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Uncertainty modelling of wind turbine generating system in power flow analysis of radial distribution network

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ABSTRACT

In this paper, interval arithmetic (IA) is used for taking into account the uncertainties of the active power produced by a wind turbine generating system (WTGS) in the power flow computation of a balanced radial distribution system. The effectiveness of the proposed method has been investigated by comparing the results obtained by this method with those obtained by Monte Carlo simulation (MCS) technique on two different balanced radial distribution systems. It has been found that the results obtained by these two methods (IA and MCS) are very close to each other while the computation time required by IA based method is significantly less than that required by MCS.

$V_{il}^{(k)}$	interval valued complex voltage of node '*i*' corresponding to iteration '*k*'
$v_u^I(j)$	upper limit of the interval of voltage magnitude of bus '*j*' obtained by interval load flow technique (ILFT)
$v_l^I(j)$	lower limit of the interval of voltage magnitude of bus '*j*' obtained by ILFT
$v_u^M(j)$	upper limit of the interval of voltage magnitude of bus '*j*' obtained by MCS
$v_l^M(j)$	lower limit of the interval of voltage magnitude of bus '*j*' obtained by MCS

1. Introduction

Concerns about global warming, depletion of fossil fuels and overall environmental degradation are the major forces nowadays for increasing deployment of renewable energy resources around the world. Among various renewable energy resources, wind energy is one of the most non-polluting, free and seemingly endless sources of electrical energy. As a result, increasing level of wind energy penetration into the grid is being planned and executed in many countries around the world [1]. For successful integration of the wind turbine generating system (WTGS) into an electrical grid, the effect of a WTGS on the steady state operation of the grid must be properly analyzed. To address this need, several works in the literature [2–5] have developed various steady state models of WTGS for incorporating into the load flow solution of the transmission and distribution networks. Modelling of wind farms in load flow solution of a transmission grid has been discussed in Ref. [2]. In this work, two different models of the wind farms have been proposed. However, the performances of the proposed models have been demonstrated on a very small system. Different models of WTGS for load flow solution of balanced radial distribution system have been described in Ref. [3,4]. An integrated AC-DC load flow method for a variable speed offshore wind farm has been proposed in Ref. [5].

Now, in contrast to the output of a fossil fuel based power plant, that of a WTGS is not constant. It is dependent on the speed of the wind and as a result, the real power output of a WTGS experiences seasonal, monthly and daily variations. For successful integration of wind energy to the grid, the effect of this variation on the operation of the grid must be properly analyzed, which has not been tackled in Ref. [2–5]. To address this need, several approaches have been suggested in the literature to consider this uncertainty into the steady state analysis of a power system network. Probabilistic methods for considering the uncertainties of power produced by a WTGS into the power flow solution of transmission system are reported in Ref. [6–9].

An early work for considering the wind generation uncertainty into power flow solution of distribution system is presented in Ref. [10], in which the probabilistic model of the active power produced and the reactive power absorbed by the induction generator (IG) based wind turbines (WT) has been considered and

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subsequently, these probabilistic models have been incorporated into the linearized power flow equations of a radial distribution system. Probabilistic three phase load flow algorithm for unbalanced distribution system with wind farms has been presented in Ref. [11] in which computationally intensive Monte Carlo Simulation (MCS) method had been used for computing the values of all the quantities of interest. Time series approaches have been presented in Refs. [12,13] for solving the power flow problem of an electrical network with high wind penetration, in which, computationally intensive repeated power flow solutions had been used for considering the 'time series' of the generation and demand into the load flow solution.

To extend the work on consideration of wind generation uncertainty into the power flow solution of a radial distribution network further, application of interval arithmetic (IA) is proposed in this paper. In this approach the uncertain wind generation is represented by an interval number and subsequently, IA is used to compute the power flow solution and the reactive power consumed by the WTGS. Thus, neither linearization of the power flow equations nor computationally expensive MCS method is necessary for considering the wind generation uncertainty into the load flow solution. It is to be noted that the application of IA for load flow study of a transmission network has already been discussed quite some time ago [14]. Subsequently, further applications of IA in power flow solution of transmission system [15] and radial distribution system [16] have also been reported in the literature. However, application of IA for load flow study of a distribution network in the presence of WTGS has not so far been reported in the literature. The paper is organized as follows. In Section 2, the proposed interval arithmetic based load flow algorithm with WTGS is described in detail. The main results of this work along with the relevant discussions are given in Section 3. Lastly, Section 4 concludes the work. It is to be further noted that the basic concepts and relations of interval arithmetic are readily available in Ref. [17] and hence are not repeated here due to limitation of space.

