J Electr Eng Technol.2018; 13(2): 669-676
http://doi.org/10.5370/JEET.2018.13.2.669

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

A Practical Voltage Error Correction Technique for Distribution System under Distribution Automation Environment

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Abstract – Transmission system has been well studied since long time and power system techniques of distribution system are more or less derived from transmission system. However, unlike transmission systems, many practical issues are encountered in the distribution system. Considerable amount of error is observed in voltage obtained from the Feeder Remote Terminal Units (FRTUs) measured by the pole mounted PTs along the distribution feeder. Load uncertainty is also an issue in distribution system. Further, penetration of Distributed Generators (DGs) creates voltage variations in the system. Hybrid radial/ loop distribution system also make it complicated to handle distribution system. How these constraints to be handled under Distribution Automation (DAS) environment in order to obtain error free voltage is described in this paper and therefore, a new approach of voltage error correction technique has been proposed. The proposed technique utilizes reliable data from substation and the FRTUs installed in DAS. The proposed technique adopts an iterative process for voltage error correction. It has been tested and proved accurate not only for conventional radial systems but also for loop distribution systems.

Keywords: Distribution system, Voltage measurement, Voltage error correction, Distribution automation system, Distributed generations

1. Introduction

Distribution Automation System (DAS) has brought great improvements in operation and control of distribution systems. Under DAS environment, Feeder Remote Terminal Units (FRTUs) collect current and voltage data from CTs and PTs and send these data to the control center via communication network. Based on measured data, the control center performs monitoring and control functions of outage management, loss reduction, contingency analysis, service restoration and etc. The accuracy of received data plays a critical role, however it is observed that due to size limitation, pole-mounted PT has considerable measurement errors. The integration of DGs into the network is also increasing as these types of generations offer environmental and economic benefits. However their integration causes technical problems like voltage variations. Therefore voltage error correction is strongly needed for monitoring and control functions.

State estimation techniques are efficiently used for estimating voltage in transmission systems. Measurement devices specifically PTs in transmission systems are comparatively reliable and provide accurate voltage measurements. A transmission system can be considered well balanced with lumped loads at the buses. So, estimation techniques based on error minimization like WLS method efficiently serve the purpose. But these estimation techniques used for transmission systems can hardly be applied to distribution systems due to practical issues of distribution system like high errors involved in voltage measurement [1] and unbalanced, distributed and uncertain nature of loads. Integration of DGs into the network causes another difficulty like voltage variations [2]. Regarding estimation techniques used in distribution systems, pseudo-measured loads are considered with weights by using WLS method, but in these methods, high measurement errors decrease confidence of the obtained results [3-8]. Also conventional methods based on least square technique may fail to give solution in many cases due to ill-conditioned gain matrix and Jacobian matrices. Loop formation also encountered in distribution system [9], increasing the complexity in distribution system voltage error correction.

In [1] by using an accuracy assessment test, presence of huge error has been identified using on field devices. However, it is not possible to always do field device assessment, therefore using more relatively reliable devices and data at the DAS control center, error in measurement has been removed in this paper. In this paper a new voltage error correction technique for distribution system is proposed overcoming all these practical issues. The proposed technique is based on iterative process. It uses current and voltage data obtained from FRTUs (Feeder Remote Terminal Units). The proposed technique covers a single feeder network with or without DGs and also a multiple feeder loop system with or without DGs. There is

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Received: June 26, 2017; Accepted: December 31, 2017

single reference bus in transmission systems and so is true for a radial distribution system where distribution substation becomes reference bus. However, after the formation of a loop in a distribution system, there exists no reference bus. In this paper reference bus refers to slack bus. For the loop case, first angle difference of substations is needed to be computed and then the proposed error correction technique can be applied. DGs are considered as constant PQ loads [10, 11]. The paper is divided into four sections. Section 2 explains the practical issues in detail and Section 3 describes the proposed voltage error correction technique. Test results of proposed method will follow in Section 4.

