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A Three-Phase Line Flow Calculation Approach for Distribution Automation

Wei-Tzer Huang, Kai-Chao Yao, Chun-Ching Wu
Department of Industrial Education and Technology
National Changhua University of Education
Changhua 50007, Taiwan
{vichuang; kcyao}@cc.ncue.edu.tw

***Abstract* - A fast and high-efficient sensitivity-based approach for real-time three-phase line flow calculation is proposed in this paper, this approach combines the three-phase power-flow (TPPF) solution techniques with the new sensitivity factor, named three-phase Z_{BUS} distribution factor (TPZBD). The TPZBD is associated with both the changes of real and reactive power injections of individual phase at each bus into the three-phase line flow. Hence, the proposed TPZBD directly reflects load demand changes to the line flow. Accordingly, any feasible TPPF solution technique must be used to solve for the base case line flow solution at first time, based on the solution and TPZBD formulas, the real-time three-phase line flow is determined rapidly by the presented approach without any iteration after load demand changes. Finally, a 7-node sample system that is modified from Taipower distribution feeders is used to test the proposed approach. The results of this paper demonstrate that the proposed approach is capable of calculating real-time three-phase line flow for distribution automation.**

***Index Terms* -*Distribution Systems, Line Flow Calculation, Sensitivity Factors, Three-phase Power-Flow, TPZBD, Z_{BUS} Impedance Matrix*.**

I. Introduction

Generally, electrical power distribution systems are inherently three-phase unbalanced. This phenomenon is caused by non-transposition and uncompleted three-phase feeder arrangements, such as the two-phase or single-phase lines in laterals or sub-laterals, the unbalanced structure of three-phase transformer connections, and the load characteristics. Therefore, executing a TPPF program is essential in electric power distribution system planning, operation, and control. Up to date, two conventional techniques used in power flow solutions are Gauss-Seidel and Newton-Raphson based algorithms [1], [2]. These algorithms have their advantages and disadvantages in terms of accuracy, iteration number, execution time, memory storage, and so forth. Nevertheless, the convergence problem may exist in the solution algorithms of unbalanced three-phase power flows. To ameliorate the convergence problem, specialized algorithms have been proposed to enhance robustness and efficiency [3],[4]; however, these algorithms still have to perform the iteration process during the solution procedure; thus, if the iteration numbers can be reduced or eliminated, the real-time applications of these algorithms will be more reliable and feasible. Consequently, a new sensitivity factor, TPZBD, is proposed to deal with real-time three-phase line flow calculation. Fig. 1 shows the schematic diagram of the proposed approach and its applications, such as distribution automation, optimization, on-line dispatch, and security control for modern power distribution systems. This approach does not need any iteration after the first time TPPF solution that can be solved by any TPPF methods and is based on the concept of sensitivity factors proposed in [5]-[9]. These sensitivity factors are Generation Shift Distribution Factor (GSDF) [5], Z-Bus Distribution Factor (ZBD) [6], Generalized Generation Shift Distribution Factor (GGDF) [8], and Power Transfer Distribution Factor (PTDF) [7]. As demonstrated in [6], the accuracy of ZBD in calculating single-phase transmission line flow is much better than that of the other sensitivity factor algorithms. Accordingly, the author *et al.* [10] proposed Z_{BUS} distribution factor (ZBDF) for the distribution line flow calculation, and the formulas are derived on the assumption of constant voltage magnitudes; therefore, the accuracy of the algorithm is affected by the assumption. Consequently, to improve this weakness, a new TPZBD, which modified from the ZBDF is proposed in this paper. The theory, formula derivation, and numerical results of the TPZBD approach will be illustrated and discussed in detail in the following sections.

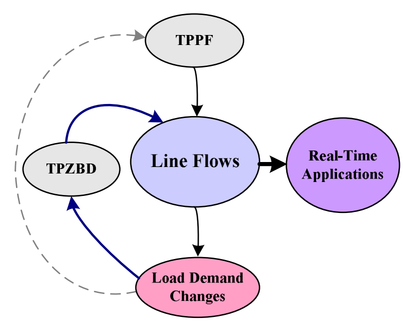

Fig. 1 Schematic diagram of real-time line flow calculation

II. Derivation of the Proposed Approach

The concept of the proposed approach is based on the base case TPPF solutions and the changes of complex power injections of individual phase at each bus into the three-phase line flow. Therefore, to set up the base case TPPF solutions is essential. Any feasible TPPF solution method can be used as the base case line flow solution. In this paper, the Gauss implicit Z_{BUS} method is selected as the base case solution method. A new approach for real-time three-phase line flow calculation can be derived by integrating the base case line flow solution and the corresponding data that include Z-impedance matrix, primitive impedance, and load demand changes of individual phase into TPZBD formula.

