design, engineering and planning of the evolving distribution system. This rapid development positions the PV system as the most common and major source of power generation for smart grid applications in several parts of the world [4–6]. The potential positive benefits of PV integration include reduced network flows on the power delivery system and hence power losses and enhanced voltage profile [7–9,58]. However, it is very uncertain if the distribution network is capable of handling effectively the high penetration of this intermittent power source. Also, the associated integration challenges such as equipment overloading and reverse power flow during low load conditions, interaction with grid regulating devices (e.g., load tap changer and capacitor) and local overvoltages present major concerns to utilities [1,10–12]. As the deployment of PV system continues to outpace the development of sufficient grid codes, it is now pertinent to update the current interconnection standards in order to ensure a secure and reliable distribution network operation [1,59]. For instance, the IEEE 1547 suite now has a companion standard, IEEE 1547.8, which addresses DG interconnection beyond the point of common coupling (PCC) and to give supplemental support for implementation methods for expanded use of the de factor IEEE 1547 standard [13].

The evolution of conventional planning practices is pivotal in order to accelerate the graceful adoption of this new technology in the electric power system (EPS). This is a very fundamental

* Corresponding author.
E-mail address: michael.emmanuel@ecs.vuw.ac.nz (M. Emmanuel).

http://dx.doi.org/10.1016/j.epsr.2017.06.013
0378-7796/

Nomenclature

$\partial\lvert P_L\rvert/\partial P$	active power loss sensitivity to active power
$\partial\lvert Q_L\rvert/\partial Q$	reactive power loss sensitivity to reactive power
$\partial\lvert V\rvert/\partial P$	voltage sensitivity to active power
$\partial\lvert V\rvert/\partial Q$	voltage sensitivity to reactive power
ΔP_L	power losses reduction
ADSP	active distribution system planning
CUE	cost of unserved energy
DG	distributed generation
DTIM	demand time matching
ECP	equivalent conventional power
EEN	energy exceeding normal
EFC	equivalent firm power
ELCC	effective load carrying capacity
EUE	expected unserved energy
LDC	load duration capacity
LF	load factor
LSI	loss sensitivity index
OPF	optimal power factor
p(outage)	probability of annual distribution-related outage
P_L	penetration level
$P_{PV,k}$	active power injection at bus k by PV
P_{WOPV}	basecase power losses
P_{WPV}	power losses with PV
PCC	point of common coupling
PDE	power delivery element
PLCC	peak load carrying capacity
PV	Photovoltaic
$Q_{PV,k}$	reactive power injection at bus k by PV
RMS	root mean square
UE	unserved energy
VSI	voltage sensitivity index

step with the most strategic impact in distributed generation (DG) uptake. Furthermore, to allow for full integration of these intermittent power sources, their inclusion at early stages during the planning process and demand growth forecast is very important [14].

However, with the growth and increasing presence of PV-DG within the area EPS, utilities are still not clear as to how DG are to be treated in the planning process, and the computation of their incremental capacity additions remains a critical issue [15]. Three major factors in distribution system planning include peak load serving capacity, cost and reliability of service [16]. Also, having sufficient capacity to provide peak load relief remains an age-long problem in distribution planning [17]. Although the planning value of renewable DG is a function of time and location, however, the major challenge is the computation of the additional load serving capacity provided by these power sources [18,19]. The existing literature proposes different metrics for determining the capacity contributions of variable power sources such as the equivalent conventional power (ECP), peak load carrying capability (PLCC), effective load carrying capability (ELCC), equivalent firm power (EFP), load duration capacity (LDC) and demand time matching (DTIM) [20–24]. Garver [25] estimated the ELCC of generating units by introducing a new parameter which is used to characterize the loss-of-load probability as a function of reserve megawatts. Once the parameter is determined, the ELCC of the new generating system can be related to its rating and forced outage rate. Abudullah et al. [16] presented the capacity deferral credit computation of renewable DG systems using a modified load adjustment method to determine their ELCC. Also, in another study, Abudullah et al. [20] proposed a noniterative analytical method to determine the PLCC and ELCC of conventional and renewable power sources. The result showed that the higher the correlation between load demand and renewable generation units, the higher the ELCC, and vice versa. Dragoon et al. [26] presented a simplified analytical probabilistic method which maintains the network resource adequacy and evaluates the peak load carry capability of the incremental generating systems. D'Annunzio et al. [27] proposed a non-iterative approach used to evaluate the ELCC of a wind farm and Hasche et al. [28] presented a methodology to identify the minimum amount of data needed to compute the capacity value of wind power. Madaeni et al. [23,29,30] presented a comparison of methods such as the computationally intensive statistical and approximation approaches used to compute the capacity value of solar PV systems. Analysis presented showed that some approximation methods produced similar ELCC when compared with the reliability-based methods. Other related studies in [31–33] have also computed the capacity value of renewable DG such as wind and solar PV using the ELCC metric which demands substantial system reliability modelling and estimation of detailed reliability-based indices. In addition, Favuzza et al. [34] used a heuristic method of adaptive and dynamic ant colony search algorithm to solve the distribution system capacity problem using PV systems coupled with conventional techniques such as cables and transformers. The minimized objective is the overall cost of distribution network reinforcement method within a specified period with the assumption that the installed underground cables cannot be overloaded.

The extant literature presents capacity value computation in terms of ELCC without considering the impact of integrating renewable DG systems on the loading (ratings) of the power delivery system. Violating capacity constraints of the power deliver elements (PDE) such as the lines, load, transformers and switches can degrade network reliability. This is due to the strong correlation that exists between capacity and network reliability, especially if the PDE loading is close to system constraints [15]. Also, utility distribution planners may not be too comfortable with absolute probabilistic planning or approximation approaches but would rather prefer to subscribe to concrete limits [35]. This paper presents a method capable of measuring risk in the evolving active distribution system planning (ADSP) using two energy quantities referred to as the energy exceeding normal (EEN) and unserved energy (UE). Although distribution planning is fundamentally a power demand capacity problem, these energy indices can give the required understanding to deal with this problem [17]. The contributions of this article is as follows:

- Optimal deployment of a PV-DG unit for the power delivery system released capacity and loss reduction analysis using IEEE 13 and 34 test feeders.
- Risk and upgrade deferral measurements for both networks using energy quantities – EEN and UE.
- Evaluation of the additional load serving capacity provided by the PV-DG for network planning.
- Computation of reliability cost offset with EEN and cost savings on losses.

Moreover, in solving distribution circuits with distributed generators (DG), different types of load flow methods can be used such as the probabilistic load flow in [36,37]. However, in this article, an iterative power flow method known as current injection power flow has been used. In this method, loads and DG such as the solar PV system as considered in this paper are treated as injection sources, which works well with distribution networks.