2. Practical Issues in Distribution System

A typical distribution system under DAS environment is shown in Fig. 1. Switches are installed along feeder on poles, which are equipped with CTs, and PTs. Measured data are collected by FRTUs and continuously sent to the DAS control center via a communication network. Current and voltage measured at the substation (S/S) are also sent to the control center. Current and voltage at the S/S are reliable. Current measurement at the FRTUs are also usually very accurate due to adoption of high precision CT, however, voltage measured by pole-mounted PT has a considerable error since the high precision PT can't be installed on the pole due to size limitation and economic reasons. In practice, errors up to 20% are frequently observed [1]. DGs increase voltage variations in the network. So there is a strong need of voltage error correction in order to get the accurate voltages which are

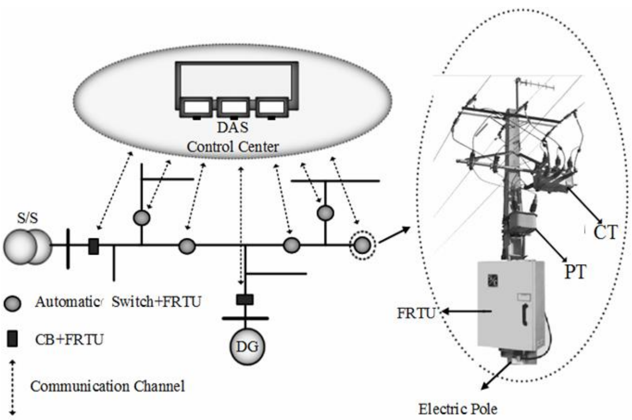

Fig. 1. DAS measurement system

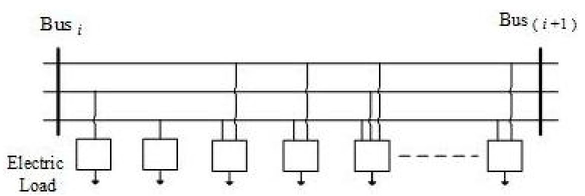

Fig. 2. Unbalanced, distributed and unknown feeder loads

important for a reliable operation and control of the system.

Distribution loads distributed along the feeder as shown in Fig. 2 creating an unbalanced characteristic. Loads keep varying so it is not possible to know exact loads. A measurement system that measures each and every distributed load may be very expensive. Loads are calculated using measurements at strategic points.

Another issue compared to transmission system is that transmission system is balanced system with lumped loads at each bus. Three types of buses exist in transmission system namely slack bus, PV bus and PQ or load bus as shown in Fig. 3(a). At the slack bus voltage magnitude V_1 and voltage angle θ_1 are known. At the PV bus real power P_{L2} and voltage magnitude V_2 are known while voltage angle θ_2 and reactive power Q_{L2} are unknown. And at the load bus real power P_{L3} and reactive power Q_{L3} are known, while voltage magnitude V_3 and angle θ_3 are unknown. At each bus, among variables V, θ, P and Q, at least two are known and remaining two can be calculated by power system equations.

On the other hand distribution systems are unbalanced with unknown loads operate either in radial or loop as shown in Fig. 3(b) and Fig. 3(c), respectively. In case of radial distribution system, considering substation bus as the slack bus, unknown voltages can be computed, by using

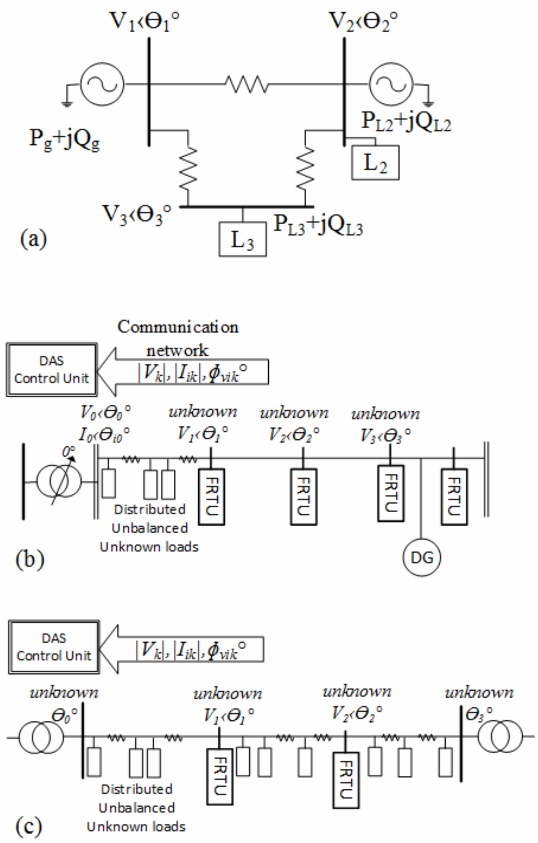

Fig. 3. Comparing characteristics of distribution and transmission system (a) transmission system (b) radial distribution system (c) loop distribution system

data from FRTUs and power system solution techniques. However in case of loop system there exists no slack bus. This makes difficult to compute voltages as shown in Fig. 3(c). Therefore, angle difference of substations is needed to be known first and then unknown voltages can be computed in the loop systems.

