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# Probabilistic Load Flow of Unbalanced Distribution Systems with Wind Farm

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**Abstract:** This paper examines the practical application of the Unscented Transform (UT) method in carrying out load flow studies in distributions systems with embedded generation and unbalanced loading. A hybrid ladder network based backward/forward sweep technique was employed in solving the distribution system load flow. The performance of the load flow technique plus the UT method is demonstrated using a real 44-Bus unbalanced distribution system with a proposed wind farm which is located in Samsun, Northern Turkey. Results obtained were compared with those from the Monte Carlo Simulation method while the effect of the wind farm on the existing network was also evaluated.

**Keywords:** Monte Carlo simulation; probabilistic load flow; unbalance; uncertainty; unscented transforms; wind energy

## 1 INTRODUCTION

The wind energy sector has witnessed a tremendous growth over the last few decades owing to the global call for clean energy, liberalized electricity market and favourable legislation to support this. At the end of 2015, the installed world wind energy capacity had reached about 433 GW while a 1.5 TW capacity is projected by 2020 [1]. Unlike most conventional energy sources, wind power output is largely dependent on the climatic condition, thus making it uncertain. Considering the high penetration level and the randomness of the wind generator output, the impact of wind energy systems (WES) on the power network must be carefully studied to ensure full compliance with existing grid codes.

Load flow studies are often carried out when the wind power plant is in planning stage, in the operation stage and progressive stage - to help determine the condition of the power system. Unfortunately, traditional load flow methods, such as the generic Newton Raphson (NR) method often applied to transmission systems, result in low convergence (or even divergence) when applied to the distribution system. This is because of some peculiarities of the distribution system such as high resistance to reactive impedance ratio, unbalance and multiphase nature etc. [2]. As such, any load flow technique for the distribution system should be able to accommodate these characteristics efficiently. Some distribution system specific load flow methods, most of which are based on the backward forward sweep (BFS) or current injection scheme have been introduced in the literature.

In [2] and [3] the BFS technique with a branch oriented numbering scheme is employed. The method is extended to cater for weakly meshed systems using the breaking point scheme. The ladder network based on BFS is used for load flow in a distribution system. In the several models of transformer configurations, voltage regulator and capacitors details are given in [4]. This method is named fast and flexible radial power flow (FFRPF), which is different type of BFS, and is given in [5]. In this case to update the voltages and currents, matrices are formed and used which related bus and branch.. Development of backward forward sweep methods (for example bus numbering, data handling etc.) is given in [6]-[9].

In the load flow studies developed NR methods have also been used [10]. A NR method with a reduction in the Jacobean matrix was recommended, to save the time. [11]. To solve the load flow in unbalanced distribution systems sequence based load flow using NR methods was recommended [12], [13]. Other methods such as the Zbus method [14], Zbranch method [15] and current injection based methods [16], [17] have also been introduced in the literature.

In the practical implementation of any of these techniques, the uncertainties within the network must be fully accounted for the required grid system characteristics. - This brought about the concept of probabilistic load flow (PLF) in [18]. These uncertainties are often caused by variations in the customer loading pattern and randomness of distributed generation output (e.g. wind energy system, solar photovoltaic, fuel cells etc.) amongst other things. In most of the previous works, the customer load has been modelled to follow the normal distribution [18]. The probabilistic distribution for the output of wind turbines is dependent on the wind speed distribution and the wind turbine characteristics curve. For long term study purposes, wind speed has been statistically modelled to follow the Weibull or Rayleigh distributions [19], as such the Weibull model is used in this research.

In this work, the UT method earlier introduced by the authors as an efficient PLF method is extended to solve the load flow problem in an unbalanced distribution system with wind generation. A hybrid method which uses the ladder network based on backward/forward sweep is employed to solve the load flow problem for a practical 44-bus system with a proposed 500 kW wind farm, i.e. an OndokuzMayis University example in Samsun/TURKEY. Results obtained using the UT method and the Weibull distribution model for the wind speed show a good agreement with those from the Monte Carlo Simulation, however at a reduced computational cost.

This paper is structured as follows. First, the state of the art for the Turkish wind power sector is reviewed to understand the paramount place of wind energy in the Turkish energy sector. The Unscented Transform method is next discussed briefly while the principle for load flow evaluation for a real distribution system is then presented. The practicality of using Unscented Transform in distribution systems is finally demonstrated on the real 3-phase Samsun network with several unbalances and embedded wind farm.

