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Probability of adequacy evaluation considering power output correlation of renewable generators in Smart Grids

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ABSTRACT

Smart Grids implementation is mainly intended to reduce the negative impact of distributed generators' (DGs) high penetration (especially renewable DGs), and to optimally manage distributed resources in order to improve overall efficiency and power quality. In terms of service continuity, this implies being able to reduce average outages rate and duration. A possible solution is to operate in intentional islanding some portions of the distribution network when faults occur. To this aim local DGs' adequacy must be evaluated.

This paper presents a new analytical expression useful to assess the ability of local DGs to meet a potential island load. Such an expression accounts for both load shedding and curtailment policies and it encompasses the correlation among loads' power demand, the correlation among renewable DGs' power outputs for generators of the same technology, the correlation among renewable DGs' power outputs for generators of different technologies, and, finally, the correlation among loads' power demands and renewable DGs' power outputs.

Introduction

During the last decade two major issues have been characterizing planning and operation of modern distribution networks [1–4]. One is the need to increase the installed capacity of renewable distributed generation in order to meet the international environmental issues [5–7] and to bring energy production closer to load centres [8]. The other one is the pressure posed on distribution networks in terms of national regulations aiming at improving service quality and, in particular, service continuity [9–12]. In this context, the possibility to supply electrical loads in the event of fault in the main distribution system, by means of local distributed generators (DGs), is acknowledged as a valuable perspective to improve the overall system reliability. The basic concept is to operate in islanding mode some portions of the distribution network when a fault occurs, in order to minimize the unsupplied loads until the system is restored to improve reliability [13–16]. To reach such a challenging goal, it is necessary to estimate the ability of distributed generators to meet the island load [17–19]. A major issue in the adequacy [20–23] assessment procedure is taking into account the correlation existing among the power outputs of unconventional DGs (UDGs) based on the same renewable intermittent primary energy source (such as sun and wind) [24–29]. In the present work, the set made up by the islands' UDGs based on the same technology is called a *class* (e.g. solar class and wind class).

A generalized systematic approaches and the related analytical expressions have been presented in [30] to evaluate distribution system reliability in Smart Grids where island operation of micro-grids is intended to help improving local and overall reliability thanks to an advanced automation and protection scheme that allows multi-microgrid network paradigm implementation [31]. The expressions also consider a procedure to calculate the adequacy of micro-grids in the presence of both conventional and renewable DGs. The main merit of such a procedure is to provide a new general analytical expression that takes into account both load shedding (user load disconnection) and curtailment (user load reduction) policies to quantify the adequacy of a potential island. On the other hand, its main drawback is that it neglects the correlation among island loads' power demand, the correlation among power outputs of island UDGs belonging to the same class, the correlation among power output of different classes of island UDGs, and the correlation between power demands and power outputs, respectively, of island loads and UDGs.

In order to overcome the aforesaid limitations, this paper presents a new analytical expression that takes into account both load shedding and curtailment policies and, also, encompasses all the aforementioned power correlations. To do this, the proposed