3. Proposed Voltage Error Correction Technique

In this paper, a voltage error correction technique is proposed for radial and loop distribution systems. DG integration is also considered for both cases. The proposed technique computes voltages utilizing reliable data available at DAS control center such as S/S voltage and current, current magnitude, and angle difference of voltage and current at each bus. Note that although measured voltage magnitude is not reliable, however, since waveforms are not distorted, phase difference of voltage and current at measuring points are known. Since, voltages are erroneous, therefore, initially voltage at each bus is assumed to be equal to that of S/S bus voltage. The proposed technique is based on an iterative process where DGs are treated as constant negative PQ loads [10, 11].

3.1 Voltage error correction in radial system with/without DGs

The iterative process has been adopted considering the characteristics of distribution system and the variable exists. Two interdependent variables, load and voltage, are iteratively computed. Fig. 4 shows a flow chart of the proposed technique in a radial distribution system with/without DGs. The two interdependent variables are iteratively computed and the two processes are shown in box (a) and box (b). The two processes are repeated until voltages converge. In this study, the point where FRTU is installed is treated as a bus and portion between two buses is called a section. Details of the proposed technique follow below as: Equations (1), (2), and (3) are applied in sequence for the load computation. Power in each phase at a bus can be computed by using voltage magnitude, current magnitude, and angle difference of voltage and current in the respective phase as given in Eq. (1):

$$S_i(k) = |V_i(k)||I_{mi}|\, e^{j\theta_i} \tag{1}$$

where, $S_i(k)$ is the power at i^{th} bus in k^{th} iteration. k represents iteration number and i is the bus number starting from S/S bus, i = 0, 1, 2, 3,… n, as shown in Fig. 5. $|V_i(k)|$ is the magnitude of voltage at i^{th} bus, $|I_{mi}|$ and θ_i are current magnitude and angle difference of voltage and current at i^{th} bus, respectively, measured at FRTUs.

Total power consumed in a line section is computed by the difference of power at the two buses as in Eq. (2):