## 2 TURKEY: WHY WIND ENERGY?

Currently, a fairly good growth has been witnessed in Turkey and a yearly electricity consumption growth rate of about 8% has been forecasted. However, considering that Turkey imports most of the fossil fuel used to meet her electricity demands and the expected growth in consumption, much effort is being geared towards promoting renewable energy which is locally abundant. Turkey added 5840 MW of new electricity production capacity in 2017. Last year, the capacity of new natural gas power plants stood at 2621 MW. Imported coal to generate electricity in Turkey's coal-power plants totalled 1320 MW of installed capacity. Hydroelectricity power plants followed and generated 736.9 MW of new capacity. In addition to wind and hydro, Turkey added 337.9 MW of power production capacity from geothermal, biogas, solar and waste. Furthermore, 78.1 MW of additional capacity was provided from local coal, lignite, fuel oil and cogeneration [20].

This shows a heavy dependence on fossil fuels (mostly imported) with renewable energy systems playing minute roles.

However, much growth is expected within the sector over the next 10 years in view of the drive towards clean energy one the target of which is to meet up with the expected European Union's 20% renewable energy by 2020 since the nation plans joining the body. However, the government is very ambitious and targets 25% renewable energy by 2020 and about 30% by 2023 [21]. This has greatly influenced the needed positive political vigour for the growth of the sector such as favourable policies and incentive. For instance, a Renewable Energy Law 1 was passed in 2005 which provides tariff support for renewable energy generation.

Wind energy is not left out in the renewable energy sector growth and is currently the leading clean energy source in Turkey accounting for over 90% of the countries renewable capacity in 2011 (aside from small hydro project). Also, about 75% of the total renewable energy investments have been committed to the wind energy sector over the period of 6 years (2005-2011). At the end of 2011, the installed wind capacity in Turkey totalled 1.6 GW [21]. Although this figure is relatively low in comparison to some other European countries (e.g. France; 6.3 GW, Germany; 29 GW) and also the huge wind potential that abounds (88 GW technically), it is highly commendable considering that over 96% of this capacity was installed within six years. To illustrate the growth witnessed within the wind energy sector, Fig. 1 details the installed capacity over an 11 year period (2001-2011). A 20 GW installed capacity is projected for 2023 to meet up with the set renewable energy target. To achieve this target, government has given some incentives to the renewables and wind power plants. Main ones of those incentives are as follows:

Feed-In Tariff (FIT): 7.3 USD cent/kWh for 10 years of operation.

Local Content: If mechanical or electro-mechanical parts of the wind turbine are produced locally, then the investor can propose higher prices to the feed-in tariff price. Wind Power Plants can use this incentive for the first five years of operation. FIT can go up to 11 USD cent/kWh if the investor produces all wind farm parts in Turkey. However, this does not seem to be possible currently. However, some big turbine manufacturers are already manufacturing their towers and blades in Turkey. Because of this situation some projects can take 8.7 USD cent/kWh price for the wind power plants for the first 5 years of operation.

To fully achieve this desired output, special incentives have been put in place to further support the wind energy sector growth. For instance, custom duties and VAT have been waived for wind energy equipment, while the transmission companies have been put under obligation to provide grid support for all renewable energy systems. In addition, in a bid to encourage small domestic renewable energy installations, licenses are not required for generation facilities below 500 kW [22], while feed in tariffs can be received on excess generation transmitted into the distribution system. All these and the good wind profile makes investment in the wind energy sector worthwhile and a good alternative for replacing conventional electricity.

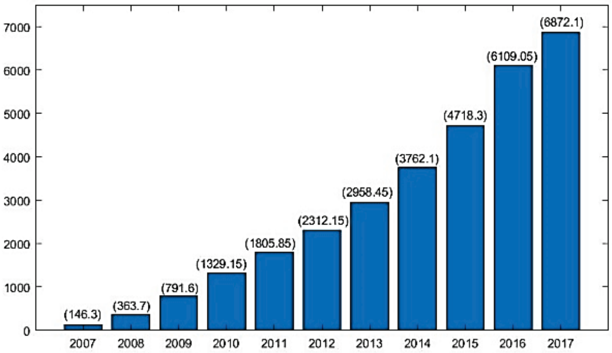

**Figure 1** Installed Wind Capacity for Turkey (2007-2017)

## 3 THE UNSCENTED TRANSFORM METHOD

The unscented transforms method was given in [23] and [24] as an approximate tool for load flow studies in the presence of uncertainties. With the UT method, the number of estimation points is greatly reduced as compared with the Monte Carlo simulation method. The UT method works by systematically approximating the PDF of a continuous distribution by using deterministically chosen points referred to as sigma points to create a discontinuous distribution such that both distributions have the same moments. The relationship between the continuous and discrete distribution moments, which forms the basis for the UT method, is given in Eq.(1).