2. IA based power flow algorithm with WTGS

As described in Section 1, to account for the uncertainty in the real power output of a WTGS (P_G), it has been represented by an interval number (denoted as P_{GI}) in this work. Such an interval can be decided on the basis of the probability distribution function (PDF) of P_G. For example, if P_G has a normal PDF having mean μ and standard deviation σ, then it is known that 99% of the values of P_G lie within the boundary between $\mu - 3\sigma$ and $\mu + 3\sigma$. Therefore, in this case, the interval can be taken as $[\mu - 3\sigma, \mu + 3\sigma]$. Similarly, for any other variation in P_G, the possible minimum and maximum values of P_G can constitute the interval. With this interval valued P_G, the reactive power absorbed by the WTGS (Q_G) is calculated by solving an interval quadratic equation and as a result, it also turns out to be an interval number. With these interval valued P_G and Q_G of the WTGS, the backward/forward load flow algorithm [18] is followed in which interval arithmetic is used in place of real arithmetic. To begin with the algorithm, initial voltages at all nodes are assumed to be equal to that of the root node. Thus, if the voltage of the root node is assumed to be fixed at $1.0\angle 0^\circ$ p.u, in the interval notation, initially the voltages of all the nodes are assumed to be equal to $[1.0, 1.0] + i[0.0, 0.0]$ p.u. With these initial interval voltages, the following procedure is followed:

Step 1: Set the initial counter $k = 1$.
Step 2: Calculate the interval voltage magnitudes of any node 'd' containing a WTGS. For this purpose, the functions for computing square and square root of any interval number are required. These functions have been adopted from Ref. [19] and hence are not repeated here.
Step 3: With the known value of P_{GI}, the interval valued reactive power absorbed by a WTGS at iteration 'k' (henceforth denoted as $Q_{GI}^{(k)}$) is calculated for both types of WTGS as follows:

(a) Pitch regulated fixed speed (PRFS) WTGS

For calculating the reactive power absorbed by the WTGS, following Ref. [3], initially the slip (s) is calculated by solving a quadratic equation of the form $as^2 + bs + c = 0$. Now, as the coefficients a, b and c depend on the interval valued P_G and bus voltage magnitude, these also would turn out to be interval numbers. For evaluating these interval coefficients (which will be denoted as 'a_I', 'b_I' and 'c_I' respectively), the expressions given in [3] can be used directly. However, to reduce the 'problem of dependence' [17], these expressions are re-written as shown below for narrowing down the width of the finally computed interval coefficients.

$$a_I = R_{1I}(X_{l2I} + X_{mI})^2(P_{GI}R_{1I} - |V_{dI}^{(k)}|^2) + P_{GI}\{X_{mI}X_{l2I} + X_{l1I}(X_{l2I} + X_{mI})\}^2 \quad (1)$$

$$b_I = R_{2I}X_{mI}^2(2P_{GI}R_{1I} - |V_{dI}^{(k)}|^2) \quad (2)$$

$$c_I = P_{GI}R_{2I}^2(X_{l1I} + X_{mI})^2 + R_{1I}R_{2I}^2\left(P_{GI}R_{1I} - \left|V_{dI}^{(k)}\right|^2\right) \quad (3)$$

In Eqs. (1)–(3) and all subsequent instances throughout the paper, the symbols R_{1I}, R_{2I}, X_{l1I}, X_{l2I} and X_{mI} denote the interval numbers for representing the stator resistance, rotor resistance, stator leakage reactance, rotor leakage reactance and magnetizing reactance of the WTGS respectively. However, it is to be noted that, all these interval numbers have been taken to be degenerate interval numbers [17] with their values equal to those given in Ref. [3]. With these interval valued coefficients calculated in Eqs. (1)–(3), the interval valued slip (s_I) can be calculated by solving the interval quadratic equation $a_I s_I^2 + b_I s_I + c_I = 0$. Now, for the typical values of R_1, R_2, X_{l1}, X_{l2} and X_m [3], it can be readily verified that $a > 0$, $b < 0$ and $c > 0$. Therefore, following Ref. [17], the two values of s_I are calculated as;

$$s_{1I} = \frac{-b_I + \sqrt{b_I^2 - 4a_I c_I}}{2a_I}; \quad s_{2I} = \frac{2c_I}{-b_I + \sqrt{b_I^2 - 4a_I c_I}} \quad (4)$$

It is to be noted that both s_{1I} and s_{2I} are interval numbers. From these two interval numbers, the final value of s_I is calculated as; $s_I = \min(s_{1I}, s_{2I})$. Finally, with this calculated value of s_I, the quantity $Q_{GI}^{(k)}$ is calculated as shown below.

$$Q_{GI}^{(k)} = \frac{[k_{2I} + k_{4I}]|V_{dI}^{(k)}|^2}{k_{5I}^2 + k_{6I}^2} \quad (5)$$

The constants k_{2I}, k_{4I}, k_{5I} and k_{6I} are given in Appendix.

(a) Semi variable speed (SVS) WTGS

For this type of WTGS, following Ref. [3], the equivalent resistance $R_{eq}(= R_2/s)$ is calculated by solving a quadratic equation of the form $a_1 R_{eq}^2 + b_1 R_{eq} + c_1 = 0$. Again, the coefficients a_1, b_1 and c_1 depend on the interval valued P_G and bus voltage magnitude and as a result, these also turn out to be interval numbers. As in the case of pitch regulated fixed speed WTGS, in this case also, the original expressions given in Ref. [3] are re-written as shown below to narrow down the width of the finally computed interval coefficients (which will be denoted as 'a_{1I}', 'b_{1I}' and 'c_{1I}' respectively).

$$a_{1I} = P_{GI}\{R_{1I}^2 + (X_{l1I} + X_{mI})^2\} - |V_{dI}^{(k)}|^2 R_{1I} \quad (6)$$