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Probabilistic three-phase load flow for unbalanced electrical systems with wind farms

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In this paper, a three phase probabilistic load flow for transmission system based on point estimation method along with three phase unbalanced induction generator model for the wind farm has been proposed. The proposed method is tested on a IEEE-118 bus three phase system and accuracy of the results have been validated by comparing the results with those obtained by Monte Carlo simulation studies. The effect of variation of standard deviation of the connected loads on the system and effect on the voltage profile has also been studied.

1. Introduction

Due to rapid increase in renewable energy sources (RES) and to address the concerns of global warming and depleting fossil fuels, transmission system can no longer be modeled as a passive network. Out of RES, wind is one of the fastest growing sources. Because of random and wide variation of wind velocity, the power output from a wind generating system (WGS) is intermittent and of fluctuating nature. When this fluctuating power is injected into the grid, it causes variations in bus voltages and line power flows of transmission system. Due to increasing penetration of WGS in the grid, these variations are going to be quite significant in the future (if not already). Therefore, for successful integration of WGS in the grid, these possible variations need to be properly analyzed, estimated and quantified. The unbalances in power systems are not always negligible, so, single-phase analysis alone is not enough and the use of the three-phase load flow method for the steady state analysis is mandatory. Also, there are unavoidable uncertainties in power system the form of wind generation, etc., which affect input data. For the evaluation of steady state operating conditions (due to time variations in phase load demands and network configurations), the uncertainty can be described only in statistical terms. This can be achieved through probabilistic three phase load flow analysis of the grid in the presence of uncertain power generation from WGS.

Probabilistic Load Flow (PLF) was first proposed by Borkowska in 1976 [1] and thereafter applied to different areas of planning and operation [2,3]. The earliest simplified probabilistic load flow formulation was using DC power flow method and loads were considered as independent random variables which was extended by various authors to AC power flow method. Probability Density Function (PDF) and Cumulative Distribution Function (CDF) of the quantities of interest have been calculated in [1–5]. In [5], Fourier Transform based convolution using DC power flow method has been used to find out the PDF and CDF of the variables of interest. In [6] only the mean and the standard deviations (of the quantities of interest) have been calculated using an extended Point estimate method (PEM). In [1–4] initially the moments and cumulants of the variables of interest have been calculated using a suitable technique (such as PEM [4,5] and weighted sum of cumulants of input variables [6,7]) and subsequently the PDF and CDF have been computed using an appropriate series expansion (such as Cornish-Fisher [4,5] and Gram-Charlier [6,7]). Further, in all these works the obtained results from PLF have also been compared with the results obtained by Monte-Carlo simulation (MCS) studies.

For considering the uncertainties in WGS, basically two approaches have been used in the literature. In the first approach, a WGS has been modeled as an uncertain real power injection using Beta distribution [1–3]. In the second approach the uncertainty in the wind speed has been considered using Weibull distribution [4–6] and Rayleigh distribution [8] and subsequently the

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Acronyms and nomenclature

CDF	cumulative distribution function
CF	Cornish-Fisher
DLF	deterministic load flow
GC	Gram-Charlier
MCS	Monte Carlo simulation
PDF	probability density function
PEM	point estimate method
PLF	probabilistic load flow
RES	renewable energy sources
WGS	wind generating system
sp	specified value of the variable
N_c	number of load busbars
N_g	number of generator terminal busbars
N	number of network busbars
P_i^{ph}, Q_i^{ph}	active and reactive powers at busbar i with phase ph
V_i^{ph}, θ_i^{ph}	voltage magnitude and angle at busbar i with phase ph
$\boldsymbol{I}_{as,j}$	phase currents for the jth induction machine
$\boldsymbol{V}_{\Delta,j}$	line-to-line voltages where jth asynchronous machine is connected
$\boldsymbol{P_e}$	three phase active powers generated by Ns asynchronous machines
$\boldsymbol{P_W}$	actual powers given by a power curves of the wind turbines
α, β	series admittance of three phase transmission line
β_n	shunt admittance of three phase transmission line
$\boldsymbol{P_x}$	correlation matrix
$\boldsymbol{C_x}$	variance-covariance matrix
$(x_{l,k})^{ph}$	kth point of lth random variable of phase ph
$(w_{l,k})^{ph}$	kth weight of lth random variable of phase ph

corresponding injected real power by the WGS has been calculated using the speed-power relationship of the wind generator [9].

In the above literature, the unbalances in loads and in other ac systems are considered to be negligible and single phase model of power system is considered. These unbalances are not always negligible as in case of long untransposed lines, AC traction plants and electrical furnaces. So, for the evaluation of steady state operating condition, three phase load flow analysis is required.

Not much literature is available for the three phase probabilistic load flow analysis. In [10] the classical Monte Carlo simulation procedure and a simplified approach based on the linearization of load flow equations around an expected value region is used.