$$E(\hat{u}^k) = \int \hat{u}^k w(\hat{u}) \mathrm{d}\hat{u} = \sum_i w_i S_i^k \tag{1}$$

where $S_i$ represents the sigma points (discrete estimation points) and with corresponding weights; $w(\hat{u})$ is the PDF of the continuous distribution.

The above equation is solved as a Gaussian quadrature problem to obtain the desired sigma points and weights. In this work, the enhanced UT method (based on dimension reduction) earlier introduced in [25] which uses reduced number of sigma points as compared with the method is used. Further details on the dimension reduction principle are found in [26].

## 4 PROBABILISTIC LOAD FLOW FOR THREE PHASE DISTRIBUTION SYSTEMS (BALANCED AND UNBALANCED)

The distribution system unlike the transmission system has some peculiar features as earlier mentioned which limits the application of transmission system load flow programmes like the basic Newton Raphson method. The load flow in this study is carried out based on the backward/forward sweep. When the voltage is updated in the forward sweep, the current is occurred in the backward sweep. The procedure for carrying out the load flow has been adapted from those described in [27] and is summarized below.

Step 1: According to network information, to determine the connected nodes putting order, formulate a parent child matrix. As an example, IEEE 15 bus test system is shown in Fig. 2, and created the parent child matrix $\boldsymbol{M}_{\mathrm{PC}}$ in Tab. 1. $\boldsymbol{M}_{\mathrm{PC}}$ matrix establishment is very easy, it does not contain renumbering the nodes, decreasing the value of receiving node number becomes the branch number is the rule. $\boldsymbol{M}_{\mathrm{PC}}$ matrix shows that sending and receiving nodes is very important for the forward and backward sweep.

**Table 1** The $\boldsymbol{M}_{\mathrm{PC}}$ Matrix for the15 Bus Test System

| Node | Parent | Children |
|---|---|---|
| 1 | - | 2,5 |
| 2 | 1 | 6,9,3 |
| 3 | 2 | 4,11 |
| 4 | 3 | 5,14 |
| 5 | 4 | - |
| 6 | 2 | 7,8 |
| 7 | 6 | - |
| 8 | 6 | - |
| 9 | 2 | 10 |
| 10 | 9 | - |
| 11 | 3 | 12 |
| 12 | 11 | 13 |
| 13 | 12 | - |
| 14 | 4 | - |
| 15 | 4 | - |