A. Three-Phase Power-Flow (TPPF) Solution Method

The Gauss implicit Z_{BUS} method is applied in calculating three-phase line flow under the base loading condition. Besides, this method can be used to check the mismatches of line flow solutions between the conventional TPPF method and the proposed TPZBD approach. The Gauss implicit Z_{BUS} method is based on the principle of superposition applied to bus voltages along the feeders. The voltage on each bus can be considered to be brought about by two different types of sources: the specified incoming bus voltage of distribution substation and the current injections, which are generated by loads, distributed generators, capacitors, and reactors. The solution steps of this power flow algorithm are described as follows.

Step 1: Initialize bus voltage estimates and form the Z_{BUS} impedance matrix.

Step 2: Compute the bus current injections by (1) for loads, distributed generators, shunt elements, etc.

$$\overline{\mathbf{I}}_i^{abc(k)} = \left(\frac{\overline{\mathbf{S}}_i^{abc}}{\overline{\mathbf{V}}_i^{abc(k)}} \right)^* = \left(\frac{\overline{\mathbf{P}}_i^{abc} + \mathbf{j}\overline{\mathbf{Q}}_i^{abc}}{\overline{\mathbf{V}}_i^{abc(k)}} \right)^* \tag{1}$$

Where $\overline{\mathbf{V}}_i^{abc(k)}$ denotes the voltage of bus i and $\overline{\mathbf{S}}_i^{abc}$ denotes the specified complex power of bus i at the kth iteration.

Step 3: Calculate the voltage deviations due to the current injections by (2).

$$\Delta\overline{\mathbf{V}}_{Bus}^{abc(k)} = \mathbf{Z}_{Bus}^{abc} \cdot \overline{\mathbf{I}}_{Bus}^{abc(k)} \tag{2}$$

Where $\Delta\overline{\mathbf{V}}_{Bus}^{abc(k)}$ denotes the vector of voltage derivations of the kth iteration. In addition, $\overline{\mathbf{I}}_{Bus}^{abc(k)}$ denotes the vector of current injection derivations of the kth iteration.

Step 4: Apply voltage superposition principle by (3) and update each bus voltage.

$$\overline{\mathbf{V}}_{Bus}^{abc(k+1)} = \overline{\mathbf{V}}_{NL}^{abc} + \Delta\overline{\mathbf{V}}_{Bus}^{abc(k)} \tag{3}$$

Where $\overline{\mathbf{V}}_{NL}^{abc}$ denotes the vector of no load swing bus voltages.

Step 5: Check for convergence. If there is no convergence, go to step 3.

Step 6: Compute the three-phase line flow.

B. Three-Phase Power-Flow (TPPF) Solution Method

Based on the bus frame reference, the performance equation for an n-bus distribution system can be expressed as:

$$\overline{\mathbf{V}}_{n\times 1}^{abc} = \mathbf{Z}_{n\times n}^{abc} \cdot \overline{\mathbf{I}}_{n\times 1}^{abc} \tag{4}$$

This equation shows the relations among the bus injected current, impedance, and voltage.

The complex form of TPZBD can be defined as:

$$\mathbf{H}(m_{abc}, i_{abc}) = \frac{\partial \overline{\mathbf{S}}_m^{abc}}{\partial \overline{\mathbf{S}}_i^{abc}} = \begin{bmatrix} \frac{\partial S_m^a}{\partial S_i^a} & \frac{\partial S_m^a}{\partial S_i^b} & \frac{\partial S_m^a}{\partial S_i^c} \\ \frac{\partial S_m^b}{\partial S_i^a} & \frac{\partial S_m^b}{\partial S_i^b} & \frac{\partial S_m^b}{\partial S_i^c} \\ \frac{\partial S_m^c}{\partial S_i^a} & \frac{\partial S_m^c}{\partial S_i^b} & \frac{\partial S_m^c}{\partial S_i^c} \end{bmatrix} \tag{5}$$

The physical meaning of (5) is that all changes of bus injected complex power will reflect in the line flow. As shown in Fig. 2, $\overline{\mathbf{S}}_i^{abc}$ is the complex power injection of the individual phase of the ith bus, and $\overline{\mathbf{S}}_m^{abc}$ is the three-phase complex line flow in the mth feeder segment. Supposing that feeder segment m is from bus p to bus q, then (5) can be further rewritten as

$$\mathbf{H}\left(m_{abc}, i_{abc}\right) = \frac{\partial\left(\overline{\mathbf{V}}_p^{abc} \cdot \overline{\mathbf{I}}_{pq}^{abc*}\right)}{\partial\left(\overline{\mathbf{V}}_i^{abc} \cdot \overline{\mathbf{I}}_i^{abc*}\right)} \tag{6}$$

