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ScienceDirect
Solar Energy 81 (2007) 1473–1481
SOLAR ENERGY
www.elsevier.com/locate/solener

Probabilistic load flow using Monte Carlo techniques for distribution networks with photovoltaic generators

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Received 26 September 2006; accepted 28 February 2007
Available online 22 March 2007

Communicated by: Associate Editor H. Gabler

Abstract

Connections of distributed generation (DG) systems to distribution networks are increasing in number, though they may often be associated with the need of costly grid reinforcements or new control issues to maintain optimal operation. Appropriate analysis tools are required to check distribution networks operating conditions in the evolving scenario. Load flow (LF) calculations are typically needed to assess the allowed DG penetration level for a given network in order to ensure, for example, that voltage and current limits are not exceeded.

The present paper deals with the solution of the LF problem in distribution networks with photovoltaic (PV) DG. Suitable models for prediction of the active power produced by PV DG units and the power absorbed by the loads are to be used to represent the uncertainty of solar energy availability and loads variation. The proposed models have been incorporated in a radial distribution probabilistic load flow (PLF) program that has been developed by using Monte Carlo techniques. The developed program allows probabilistic predictions of power flows at the various sections of distribution feeders and voltage profiles at all nodes of a network.

After presenting theoretical concepts and software implementation, a practical case is also discussed to show the application of the study in order to assess the maximum PV peak power that can be installed into a distribution network without violating voltage and current constraints. A comparison between Deterministic Load Flow (DLF) and PLF analyses is also performed.

Keywords: Electrical distribution networks; Photovoltaic generators; Probabilistic load flow

1. Introduction

Distributed generation (DG) can be defined as electric power generation within distribution networks or on the customer side of the network. Network integration of DG is a very complex issue that is significantly different from traditional network integration of power generation into transmission networks, since actual distribution networks are designed as radially operated, passive systems. For this reason connection of DG to the distribution system may be associated with costly grid reinforcements or new control issues to maintain optimal operating conditions (e.g. acceptable voltage quality, correct protections operation, etc.). However, the general view is that DG is expected to play an important role in future electrical energy systems. Two major reasons for an increased utilization of DG are liberalized markets and the global trend of reducing greenhouse gas emissions, which leads to more renewable energy based power sources.

With regard to LV distribution networks, an example of grid-connected renewable energy generators has been provided in many European Countries by the implementation of the "photovoltaic (PV) roof-tops" programs, supported by national governments.

At the LV level, one of the most relevant issues is the quality of the voltage supplied to customers, according to

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doi:10.1016/j.solener.2007.02.007

Nomenclature

- $[A]$ network incidence matrix, dimension is $(n \times n)$
- $[\overline{I}]$ vector of the node currents, dimension $(n \times 1)$
- $[\overline{J}]$ vector of the branch currents, dimension $(n \times 1)$
- $[\overline{Z}]$ network complex impedance matrix, dimension $(n \times n)$
- $[\overline{Z}_b]$ diagonal matrix whose elements are the complex impedances of the corresponding branches, dimension $(n \times n)$
- $\overline{S}_i$ complex power at node i
- $\overline{V}_i$ voltage phasor at node i
- $\overline{I}_i$ current phasor at node i
- $\overline{I}_i^*$ complex conjugate of $\overline{I}_i$
- P_i net real power at node i
- Q_i net reactive power at node i
- P_{Li} and Q_{Li} real and reactive power absorbed by the load at node i
- P_{Gi} and Q_{Gi} real and reactive power delivered by the generators at node i
- R_{ij} and X_{ij} real and imaginary part of $\overline{Z}_{ij}$, which is the generic element of matrix $[\overline{Z}]$
- r and x line resistance and reactance per kilometre
- $V_{\min}$ and $V_{\max}$ minimum and maximum voltage values allowed by EN 50160
- $I_{\max}$ line current carrying capacity
- $\boldsymbol{P}_L$ random variable "load demand"
- $\overline{\boldsymbol{P}}_L$ mean value of $\boldsymbol{P}_L$
- σ standard deviation of $\boldsymbol{P}_L$
- $\boldsymbol{k}_t$ random variable "hourly clearness index"
- k_{tu} upper bound for $\boldsymbol{k}_t$
- $\boldsymbol{C}$, $\boldsymbol{\lambda}$ parameters of the probability density function for $\boldsymbol{k}_t$
- $\boldsymbol{I}_t$ random variable "irradiance on an horizontal plane"
- $\boldsymbol{I}_0$ random variable "extraterrestrial total solar irradiance"
- $\boldsymbol{I}_\beta$ random variable "irradiance on a surface with inclination β to the horizontal plane"
- $\boldsymbol{P}_{pv}$ random variable "power output of the PV system"
- A_C PV array surface area
- $\boldsymbol{\eta}$ efficiency of the PV system in realistic reporting conditions (RRC)
- $\boldsymbol{\delta}$ declination angle
- ρ reflectance of the ground
- ϕ latitude
- $\boldsymbol{\omega}$ hour angle
- $\boldsymbol{\omega}_s$ sunset hour angle
- P_{PVpeak} total photovoltaic peak power installed in the network
- $P_{PVpeak(max)DLF}$ maximum value of P_{PVpeak} that can be installed in the network without violating voltage and current constraints calculated by means of a DLF
- $P_{PVpeak(max)PLF}$ maximum value of P_{PVpeak} that can be installed in the network without violating voltage and current constraints calculated by means of a PLF
- P_{LTOT} network overall contractual load
- μ_{OV} yearly average number of hours with overvoltage
- σ_{OV} yearly average standard deviation of the number of hours with overvoltage
- μ_{UV} yearly average number of hours with undervoltage
- σ_{UV} yearly average standard deviation of the number of hours with undervoltage
- μ_{OC} yearly average number of hours with overcurrent
- σ_{OC} yearly average standard deviation of the number of hours with overcurrent

the European Standard EN 50160 (European Standard EN 50160, 1999), especially in terms of possible overvoltage caused by connection of generators (Conti et al., 2003a,b).

Appropriate load-flow (LF) calculations are needed to assess the allowed DG penetration level for a given network in order to ensure that the maximum voltage at the point of common coupling (PCC) and lines current carrying capacity are not exceeded (Conti et al., 2003c).

However, when connection of generators based on renewable energy (such as solar energy) is considered, it is not possible to achieve a realistic evaluation of where and when overvoltages may occur by simply using traditional deterministic LF (DLF) analysis. In fact, this analysis (recalled in Section 2) is normally based on some selected combinations of consumer loads and PV power productions. Consequently, it does not take into account the statistical variation of loads and solar radiation.

Then, to solve this problem, the paper presents a probabilistic load flow (PLF), based on Monte Carlo techniques, for radial distribution networks with PV DG (Section 3). The procedure incorporates suitable models for the active power produced by PV DG units and the power absorbed by the loads in order to represent the uncertainty for solar energy availability and load variation.

In Section 4 the development of a software tool to implement the method proposed will be presented in order to assess voltages and currents in a distribution network, calculated hour by hour throughout a year. Then, the application to a practical case study will be discussed to show the results of the proposed method. In particular, the results obtained by the DLF (Section 6) and the PLF (Section 7) applied to a realistic LV distribution network with PV DG (described in Section 5) will be compared. The two LF analyses will be used to assess the maximum