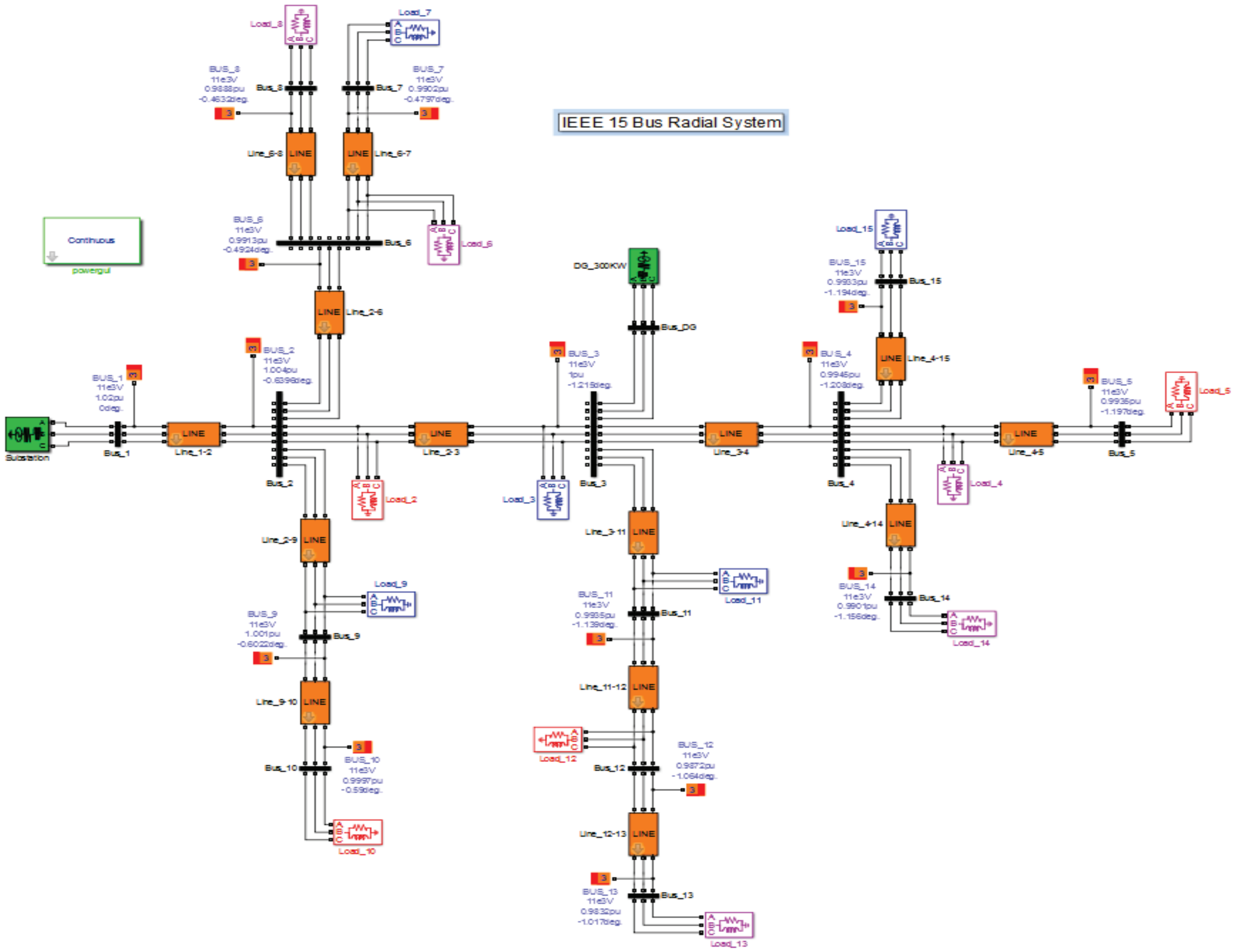

**Figure 2** IEEE 15 Bus Distribution Test System

Step 2: Shunt capacitor, distributed generation, total nodal current from loads etc. has to be calculated. - The load connection type (Delta or Wye) and load type (constant impedance, current and power) are important when calculating these currents. See the details in [27].

Step 3: Updating the current in the branches working from the end node towards the source node by backward sweep. Connector used in the switch, transformer and distribution line - between the nodes determines the update formula. As an example, the update formulas determined for nodes between Eq. (2) and Eq. (4) distribution lines Eq.

(5) switches and Eq. (6) transformers. The transformer structure determines the values of the $c_t$ and $d_t$ coefficients in Eq. (6). Other structures and values of the coefficients are given in Appendix.

$$I_{kp} = I_{GCLk} + \sum I(\text{children nodes})_k \tag{2}$$

$$I_k = c[V_k] + I_{kp} \tag{3}$$

$$c = [Y_k] - \frac{1}{4}[Z_k][Y_k]^2 \tag{4}$$

$$I_k = I_{kp} \tag{5}$$

$$I_k = c_t[V_k] + d_t[I_{k+1}] \tag{6}$$

where $I_{GCL}$ indicates the total current integrated by the loads on node $k$ and (embedded/distributed) generators, capacitors. The nodal current on bus $k$ and currents from children branches put together as $I_{kp} \cdot t$. The branch current for line $k$ is $I_k$, the voltage on node $k$ is $V_k$, impedance is $Z_k$ and admittance $Y_k$ are the matrix for line $k$. In this case the coefficients related to the transformer specification are $c_t$ and $d_t$.