In (6), the $\overline{\mathbf{V}}_p^{abc}$ and $\overline{\mathbf{V}}_i^{abc}$ represent the bus voltages on bus p and i respectively, and can be obtained from the base case power flow solution. Thus, equation (6) can be expressed as

$$\mathbf{H}\left(m_{abc}, i_{abc}\right) = \frac{\overline{\mathbf{V}}_p^{abc0}}{\overline{\mathbf{V}}_i^{abc0}} \cdot \frac{\partial\left(\frac{\overline{\mathbf{V}}_p^{abc} - \overline{\mathbf{V}}_q^{abc}}{\mathbf{z}_m^{abc}}\right)^*}{\partial\left(\overline{\mathbf{I}}_i^{abc*}\right)} \tag{7}$$

Where $\overline{\mathbf{V}}_p^{abc0}$ and $\overline{\mathbf{V}}_i^{abc0}$ represent the base case bus voltages, and $\mathbf{z}_m^{abc}$ is the vector of primitive impedance of the mth feeder segment. Rewritten (7) as

$$\mathbf{H}\left(m_{abc}, i_{abc}\right) = \frac{\overline{\mathbf{V}}_p^{abc0}}{\overline{\mathbf{V}}_i^{abc0}} \cdot \frac{1}{\mathbf{z}_m^{abc*}} \cdot \left(\frac{\partial \overline{\mathbf{V}}_p^{abc*}}{\partial\, \overline{\mathbf{I}}_i^{abc*}} - \frac{\partial \overline{\mathbf{V}}_q^{abc*}}{\partial\, \overline{\mathbf{I}}_i^{abc*}} \right) \tag{8}$$

In (8), the terms $\partial \mathbf{V}_p^{abc*} / \partial \mathbf{I}_i^{abc*}$ and $\partial \mathbf{V}_q^{abc*} / \partial \mathbf{I}_i^{abc*}$ mean that the changes of bus injected current will reflect in the bus voltage. In other words, the ratio of bus p (q) voltage to the bus i current injection is the transfer impedance when other buses are open-circuited. It can be obtained from the bus impedance matrix. Consequently, the TPZBD can be formulated as:

$$\mathbf{H}\left(m_{abc}, i_{abc}\right) = \frac{\overline{\mathbf{V}}_p^{abc0}}{\overline{\mathbf{V}}_i^{abc0}} \cdot \frac{\left(\mathbf{Z}_{i_{abc}}^{p_{abc}*} - \mathbf{Z}_{i_{abc}}^{q_{abc}*}\right)}{\mathbf{z}_m^{abc*}} \tag{9}$$

Where $\mathbf{Z}_{i_{abc}}^{p_{abc}*}$ and $\mathbf{Z}_{i_{abc}}^{q_{abc}*}$ are the sub- matrices in $\mathbf{Z_{Bus}}$. In addition, the $\mathbf{E}\left(m_{abc}, i_{abc}\right)$ and $\mathbf{G}\left(m_{abc}, i_{abc}\right)$ are defined as the real and imaginary parts of $\mathbf{H}\left(m_{abc}, i_{abc}\right)$, and they can also be expanded as (10)~(12).

$$\mathbf{H}\left(m_{abc}, i_{abc}\right) = \begin{bmatrix} H(m_a, i_a) & H(m_a, i_b) & H(m_a, i_c) \\ H(m_b, i_a) & H(m_b, i_b) & H(m_b, i_c) \\ H(m_c, i_a) & H(m_c, i_b) & H(m_c, i_c) \end{bmatrix} \tag{10}$$

$$\mathbf{E}\left(m_{abc}, i_{abc}\right) = \begin{bmatrix} E(m_a, i_a) & E(m_a, i_b) & E(m_a, i_c) \\ E(m_b, i_a) & E(m_b, i_b) & E(m_b, i_c) \\ E(m_c, i_a) & E(m_c, i_b) & E(m_c, i_c) \end{bmatrix} \tag{11}$$

$$\mathbf{G}\left(m_{abc}, i_{abc}\right) = \begin{bmatrix} G(m_a, i_a) & G(m_a, i_b) & G(m_a, i_c) \\ G(m_b, i_a) & G(m_b, i_b) & G(m_b, i_c) \\ G(m_c, i_a) & G(m_c, i_b) & G(m_c, i_c) \end{bmatrix} \tag{12}$$

Referring to [3]-[5], the developed equivalent decoupled three-phase feeder models and power transformer models are considered to build the system Z-impedance matrix. According to the constructed Z_{BUS} and the primitive impedance, (9) can be formulated as the sensitivity factors of correlative parameters.