However, none of these proposed approaches considers the presence of wind generators. Since, the wind farms are nowadays one of the most frequent distributed sources employed, we consider the unbalanced three-phase systems including wind farms with asynchronous machines.

To address the above issue, the model of wind farm with asynchronous machine is added to three phase transmission load flow. The basic objective is to calculate the PDFs/CDFs of the variables of interest in the presence of uncertain loads and uncertain wind power generation. To compute the moments of variables of interest, PEM [11,12] has been used in this work and subsequently the CDF has been determined by using the Cornish-Fisher expansion [4].

The main contributions of this paper are as follows: (a) formulation of a probabilistic unbalanced three phase load flow for transmission system using point estimation method and (b) extension of point estimation based three phase load flow by including the wind generation uncertainties in the form of wind farm and check the applicability of the proposed technique by comparison with benchmark method i.e. Monte Carlo simulation.

This paper is organized as follows: In Section 2, three phase deterministic load flow is discussed. In Section 3, three phase induction machine is discussed. In Section 4, the basic procedure of PEM based PLF is described. In this section, three point, five point and seven point estimate methods and correlation in PEM are discussed. Lastly, in Sections 5 and 6, main results and conclusions of this work are presented, respectively.

2. Three phase deterministic load flow

The basics of deterministic three phase load flow is reported in [5], which is the basis of three phase PLF. Let us consider an unbalanced power system in which load busbars are from 1 to N_c, the busbars from N_c+1 to N_c+N_g are generator terminal busbars, and from N_c+N_g+1 to $N_c+2N_g=N$ are generator internal busbars, slack busbars are the last terminal and internal busbars.

Three phase system behavior with system admittance matrix y_{ik}^{phm} is described by the equation:

$$I_i^{ph} = \sum_{k=1}^{N}\sum_{m=1}^{3} y_{ik}^{phm} V_k^m; \tag{1}$$

where $ph = 1,2,3$ and $i = 1,\ldots,N_c$.

Since, $V_i^{ph}(I_i^{ph})^* = P_i^{ph} + Q_i^{ph}$, Eq. (1) can be expressed as:-

$$P_i^{ph} + Q_i^{ph} = V_i^{ph}\left(\sum_{k=1}^{N}\sum_{m=1}^{3} y_{ik}^{phm} V_k^m\right)^* \tag{2}$$

y_{ik}^{phm} can be resolved into $G_{ik}^{phm} + jB_{ik}^{phm}$ and finally, Eq. (2) can be expressed as:-

$$\begin{aligned} P_i^{ph} &= V_i^{ph}\sum_{k=1}^{N}\sum_{m=1}^{3} V_k^m\left[G_{ik}^{phm}\cos\theta_{ik}^{phm} + B_{ik}^{phm}\sin\theta^{phm}\right] \\ Q_i^{ph} &= V_i^{ph}\sum_{k=1}^{N}\sum_{m=1}^{3} V_k^m\left[G_{ik}^{phm}\sin\theta_{ik}^{phm} - B_{ik}^{phm}\cos\theta^{phm}\right] \end{aligned} \tag{3}$$

where $ph = 1,2,3$ and $i = 1,\ldots,N_c$ and the voltage and angle are unknown in each phase.

For the load busbars, at each of the three phases, the active $((P_i^{ph})^{sp})$ and reactive $((Q_i^{ph})^{sp})$ powers are specified. For each of the three phases at every load and generator terminal busbar, the calculated active and reactive powers are obtained using Eq. (3).

At the generator terminal busbars with the exception of slack, the active P_i^{ph} and reactive Q_i^{ph} load powers at each of three phases, are specified, along with the three phase active power at internal generator busbar. At the terminal generator busbar the voltage regulator law is also specified.

The equations for these busbars are:

$$\begin{aligned} P_i^{ph} &= V_i^{ph}\sum_{k=1}^{N}\sum_{m=1}^{3} V_k^m\left[G_{ik}^{phm}\cos\theta_{ik}^{phm} + B_{ik}^{phm}\sin\theta_{ik}^{phm}\right] \\ Q_i^{ph} &= V_i^{ph}\sum_{k=1}^{N}\sum_{m=1}^{3} V_k^m\left[G_{ik}^{phm}\sin\theta_{ik}^{phm} - B_{ik}^{phm}\cos\theta_{ik}^{phm}\right] \\ P_j^{gen} &= \sum_{ph=1}^{3} V_j^{ph}\sum_{k=1}^{N}\sum_{m=1}^{3} V_k^m\left[G_{jk}^{phm}\cos\theta_{jk}^{phm} + B_{jk}^{phm}\sin\theta_{jk}^{phm}\right] \\ (V_i)^{sp} &= f(\overline{V}_i^1, \overline{V}_i^2, \overline{V}_i^3,) \end{aligned} \tag{4}$$

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