Step 4: Estimation in the voltage of each node, evaluating the voltage drop across the lines is the main aim in the forward sweep. The source node voltage is utilized to stepwise going to the end node voltage. Example starting from source node to utilization stepwise going to end node is given in Eq. (7).

$$V_k = [A][V_{k-1}] - [B][I_k] \tag{7}$$

Type of connection between the nodes is defined by $A$ and $B$ parameters. In the case [4] connection types, $A$ and $B$ parameters are values of the wye-wye transformer. At the nodes between the switches, a zero drop is reputed intersection of the switches.

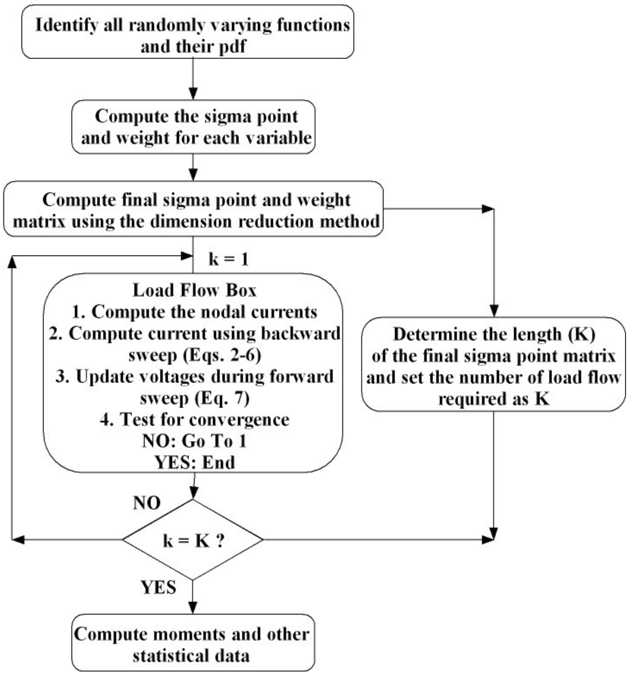

**Figure 3** Probabilistic Load Flow Implementation Using the UT Method

Step 5: The convergence test is applied to provide the errors are within the limits when the backward and forward sweeps are completed. When the present iteration and the voltage (on all phases) errors between the previous iteration are within the appointed limits iteration is finished.

A summary definition of the application procedure for the unbalanced load flow using the UT method is given in Fig. 3.

## 5 RESULTS AND DISCUSSION

UT method of application in 3-phase distribution system is examined in this section. The method is employed for probabilistic load flow studies in a practical 44-Bus unbalanced distribution system with built-in wind generation. Mixture of 3 phase, 2 phase and single phase loads of 20 load buses is the test system typical network. A one line diagram of the network is shown in Appendix 1. The proposed wind turbine will be located at bus 44 (about 1km from bus 2) with the output fed into the network at bus 2.

### 5.1 Case 1: Load Flow with Load Variation Only

Initially, the performance of the system with load unbalance and load variations only is examined. During this test, 114 random variables were considered which comprise active and reactive load variations. Because the load data was not recorded at the same time interval as with the wind speed, the load is supposed to follow the regular distribution with a 20% deviation from the mean (recorded). Selected results for the voltage magnitudes and angles are given in Tab. 2. It is given that the voltages for all the buses fall within the ±10% stipulated distribution system margin. The last row is the solution of classical power flow using Newton-Raphson.

**Table 2** Selected Result Using the MCS and UT Methods

| Method | | $V_{17}^{a}$ | $\delta_{17}^{a}$ | $V_{17}^{b}$ | $\delta_{17}^{b}$ | $V_{17}^{c}$ | $\delta_{17}^{c}$ |
|---|---|---|---|---|---|---|---|
| UT | $\mu$ | 0.994 | −0.354 | 0.9944 | −120.34 | 0.9945 | 119.64 |
| | $\sigma$ | 0.000 | 0.017 | 0.0002 | 0.0178 | 0.0002 | 0.0178 |
| MCS | $\mu$ | 0.994 | −0.354 | 0.9944 | −120.34 | 0.9945 | 119.64 |
| | $\sigma$ | 0.000 | 0.0177 | 0.0002 | 0.01782 | 0.0002 | 0.0179 |
| Newton-Raphson | | 0.988 | −1.102 | | | | |

UT method (which involved 571 computations) results are also compared with the Monte Carlo Simulation using 10000 samples to evaluate the accuracy of the former. Standard deviation for the voltage magnitude and the average percentage error in the average and angles presented in Tab. 3 confirms the accuracy of the UT method. To further reflect the certainty of the UT method, the percentage error in the voltage magnitude on all the buses is presented in Fig. 4. From the graph, it is seen that the highest error obtainable with using the UT method relative to the MCS method is less than a thousandth per cent (0.001%) which reveals a good fit of the method.