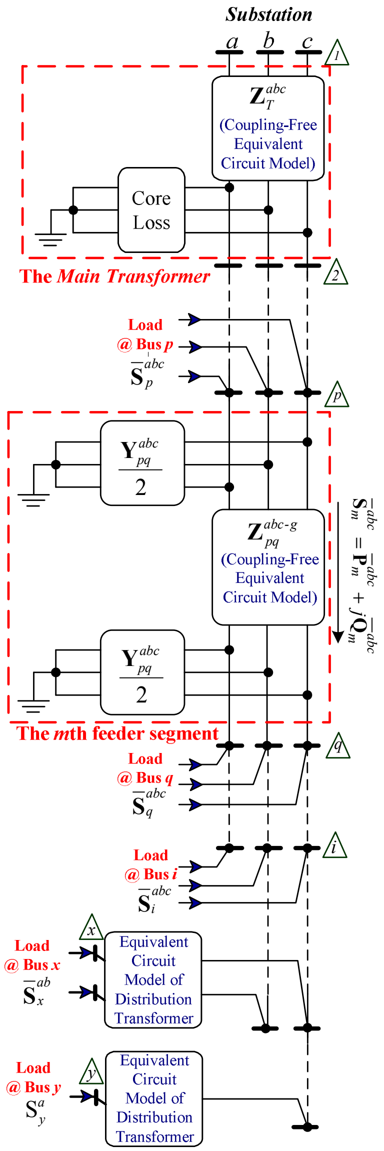

Fig. 2 Equivalent model of the distribution systems

Furthermore, according to the definition of complex power, sensitivity factors mentioned above, as well as the base case TPPF solutions, the formulation for real and reactive line flow calculations that can be used in real-time applications are derived. Equation (13) shows the complex power line flow calculation formula of individual phase after the load demand changes, and the three-phase real power line flow can be expressed as (14). Likewise, the reactive power line flow calculation formula for each phase are expressed in (15).

$$\overline{\mathbf{S}}_m^{abc} = \overline{\mathbf{S}}_m^{abc0} + \mathbf{H}\left(m_{abc}, i_{abc}\right)\cdot \Delta\overline{\mathbf{S}}_i^{abc} \tag{13}$$

$$\overline{\mathbf{P}}_m^{abc} = \overline{\mathbf{P}}_m^{abc0} + \mathbf{E}\left(m_{abc}, i_{abc}\right)\cdot \Delta\overline{\mathbf{P}}_i^{abc} - \mathbf{G}\left(m_{abc}, i_{abc}\right)\cdot \Delta\overline{\mathbf{Q}}_i^{abc} \tag{14}$$

$$\overline{\mathbf{Q}}_m^{abc} = \overline{\mathbf{Q}}_m^{abc0} + \mathbf{G}\left(m_{abc}, i_{abc}\right)\cdot \Delta\overline{\mathbf{P}}_i^{abc} + \mathbf{E}\left(m_{abc}, i_{abc}\right)\cdot \Delta\overline{\mathbf{Q}}_i^{abc} \tag{15}$$

In the above equations, $\Delta\overline{\mathbf{P}}_i^{abc}$ and $\Delta\overline{\mathbf{Q}}_i^{abc}$ represent the changes of real and reactive power demands in bus i. In addition, $\overline{\mathbf{P}}_m^{abc0}$ and $\overline{\mathbf{Q}}_m^{abc0}$ represent the base case real and reactive line flows of the mth feeder segment.

III. Solution Procedure of the Proposed Approach

In this paper, the proposed approach can handle the random system load demand changes and reflect the complex power injections into line flow precisely. As shown in Fig. 3, the line flow base must be renewed again when system load demand changes from base case to a new point P. In this new loading point P, the amounts of change of bus complex power demands can be expressed as changes from the base loads. These variation terms must be balanced by the total complex power generation. Assume that the load demand changes must be absorbed by the swing bus at the distribution substation from subtransmission systems. Therefore, the overall change complex power balance equations can be expressed as:

$$\Delta\overline{\mathbf{P}}_S^{abc} = \sum_{\mathbf{i=1}}^{\mathbf{n}} \Delta\overline{\mathbf{P}}_i^{abc} + \Delta\overline{\mathbf{P}}_L^{abc} \tag{16}$$

And

$$\Delta\overline{\mathbf{Q}}_S^{abc} = \sum_{\mathbf{i=1}}^{\mathbf{n}} \Delta\overline{\mathbf{Q}}_i^{abc} + \Delta\overline{\mathbf{Q}}_L^{abc} \tag{17}$$