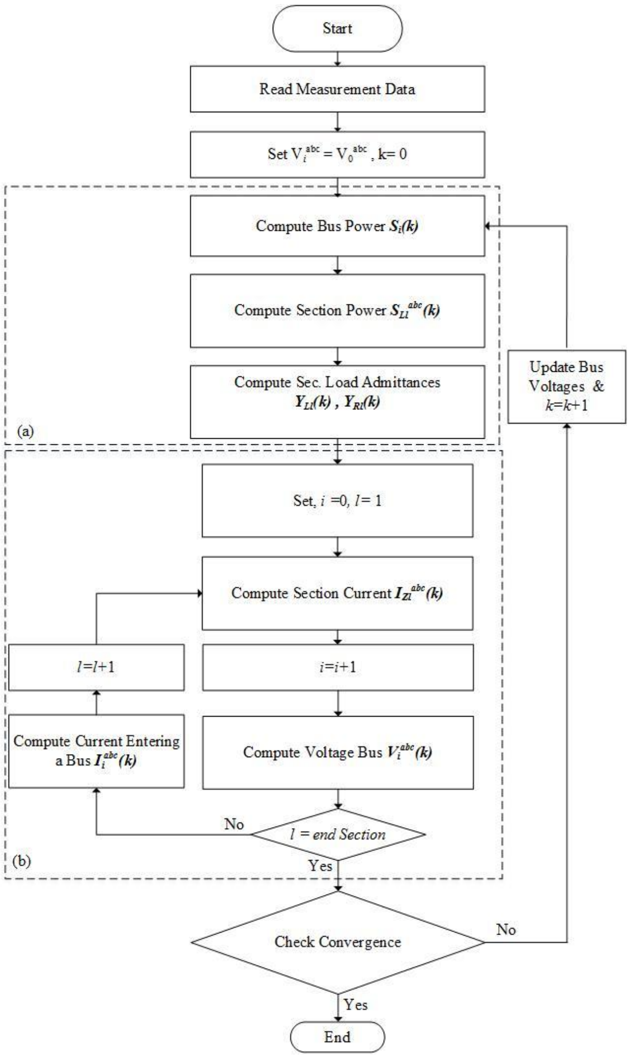

Fig. 4. Flowchart of voltage error correction in radial system

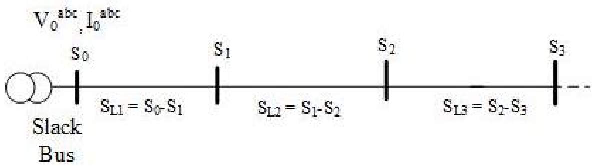

Fig. 5. Computation of line section power

$$S_{Ll}^{abc}(k) = S_i^{abc}(k) - S_{(i+1)}^{abc}(k) \tag{2}$$

where, $S_{Ll}^{abc}(k)$ is three phasor power consumed in line section l as shown in Fig. 5. $S_i^{abc}(k)$ and $S_{(i+1)}^{abc}(k)$ are power at bus i and i+1 respectively.

Load modeling is done by using the total power consumed in each section. The total power consumed in a section is divided by two in order to model the distributed load of Fig. 2 as pie model. The load modeling is shown in Fig. 6. The admittance of loads in each phase can be computed by Eq. (3):

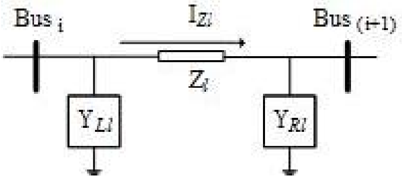

Fig. 6. Load modeling

$$Y_{Ll}(k) = \frac{\overset{*}{S}_{Ll}(k)}{2\,V_i(k)\,\overset{*}{V}_i(k)} \tag{3a}$$

$$Y_{Rl}(k) = \frac{\overset{*}{S}_{Ll}(k)}{2\,V_{(i+1)}(k)\,\overset{*}{V}_{(i+1)}(k)} \tag{3b}$$

where, $Y_{Ll}(k)$ and $Y_{Rl}(k)$ are the two load admittances of respective phase.

Voltage at each bus is computed by using S/S voltage and current and the computed admittances of loads. Voltage at each bus can be computed in forward sweep starting from the S/S by Eqs. (4), (5), and (6) in each section in sequence, which are used for the calculation of branch current, bus voltage and current entering into a bus.

$$I_{Zl}^{abc}(k) = I_i^{abc}(k) - Y_{Ll}^{abc}(k)\ V_i^{abc}(k) \tag{4}$$

where, $I_{Zl}^{abc}(k)$ is the current in l^{th} branch. $V_i^{abc}(k)$ is a $3x1$ matrix of voltage at bus i^{th} and $I_i^{abc}(k)$ is $3x1$ matrix of current entering i^{th} bus. $Y_{Ll}^{abc}(k)$ is $3x3$ matrix with diagonal elements $Y_{Ll}(k)$ of respective phase and off-diagonal elements are zero

$$V_{(i+1)}^{abc}(k) = V_i^{abc}(k) - Z_l^{abc}\ I_{Zl}^{abc}(k) \tag{5}$$

where, Z_l^{abc} is the impedance of line l. $V_{(i+1)}^{abc}(k)$ is voltage at $(i+1)^{th}$ bus

$$I_{(i+1)}^{abc}(k) = I_{Zl}^{abc}(k) - Y_{Rl}^{abc}(k)\ V_{(i+1)}^{abc}(k) \tag{6}$$

where, $I_{(i+1)}^{abc}(k)$ is current entering $(i+1)^{th}$ bus. $Y_{Rl}^{abc}(k)$ is $3x3$ matrices with diagonal elements $Y_{Rl}(k)$ of respective phase and off-diagonal elements are zero

3.2 Voltage error correction in loop system with/ without DGs

When two feeders form a loop, there exists angle difference between the S/Ss, which is unknown. For the voltage correction in a loop system, this angle difference is needed to be known first and then proposed voltage error correction technique can be applied using superposition theorem.