**Table 3** Average Percentage Error for the UT Method

| Error | $\varepsilon_V$ (%) | $\varepsilon_\delta$ (%) |
|---|---|---|
| $\varepsilon_\mu$ (%) | 0.000156 | 0.000793 |
| $\varepsilon_\sigma$ (%) | 0.577696 | 0.402426 |

Assuming the computation time for the MCS method is 1 pu, the computation time for the UT method is 0.0602 pu showing that significant time saving is achievable by using the UT method.

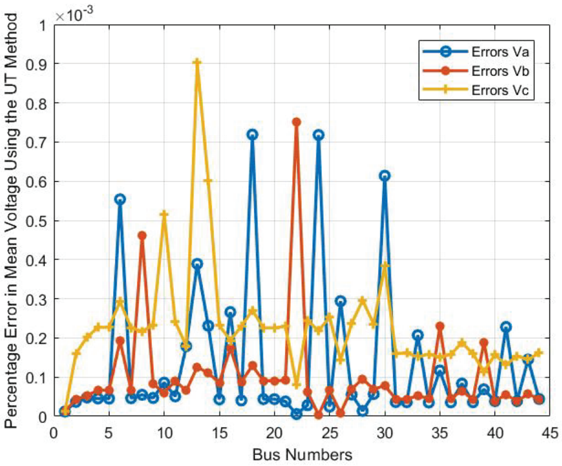

**Figure 4** Percentage Errors in Mean Voltage Magnitude on all Buses Using the UT Method

## 5.2 Case 2: Effect of Load and Wind Power Variation

In this section, the output of the 500 kW wind turbine is added to the system studied in Case 1, to fully understand its possible effects on the network. Although the effects of the wind farm are not fully noticed due to the connection of the system to the external grid, a slight improvement is achieved in the voltage values on all the buses as illustrated in Fig. 5. The average percentage error in the voltage magnitude and angle estimation using the UT method is presented in Tab. 4. This shows no wide variation compared with those in Tab. 3 (before the installation of the wind farm), thus confirming the adequacy of the UT method in treating networks with both symmetrical and asymmetrical distributions.

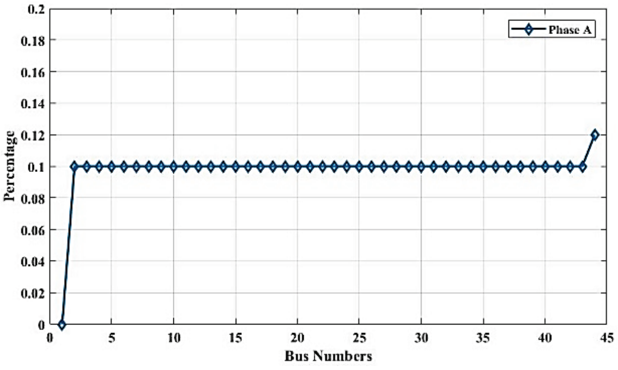

**Figure 5** Voltage Profile Improvement on Phase A with Wind Farm Added

**Table 4** Average Percentage Error for the UT Method with Wind Farm Added

| Error | $\varepsilon_V$ (%) | $\varepsilon_\delta$ (%) |
|---|---|---|
| $\varepsilon_\mu$ (%) | 0.000106 | 0.004694 |
| $\varepsilon_\sigma$ (%) | 0.731226 | 0.860531 |

The 95th percentile of the voltage magnitude is also estimated using both methods. The average error in the value using the UT method relative to the MCS method is presented in Tab. 5 for Cases 1 and 2.

**Table 5** Average Percentage Error in 95th Percentile

| Error | Case 1 (%) | Case 2 (%) |
|---|---|---|
| $\varepsilon_V^{pc}$ (%) | 0.00061 | 0.00097 |

Since voltage unbalance factor (VUF) is an important parameter for distribution system, the mean VUF using the UT method is presented in Fig. 6 while its percentage error plot (relative to the MCS) is shown in Fig. 7. The voltage unbalanced factors for both cases are presented in Tab. 5. In both cases, the unbalanced factor was less than the stipulated maximum (2%), while the error in the mean VUF for the UT relative to the MCS is less than 3% for all the buses.