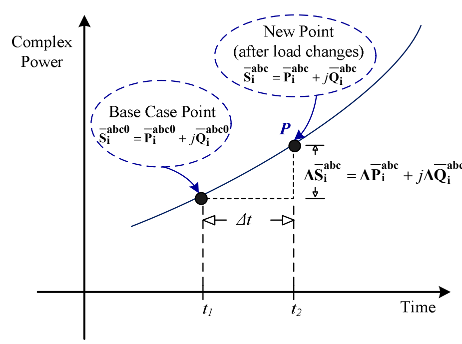

Fig. 3 System load demand changes curve

Where $\Delta\overline{\mathbf{P}}_S^{abc}$ and $\Delta\overline{\mathbf{Q}}_S^{abc}$ denote the individual phase real and reactive power changes in the swing bus, respectively; and $\Delta\overline{\mathbf{P}}_i^{abc}$ and $\Delta\overline{\mathbf{Q}}_i^{abc}$ represent the changes of individual phase real and reactive power demands in bus i, respectively. Meanwhile, $\Delta\overline{\mathbf{P}}_L^{abc}$ and $\Delta\overline{\mathbf{Q}}_L^{abc}$ are the total individual phase real and reactive power loss changes, respectively, and can be neglected. The solution procedure of the proposed approach can be expressed by the flow chart, as shown in Fig. 4.

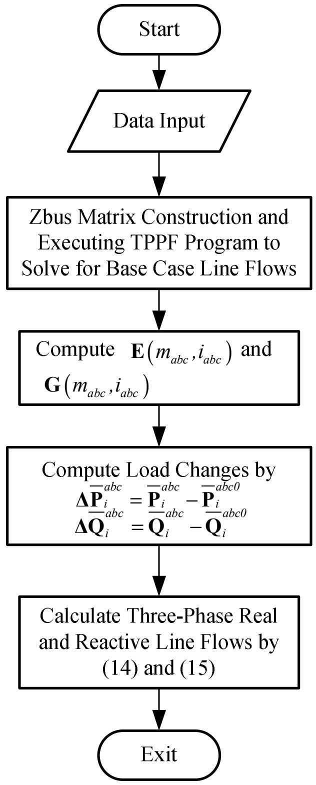

Fig. 4 Flow chart of the proposed approach

IV. Simulation Results

A. Descriptions of the sample system

To verify the performance of the proposed approach, the algorithms of TPZBD and TPPF are implemented by a MATLAB R2008a software package and tested on a Windows XP-based Intel® Core™2 Quad CPU Q6600 @2.4 GHz PC. Fig. 5 shows a one-line diagram of the sample system with two feeders, which are fed by a main transformer in a distribution substation. Actually, this system is modified from the Taipower distribution systems serving rural areas, wherein a main transformer usually services five radial overhead feeders. In this paper, only two radial feeders, F#1 and F#2, with two types of feeder arrangement and their loads are used to test the proposed approach, described as follows:

Radial: Two feeders, F#1 and F#2, are not tied together at their ends; they radiate from the distribution substation and normally open at their ends.

Normally closed-loop: Two feeders, F#1 and F#2, are tied together by a tied line at their ends to form a normally closed-loop circuit.

Furthermore, the main transformer has the following operation parameters: 25 MVA, 69 kV/11.4 kV, and a leakage impedance of 0.0049+j0.08 *pu*. The feeder mains are 3A477XPW conductors with impedance matrix as shown below:

$$z_s^{abc} = \begin{bmatrix} 0.1310+j0.3710 & 0.0337+j0.0978 & 0.0337+j0.0981 \\ 0.0337+j0.0978 & 0.1310+j0.3710 & 0.0337+j0.0978 \\ 0.0337+j0.0981 & 0.0337+j0.0978 & 0.1310+j0.3710 \end{bmatrix}$$

The equivalent loads are listed in Table I and are assumed as load demand under base case, which used for computing the TPPF solution. After the load demand changes as shown in Table II, the TPZBD algorithm was adopted to calculate the line flow instead of conventional iteration method.