To calculate angle difference of substations, consider a two feeder systems in Fig. 7 where $\Delta\theta_m$ represents the measured angle difference of voltages across the tie open switch. In DAS, from the received voltage signals of FRTU at the tie switch, synchronized phase difference of voltages across tie open switch 3 can be obtained. This angle difference across tie open switch is used to compute the angle difference across the S/Ss. Note that the angle difference of the two S/Ss will remain same irrespective of whether tie switch is open or closed. Followings are the steps for angle difference calculation across S/Ss

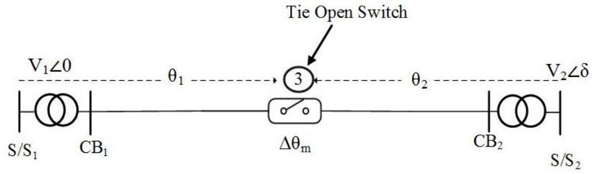

Fig. 7. Computing angle difference between two S/Ss

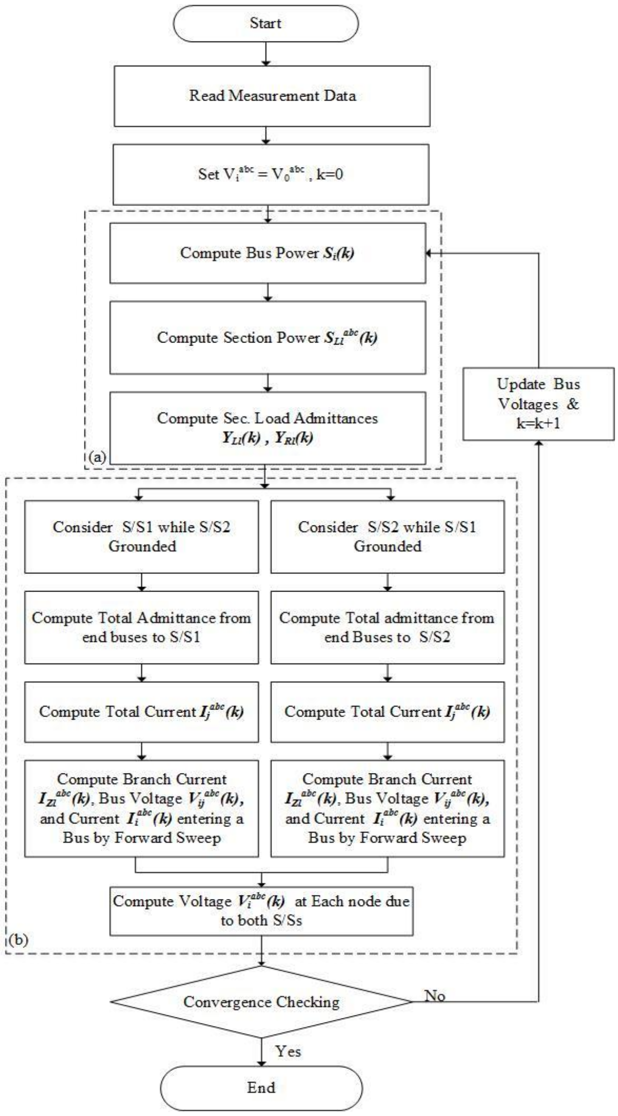

Fig. 8. Flow chart of voltage error correction in loop system

Sept 1: Initially assuming angle at both S/Ss equal to 0, perform load flow calculation for each radial feeder and identify angles θ_1 and θ_2 of the two open ends of switch 3.

Sept 2: Now, keeping S/S_1 as a reference angle as 0, calculate the angle at S/S_2 using Eq.(7):

$$\delta = \theta_1 - \theta_2 - \Delta\theta_m \tag{7}$$

Note that $\boldsymbol{\delta}$ represents angle at S/S_2 with respect to S/S_1 considered as reference i.e. 0. This angle difference will remain same irrespective of whether switch 3 is opened or closed.

Knowing the angle difference, proposed error correction technique can be applied using superposition theorem. For a loop system, the iterative technique similar to the radial system's, is adopted. Fig. 8 shows a flow chart of the proposed iterative technique for loop system with/ without DGs. Initially voltages at each bus are assumed equal to voltage of S/S. The two interdependent variables, load and voltage, are iteratively computed and the processes are described in box (a) and (b) respectively. Two processes are repeated until voltages converge. Details of the proposed technique follow below.

Applying Eqs. (1), (2) and (3) in sequence in each section, section load is computed as done in a radial system. Followings are the detailed procedure for voltage calculation in case of a loop system:

1. As superposition theorem is used to compute voltage at each bus. Therefore, one S/S is considered at a time while other is assumed to be grounded as shown in Fig. 9. Fig. 9(a) shows a loop system and Fig. 9(b) shows application of superposition theorem.