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Nomenclature

i	load point (LP) identification index
k	faulted branch identification index
λ_i	LP i annual outage rate
U_i	LP i annual outage duration
$\lambda_{i,k}$	LP i annual outage rate due to a fault in branch k
$U_{i,k}$	LP i annual outage duration due to a fault in branch k
f_k	branch k failure rate (number of faults/year)
$t_{R,k}$	branch k repair time
CBS	switch represented by a combination of circuit breaker (CB) and sectionalizer (a sectionalizer is always installed where a CB is placed, hence when a CB is mentioned, it refers to the CB of a CBS)
j	switch (CBS or sectionalizer) identification index, equal to the identification index of the branch in which it is installed (j indicates also the island created after opening switch j)
PoA	probability of adequacy (it estimates the ability of local DGs to meet the island load)
$\rho_{A,j}$	PoA of local DGs in island j
$\rho_{A,sc}$	PoA of local DGs in island sc (sc indicates the sectionalizer closest to the fault among those installed between CBS j and the fault)
$t_{S,j}$	sectionalizer j switching time
$t_{S,sc}$	sectionalizer sc switching time
$t_{AV,j}$	time to be available for the local DGs of island j (time needed to reconnect the generators)
$t_{AV,sc}$	time to be available for the local DGs of island sc
np	number of periods which the years is divided into
p	period identification index (a number between 1 and np, e.g. a value between 1 and 4 when the years is divided into the four seasons)
t	day type identification index (1 stands for workday, 2 stands for holiday and weekend)
h	hour identification index (a value between 1 and 24)
nl	number of power levels for the load model of an LP or the generation model of a UDGs' class
l	level identification index (a number between 1 and nl)
$\rho^L_{i,p,t,h,l}$	probability that LP i absorbs an active power equal to level l, at hour h, in day t, of period p
$\rho^L_{i,\,l}$	probability that LP i absorbs an active power equal to level l during the year
nd	data number of collected historical data, in term of active power absorbed by a LP at hour h in all days of type t belonging to p
c	class identification index, defined as a set of generators made up of unconventional DGs based on the same technologies
d	distributed generator identification index, equal to the number of the node at which it is connected
nu	number of UDGs in a class for a given island
ns	number of sets, where a set is made up by the generators' power outputs of a specific island's class for a given period and hour (the number of data items in each set is equal to nu: $P^U_{1,s}P^U_{2,s},\ldots,P^U_{nu,s}$)
s	set identification index (a number between 1 and ns)
$P^{U_c}_{cmb,s}$	power output of combination cmb for set s of class c, whose value depends on the powers of set s and on the generators' states combination cmb, where each state is up or down
$\rho^{U_c}_{cmb,s}$	probability related to $P^{U_c}_{cmb,s}$
$\rho^{U_c}_{p,h,l}$	probability associated to power level l in the hourly generation model of class c, related to period p at hour h
$\rho^C_{d,l}$	probability associated to power level l in the conventional generator model of DG d
$\rho^G_{d,\,l}$	probability that DG d provide a power equal to level l during the year
N_j	number of working points at which island j can operate
$nl_{L,i}$	number of power levels for LP i
$nl_{G,d}$	number of power levels for DG d
NL_j	number of LPs belonging to island j
NG_j	number of DGs belonging to island j
m	one combination, with $m \in [1, N_j]$
$P^L_{j,m}$	total power demand in island j for the m-th combination
$P^G_{j,m}$	total power output available in island j for the m-th combination
$\rho_{j,m}$	occurrence probability of the m-th combination
wd_p, hd_p	number of workdays (W) and holydays (H), respectively, in period p
$\rho^W_{A,j,p,h}, \rho^H_{A,j,p,h}$	PoA of island j, respectively, in W and H days of period p and hour h
$N^W_{j,p,h}, N^H_{j,p,h}$	number of working points at which island j can operate at period p, hour h, in W and H days, respectively
$P^{LW}_{j,p,h,m}, P^{LH}_{j,p,h,m}$	total power demand in island j considering the m-th combination at period p, hour h, in W and H days, respectively
$P^G_{j,p,h,m}$	total power output available in island j for the m-th combination at period p and hour h
$\rho^W_{j,p,h,m}, \rho^H_{j,p,h,m}$	probability of the m-th combination at period p, hour h, in W and H days, respectively

expression exploits hourly generation models that account for power output correlation for a class of UDGs in an island. Moreover, the proposed formulation is based on hourly load models too. From a practical viewpoint, one load model and one generation model have to be developed for each LP and each UDGs' class of an island, respectively. It is worth to note that hourly load and generation models permit to take into consideration correlation among loads, correlation among different classes of UDGs and correlation among loads and UDGs [28].

Distribution system reliability and local DGs adequacy

Typical indexes to evaluate distribution system reliability [32] can be estimated by means of the annual outage rate (λ_i) and duration (U_i) of all load points (LPs), which, respectively, are the number of outages and the total outage time in a year for the i-th LP [20]. Their value mainly depends on LP power demand and location, DGs type, capacity and position, fault location, switches type and installation point. It is known that the following expressions can be applied in order to compute their value:

$$\lambda_i = \sum_k \lambda_{i,k} \tag{1}$$

$$U_i = \sum_k U_{i,k} \tag{2}$$

where $\lambda_{i,k}$ is the LP i annual outage rate due to a fault in branch k; $U_{i,k}$ is the LP i annual outage duration due to a fault in branch k.

Table 1 shows the expressions presented in [30] for all possible cases defined by the relative position of LPs, faults and switches, in networks with and without DGs for distribution systems where island operation is allowed and not allowed.

Fig. 1 and Table 2 help to understand how to identify the various cases (see [30] for more details).