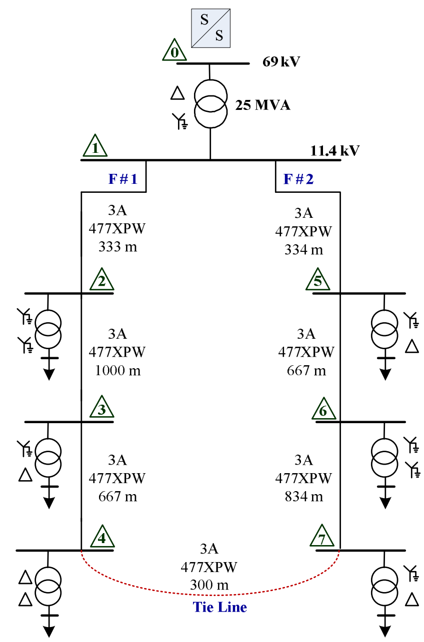

Fig. 5 Sample system

TABLE I
INDIVIDUAL PHASE LOADS FOR THE SAMPLE SYSTEM

Bus No	Phase A (kW)	Phase A (kvar)	Phase B (kW)	Phase B (kvar)	Phase C (kW)	Phase C (kvar)
2	364.80	119.90	356.40	123.65	386.40	131.14
3	729.60	239.81	712.80	247.30	772.80	262.29
4	1021.44	335.73	997.92	346.22	1081.92	367.21
5	167.58	55.08	145.15	50.36	153.01	51.93
6	319.20	104.92	276.48	95.92	291.46	98.92
7	438.90	144.26	380.16	131.89	400.75	136.02

TABLE II
INDIVIDUAL PHASE LOADS FOR THE SAMPLE SYSTEM AFTER LOAD DEMAND CHANGES

Bus No	Phase A (kW)	Phase A (kvar)	Phase B (kW)	Phase B (kvar)	Phase C (kW)	Phase C (kvar)
2	357.50	117.50	342.14	118.70	363.22	123.27
3	758.78	249.40	755.57	262.14	834.62	283.27
4	990.80	325.66	938.04	325.45	984.55	334.16
5	177.63	58.38	150.96	52.37	156.07	52.97
6	287.28	94.43	259.89	90.16	279.80	94.96
7	460.85	151.47	391.56	135.85	408.77	138.74

B. Analysis and Discussion of the Numerical Results

First, the base case three-phase line flow solution is executed under the load condition as shown in Table I. The simulation results listed in Table III and Table IV are compared with those of the commercial package CYME. The outcomes show that the TPPF program implemented in this paper is accurate. Supposing that the system load demand changes from the base load are random listed in Table II, and then the TPZBD algorithm is thereby adopted to compute the three-phase complex line flow instead of running the conventional TPPF. Two types of feeder arrangements are tested using the proposed approach. The numerical results are shown in the following subsections.

1) Radial Feeders: The numerical results for radial feeders under unbalanced three-phase load condition are shown in Tables V and VI. As shown by the results, all the corresponding values of these two tables are very close. The maximum real power flow mismatch is only 0.1 kW compared with the solution of the Gauss implicit Z_{BUS} method, and the maximum error percentage is merely 0.0217 %. Moreover, the maximum reactive power flow mismatch and error percentage are just 2.2 kvar and 0.1741 %, respectively. From the numerical results shown above, it appears that the proposed approach for the solutions of real power flow is much more accurate than the solutions of the reactive power flow. The major reason is that the reactive power is more sensitive to the bus voltage magnitude. Therefore, the more the voltage drops along the feeders, the more mismatched the reactive power flow becomes. However, no matter what the feeders are thermally limited or voltage-drop-limited, they usually serve the nominal voltage to their customers in urban or rural areas. Therefore, the errors in reactive power flow will be lessened, making the proposed approach more suitable for application in practical systems.

2) Normally Closed-Loop Feeders: The numerical results for a normally closed-loop feeder are shown in Tables VII and VIII. Table VII illustrates the real power flow errors compared with the solution of the Gauss implicit Z_{BUS} method. As can be seen, the maximum mismatch and error percentage are 1 kW and 0.1873 %, respectively. The reactive power flow errors are listed in Table VII, and as can be seen, the maximum mismatch and error percentage are 0.8 kvar and 0.4098 %, respectively. The numerical results show that the solutions are similar to those of the radial feeders; in other words, the proposed approach can also apply to normally-closed loop feeder arrangements. Furthermore, the accuracy of the reactive power flow of normally closed-loop feeders is much better than that of radial feeders. This is because the voltage drops of the normally closed-loop feeders are generally smaller than those of the radial feeders.

3) Discussions: Based on the numerical results mentioned above, the proposed approach is fast and reliable in unbalanced distribution line flow calculation without any iteration after load demand changes. Additionally, the proposed approach can be used in radial and normally closed-loop distribution feeders, in that there is no convergence problem regardless of whether the system type is radial or normally closed-loop. In summary, this approach emphasizes high reliability and fast computing characteristics in real-time line flow calculation without any iteration after load demand changes, especially for unbalanced distribution line flow calculation and its applications.