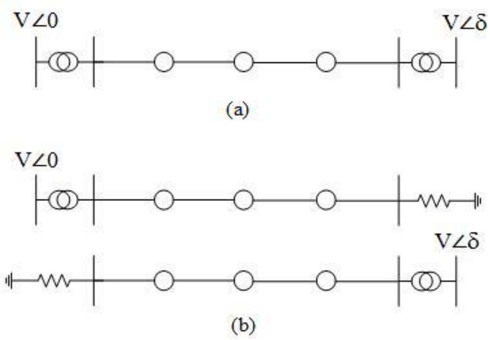

Fig. 9. Application of superposition in loop

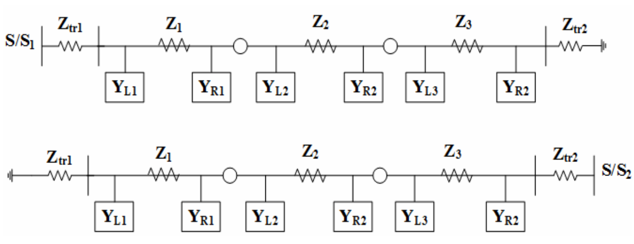

Fig. 10. Substation equivalent impedance calculation

2. Total admittance is computed, by starting from the end buses towards the S/S under consideration as shown in Fig. 10.
3. Total current due to the S/S under consideration can be computed by Eq. (8):

$$I_j^{abc}(k) = Y_j^{abc}(k) \ \ V_j^{abc}(k) \tag{8}$$

where, V_j^{abc} is the voltage at S/S_j. $I_j^{abc}(k)$ and $Y_j^{abc}(k)$ are the total current and total admittance respectively, j=1, 2 is the S/S.

4. Voltage at each bus due S/S_j can be computed using the voltage at S/S_j, total current and load admittances. Voltage at each bus can be computed in forward sweep starting from S/S_j by Eqs. (4), (5) and (6) in each section, which are used to calculate branch current, bus voltage and current entering into a bus, respectively.
5. Repeat the process of voltage computation due to the other S/S while the first is assumed to be grounded.
6. Voltage at each bus can be computed by adding voltage due to each S/S as given by Eq. (9):

$$V_i^{abc}(k) = \sum_{j=1}^{2} V_{ij}^{abc}(k) \tag{9}$$

where, $V_{ij}^{abc}(k)$ is the voltage at i^{th} bus due to each S/S.

4. Test Results

4.1 Voltage error correction in radial system

A 12 bus distribution system in Fig. 11 has been used as a test system which is unbalanced and has a S/S and a DG. All lines are assumed to carry distributed loads with unknown distributed patterns. It is assumed that each bus has FRTU installed. Section loads are given in Table 1. Line impedance of 0.471+j0.579[Ω/km] and length of

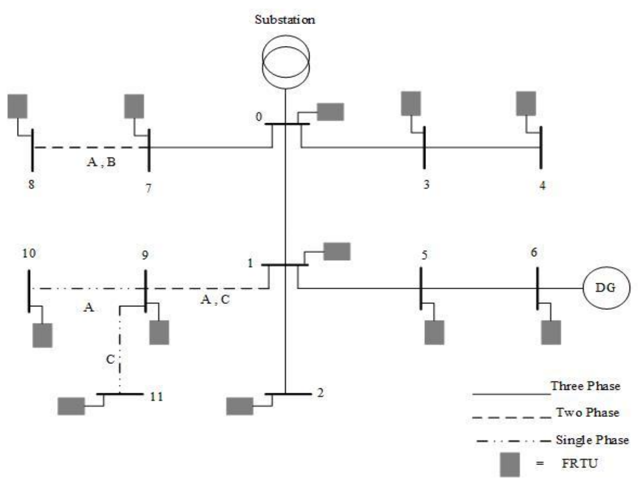

Fig. 11. A 12 bus unbalanced distribution system with DG

each line as 1 [km] is used in the simulation. 5% random error is added into actual voltage obtained from MATLAB simulation results to generate measurement voltage data. The computed results are compared to MATLAB simulation results. The MATLAB simulation results are the actual voltage.

Table 2 and Table 3 show comparison of computed and actual voltage magnitude and angle respectively, measured values of voltages are also shown in Table 2. The computed voltages are almost same as the actual values obtained from simulation, supporting the accuracy of the proposed technique. Comparison of A-phase voltage magnitude and angle of proposed method and conventional method are shown in Fig. 13 and Fig. 14 respectively, which also shows the accuracy of the proposed method.