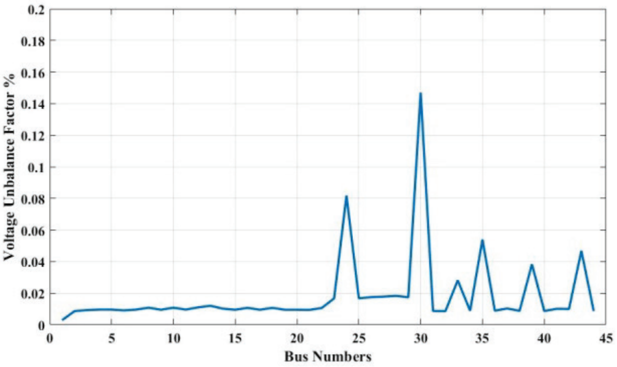

**Figure 6** Percentage Voltage Unbalance Factor for Case 2

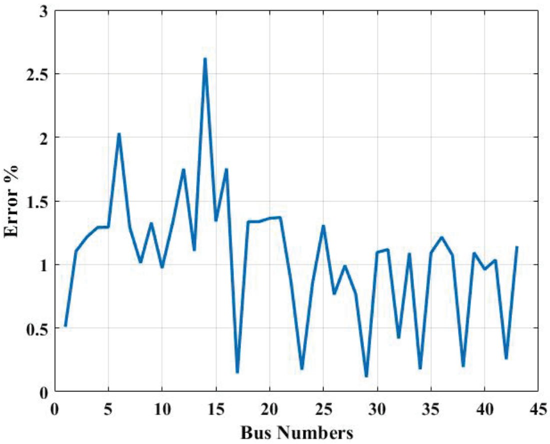

**Figure 7** Percentage Voltage Unbalance Factor Error in UT relative to MCS

**Table 6** Percentage Voltage Unbalanced Factors

| Method | | Case 1 (%) | Case 2 (%) |
|---|---|---|---|
| UT | Mean | 0.00038 | 0.00039 |
| | Max | 0.00154 | 0.00154 |
| MCS | Mean | 0.00033 | 0.00034 |
| | Max | 0.00154 | 0.00154 |

## 6 CONCLUSION

Renewable energy generators will become a major player in the energy sector as the world strives to meet up with global growing energy demands in a more sustainable way. This high level of renewable energy penetration within the power systems makes probabilistic load flow a crucial tool in system planning, operation and expansion. In this work, the applicability of the UT method was extended to solving 3 phase load flow in an unbalanced distribution system with an embedded wind farm and large number of random variables.

Results obtained show a good agreement between those from the UT method and the Monte Carlo Simulation method, however, with significant computation time reduction was achieved using the UT method. The effect of the wind farm on the existing system was studied and the results show a stable adjustment of the system (in the scenario considered).

It is worth mentioning that the variables considered were assumed to be uncorrelated in this work, however, in real life, spatial correlation exists between wind farms (and turbines) in close proximity and also among the loads. This is currently being studied and will be presented in future works on the UT method.

## Acknowledgements

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## Appendix: Transformer Parameters

The parameters for a grounded Wye to grounded Wye (Y-Y) 3 phase connected transformer as discussed in Section 4 below:

$$c_t = \begin{vmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{vmatrix}, d_t = \begin{vmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{vmatrix},$$

$$A = \frac{1}{n_t} \begin{vmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{vmatrix}, B = \begin{vmatrix} Z_a & 0 & 0 \\ 0 & Z_b & 0 \\ 0 & 0 & Z_c \end{vmatrix}.$$

The parameters for a Delta to grounded Wye (Δ-Y) 3 phase connected transformer are given below.

$$c_t = \begin{vmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{vmatrix}, d_t = \frac{1}{n_t} \begin{vmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{vmatrix},$$

$$A = \frac{1}{n_t} \begin{vmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{vmatrix}, B = \begin{vmatrix} Z_a & 0 & 0 \\ 0 & Z_b & 0 \\ 0 & 0 & Z_c \end{vmatrix}.$$

where $n_t$ is the transformer turns ratio and $Z_a$, $Z_b$ and $Z_c$ are the per-unit impedance of the transformer windings on the load side of the transformer.

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