TABLE III
SIMULATION RESULTS OF BASE CASE POWER FLOW FOR RADIAL FEEDERS (BASE MVA: 10)

Line Flow / Bus No.		Phase A		Phase B		Phase C	
From	To	Real Power	Reactive Power	Real Power	Reactive Power	Real Power	Reactive Power
0	1	0.30781	0.12327	0.29045	0.12103	0.31236	0.12947
1	2	0.21205	0.07909	0.20716	0.08093	0.22464	0.08689
1	5	0.09263	0.03218	0.08022	0.02914	0.08457	0.03015
2	3	0.17528	0.06207	0.17124	0.06371	0.18567	0.06807
3	4	0.10215	0.03467	0.09980	0.03569	0.10820	0.03797
5	6	0.07582	0.02573	0.06567	0.02339	0.06923	0.02417
6	7	0.04388	0.01462	0.03801	0.01333	0.04007	0.01376
Voltage / Bus No.		Phase A		Phase B		Phase C	
		Mag.	Ang.	Mag.	Ang.	Mag.	Ang.
0		1.000	0.00	1.000	-120.00	1.000	120.00
1		0.987	-1.67	0.987	-121.58	0.986	118.30
2		0.978	-2.86	0.978	-122.73	0.977	117.05
3		0.971	-3.85	0.971	-123.70	0.969	115.99
4		0.967	-4.43	0.967	-124.27	0.965	115.37
5		0.983	-2.19	0.984	-122.02	0.983	117.83
6		0.980	-2.61	0.981	-122.39	0.980	117.45
7		0.979	-2.86	0.980	-122.60	0.978	117.22

TABLE IV
SIMULATION RESULTS OF BASE CASE POWER FLOW FOR A NORMALLY CLOSED-LOOP FEEDERS (BASE MVA: 10)

Line Flow / Bus No.		Phase A		Phase B		Phase C	
From	To	Real Power	Reactive Power	Real Power	Reactive Power	Real Power	Reactive Power
0	1	0.30781	0.12327	0.29045	0.12103	0.31236	0.12947
1	2	0.21205	0.07909	0.20716	0.08093	0.22464	0.08689
1	5	0.09263	0.03218	0.08022	0.02914	0.08457	0.03015
2	3	0.17528	0.06207	0.17124	0.06371	0.18567	0.06807
3	4	0.10215	0.03467	0.09980	0.03569	0.10820	0.03797
5	6	0.07582	0.02573	0.06567	0.02339	0.06923	0.02417
6	7	0.04388	0.01462	0.03801	0.01333	0.04007	0.01376
Voltage / Bus No.		Phase A		Phase B		Phase C	
		Mag.	Ang.	Mag.	Ang.	Mag.	Ang.
0		1.000	0.00	1.000	-120.00	1.000	120.00
1		0.987	-1.67	0.987	-121.58	0.986	118.30
2		0.978	-2.86	0.978	-122.73	0.977	117.05
3		0.971	-3.85	0.971	-123.70	0.969	115.99
4		0.967	-4.43	0.967	-124.27	0.965	115.37
5		0.983	-2.19	0.984	-122.02	0.983	117.83
6		0.980	-2.61	0.981	-122.39	0.980	117.45
7		0.979	-2.86	0.980	-122.60	0.978	117.22

TABLE V
SIMULATION RESULTS OF THREE-PHASE REAL POWER FLOW FOR RADIAL FEEDERS (BASE MVA: 10)

Methods / Bus No.		TPPF			TPZBD		
From	To	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
0	1	0.30693	0.28735	0.30637	0.30694	0.28738	0.30641
1	2	0.21117	0.20401	0.21873	0.21117	0.20402	0.21876
1	5	0.09264	0.08029	0.08451	0.09264	0.08028	0.08451
2	3	0.17513	0.16952	0.18210	0.17513	0.16953	0.18212
3	4	0.09908	0.09381	0.09846	0.09909	0.09381	0.09846
5	6	0.07483	0.06515	0.06887	0.07482	0.06515	0.06887
6	7	0.04608	0.03915	0.04087	0.04607	0.03915	0.04087
Bus No.		Error% ((|TPPF - TPZBD |/TPPF)*100%)					
From	To	Phase A		Phase B		Phase C	
0	1	0.0033		0.0104		0.0163	
1	2	0.0000		0.0049		0.0137	
1	5	0.0000		0.0125		0.0000	
2	3	0.0000		0.0059		0.0110	
3	4	0.0101		0.0000		0.0000	
5	6	0.0134		0.0000		0.0000	
6	7	0.0033		0.0104		0.0163	

TABLE VI
SIMULATION RESULTS OF THREE-PHASE REACTIVE POWER FLOW FOR RADIAL FEEDERS (BASE MVA: 10)