Table 1. Section load data for radial test case

Line section	Active power (p.u.)	Reactive power (p.u.)
0-1	0.7700	0.0770
1-2	0.4400	0.0440
0-3	0.2400	0.0240
3-4	0.4000	0.0400
1-5	0.2400	0.0240
5-6	0.1200	0.0120
0-7	0.2560	0.0256
7-8	0.2000	0.0200
8-9	0.1500	0.0150
9-10	0.4000	0.0400

4.2 Voltage error correction in loop system

Fig. 12 shows the test system which consists of two S/Ss, a DG and one tie switch. Line length of each line section is taken as 1 km and line impedance of 0.273+j0.498[Ω/km] is used in the simulation. Transformers with resistance and inductance of 0.04 [Ω] and 0.0043[H] respectively, are used in the test case. Table 4 shows the section load data used in simulation.

First angle difference of two S/Ss is computed to be 5[degree]. With the tie switch closed, voltage error correction is performed and its results are compared with MATLAB results and are shown in Table 5. The high accuracy of the proposed error correction technique can be easily seen from negligible errors.

Table 4. Section load data for loop test case

Line Section	Active Power [p.u.]	Reactive Power [p.u.]
0-1	0.0166833	0.003333
1-2	0.0333333	0.006667
2-3	0.0266667	0.006667
3-4	0.0333333	0.010000
4-5	0.0400000	0.016667
2-6	0.0233333	0.006667
6-7	0.0333333	0.010000

Table 2. Comparison of actual and computed voltage magnitudes

	Magnitude											
BUS	Measured [p.u.]			Actual [p.u.]			Computed [p.u.]			Error (Actual-Computed) [%]		
	A	B	C	A	B	C	A	B	C	A	B	C
1	1.00888	1.00888	1.00669	0.98624	0.98900	0.98686	0.98622	0.98899	0.98684	2e-3	1e-3	2e-3
2	1.01568	1.01853	1.01632	0.98591	0.98867	0.98653	0.98589	0.98866	0.98651	2e-3	1e-3	2e-3
3	0.99556	0.99802	0.99656	0.98571	0.98814	0.98670	0.98570	0.98813	0.98669	1e-3	1e-3	1e-3
4	0.99029	0.99273	0.99128	0.98541	0.98784	0.98640	0.98540	0.98782	0.98641	1e-3	2e-3	1e-3
5	1.04786	1.04035	1.03853	0.98808	0.99043	0.98870	0.98804	0.99041	0.98867	4e-3	2e-3	3e-3
6	1.05009	1.05215	1.05076	0.99019	0.99213	0.99082	0.99015	0.99211	0.99078	4e-3	2e-3	4e-3
7	0.97585	0.97839	0.99724	0.98591	0.98848	0.98731	0.98592	0.98845	0.98731	1e-3	3e-3	1e-3
8	0.98562	0.98826	---	0.98572	0.98836	----	0.98571	0.98835	---	1e-3	1e-3	---
9	0.99553	---	0.99582	0.98567	---	0.98596	0.98565	---	0.98593	2e-3	---	3e-3
10	1.00517	---	---	0.98537	---	---	0.98535	---	---	2e-3	---	---
11	---	---	1.00547	---	--	0.98566	---	---	0.98564	---	---	2e-3

Table 3. Comparison of actual and computed voltage angles

	Angle								
BUS	Actual [Deg]			Computed [Deg]			Error [%]		
	A	B	C	A	B	C	A	B	C
1	- 3.19243	-122.62572	117.00580	-3.19246	-122.62570	117.00581	3e-3	2e-3	1e-3
2	- 3.21163	-122.64495	116.98665	-3.21167	-122.64494	116.98663	4e-3	1e-3	2e-3
3	- 3.21957	-122.68979	116.98577	- 3.21959	-122.68980	116.98576	2e-3	1e-3	1e-3
4	- 3.23702	-122.70727	116.96836	-3.23704	-122.70729	116.96834	2e-3	2e-3	2e-3
5	- 3.07061	-122.53725	117.11345	- 3.07066	-122.53720	117.11350	5e-3	5e-3	5e-3
6	- 2.93360	-122.43334	117.23631	- 2.93365	-122.43328	117.23638	5e-3	6e-3	7e-3
7	-3.20391	-122.67663	117.02456	- 3.20393	-122.67661	117.02455	2e-3	2e-3	1e-3
8	- 3.21318	-122.68718	---	- 3.21320	-122.68717	---	2e-3	1e-3	---
9	- 3.24233	---	116.96189	- 3.24237	---	116.96187	4e-3	---	2e-3
10	-3.25979	---	---	-3.25983	---	---	4e-3	---	---
11	---	---	116.94446	---	---	116.94443	---	---	3e-3