Bus No. \ Methods		TPPF			TPZBD		
From	To	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
0	1	0.12281	0.11941	0.12634	0.12295	0.11976	0.12656
1	2	0.07868	0.07949	0.08421	0.07876	0.07962	0.08432
1	5	0.03218	0.02917	0.03013	0.03218	0.02916	0.03013
2	3	0.06195	0.06292	0.06649	0.06201	0.06304	0.06654
3	4	0.0336	0.03348	0.03444	0.03361	0.03355	0.03448
5	6	0.02541	0.02322	0.02405	0.02540	0.02321	0.02405
6	7	0.01536	0.01374	0.01404	0.01535	0.01373	0.01403

Bus No.		Error% ((|TPPF - TPZBD |/TPPF)*100%)		
From	To	Phase A	Phase B	Phase C
0	1	0.1140	0.2931	**0.1741**
1	2	0.1017	0.1635	0.1306
1	5	0.0000	0.0343	0.0000
2	3	0.0969	0.1907	0.0752
3	4	0.0298	0.2091	0.1161
5	6	0.0394	0.0431	0.0000
6	7	0.1140	0.2931	**0.1741**

TABLE VII
SIMULATION RESULTS OF THREE-PHASE REAL POWER FLOW FOR A NORMALLY CLOSED-LOOP FEEDER (BASE MVA: 10)

Bus No. \ Methods		TPPF			TPZBD		
From	To	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
0	1	0.30634	0.28680	0.30576	0.30634	0.28681	0.30578
1	2	0.17192	0.16322	0.17472	0.17204	0.16334	0.17491
1	5	0.13130	0.12052	0.12792	0.13117	0.12041	0.12776
2	3	0.13604	0.12889	0.13826	0.13616	0.12901	0.13844
3	4	0.06021	0.05339	0.05486	0.06031	0.05349	0.05496
7	4	0.03866	0.04022	0.04339	0.03861	0.04015	0.04331
5	6	0.11345	0.10536	0.11224	0.11338	0.10528	0.11207
6	7	0.08470	0.07935	0.08423	0.08459	0.07922	0.08412

Bus No.		Error% ((|TPPF - TPZBD |/TPPF)*100%)		
From	To	Phase A	Phase B	Phase C
0	1	0.0000	0.0035	0.0065
1	2	0.0698	0.0735	0.1087
1	5	0.0990	0.0913	0.1251
2	3	0.0882	0.0931	0.1302
3	4	0.1661	**0.1873**	0.1823
7	4	0.1293	0.1740	0.1844
5	6	0.0617	0.0759	0.1515
6	7	0.1299	0.1638	0.1306

TABLE VIII
SIMULATION RESULTS OF THREE-PHASE REACTIVE POWER FLOW FOR A NORMALLY CLOSED-LOOP FEEDER (BASE MVA: 10)

Bus No. \ Methods		TPPF			TPZBD		
From	To	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
0	1	0.12092	0.11746	0.12409	0.12102	0.11788	0.12451
1	2	0.06187	0.06146	0.06480	0.06191	0.06168	0.0649
1	5	0.04719	0.04533	0.04738	0.04721	0.04539	0.04751
2	3	0.04690	0.04666	0.04913	0.04694	0.04677	0.04929
3	4	0.02007	0.01875	0.01885	0.02012	0.01881	0.01891
7	4	0.01264	0.01389	0.01464	0.01261	0.01384	0.01458
5	6	0.03946	0.03849	0.04028	0.03943	0.03849	0.04036
6	7	0.02865	0.02827	0.02943	0.02863	0.02825	0.02941

Bus No.		Error% ((|TPPF - TPZBD |/TPPF)*100%)		
From	To	Phase A	Phase B	Phase C
0	1	0.0827	0.3576	0.3385
1	2	0.0647	0.3580	0.1543
1	5	0.0424	0.1324	0.2744
2	3	0.0853	0.2357	0.3257
3	4	0.2491	0.3200	0.3183
7	4	0.2373	0.3600	**0.4098**
5	6	0.0760	0.0000	0.1986
6	7	0.0700	0.0707	0.0680

V. CONCLUSIONS

This paper describes a fast and reliable approach that integrates TPPF and TPZBD for the real-time line flow calculation in unbalanced distribution systems. Using the proposed approach, the three-phase line flow can be easily and robustly calculated as it reflects any changes in bus complex power injections into line flow. As given by the numerical results of radial and normally closed-loop feeder arrangements of the sample system, the line flow solutions are very close on the basis of the solution of the conventional TPPF method; besides, the solution speed is much more faster without any iteration. Furthermore, convergence problem does not exist while using the TPZBD algorithm for real-time applications after load demand changes. These outcomes demonstrate the correctness and practicability of the proposed approach for the unbalanced line flow computation after load demand changes. It has great potential in real-time applications in distribution automation, even more in microgrid online management in the near future.

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