Table 5. Comparison of actual and computed voltage for loop system (A-phase)

BUS	Magnitude			Angle		
	Actual [p.u.]	Computed [p.u.]	Diff[%]	Actual [Deg]	Computed [Deg]	Diff [%]
0	0.9855	0.9852	3e-2	-0.3104	-0.3169	0.65
1	0.9847	0.9844	3e-2	-0.2997	-0.3063	0.66
2	0.9844	0.9841	3e-2	-0.2571	-0.2637	0.66
3	0.9848	0.9844	4e-2	-0.1088	-0.1153	0.65
4	0.9857	0.9854	3e-2	0.07584	0.06936	0.64
5	0.9874	0.9871	3e-2	0.30247	0.29608	0.64
6	0.9845	0.9841	4e-2	-0.3109	-0.3175	0.66
7	0.9851	0.9846	5e-2	-0.3305	-0.3179	1.2

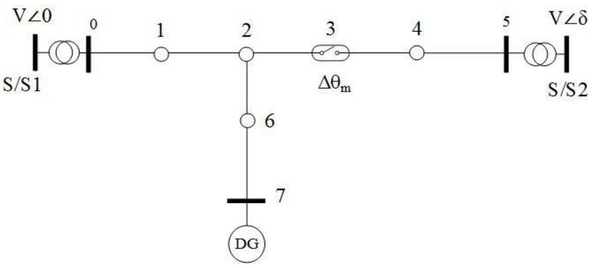

Fig. 12. A loop system with DG

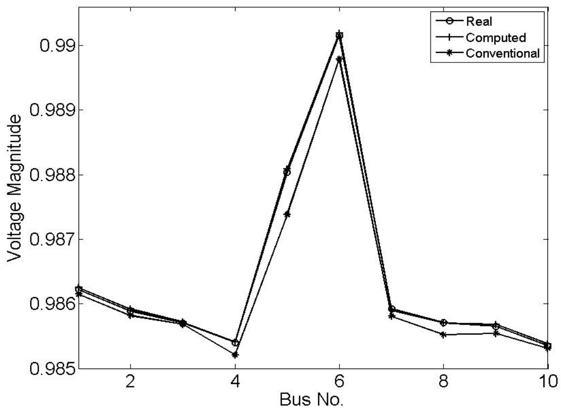

Fig. 13. Comparison of voltage magnitude of proposed and conventional method

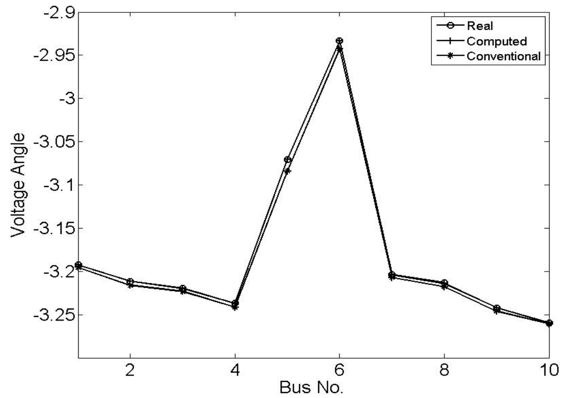

Fig. 14. Comparison of voltage angle of proposed and conventional method

5. Conclusion

In this paper, the voltage correction technique for the distribution system under DAS environment is proposed. It adopts an iterative process of load and voltage computation by overcoming practical issues i.e. considerable amount of voltage measurement errors, load uncertainty, penetration of Distributed Generators (DGs) and hybrid radial/loop systems. The proposed technique can be applied to the radial and loop system with/without DG. Comparison of computed and actual voltage has been done. The computed voltages are almost same as the actual values obtained from simulation, supporting the accuracy of the proposed technique. Comparison of voltage of proposed method and conventional methods are also perform, which also shows the accuracy of the proposed method. Higher accuracy is achieved in the proposed method due to the consideration of characteristics of distribution system.

With this voltage error correction technique applied to the real operation of distribution systems, that would provide very reliable data to many DAS functions, more efficient operation and control are expected enhancing service reliability.

Acknowledgements

This work was supported by "Human Resources Program in Energy Technology" of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea. (No. 20174030201790)

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