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A Voltage Control Method based on Constants of Four Terminals Network Modeling of Distribution Networks

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Abstract – In this paper, a new algorithm of optimal voltage control is proposed for the Distribution Automation System (DAS) based on constants of four terminal network modeling. In the proposed method, the voltage profiles along feeders are estimated from the measurement of the current and power factor by a Feeder Remote Terminal Unit (FRTU) installed at each node. Whenever the voltage profile violates the restriction, the voltage control strategy is applied to keep the voltage levels along the feeders within the pre-specified range through the modification and coordination of the transformer under-load tap changers (ULTC), step voltage regulator (SVR), as well as shunt condenser. In the case studies, the estimation and control of the voltages have been testified in a radial distribution system with 11 nodes.

Keywords: DAS, distribution system, Load flow, Voltage control

1. Introduction

Consideration of voltage control has always been a major factor in the design of distribution systems. It is a statutory requirement in many countries that customers o continuity, and freedom from distortion [1]. There are many types of voltage and reactive power control devices. For example, an automatic voltage regulator is usually installed to control the secondary bus voltage of a main transformer at a distribution substation through the action of transformer under load-tap changers (ULTC). The allowable range of the Step Voltage Regulator (SVR) is the 5% difference from the rated voltage level at maximum. A shunt condenser is installed along the distribution feeders to adjust the reactive power. While following the variation of power demand, the bus voltages vary and occasionally violate the acceptable level. In order to maintain the voltage profile within the acceptable limits and minimize power and energy losses, current setting of these control devices should be properly modified and coordinated [2-5].

In the previous works, a number of approaches based on mathematical optimization algorithms, such as nonlinear, linear, quadratic programming, Newton, and interior method have been proposed to optimize reactive power and voltage control in power systems. Many methods are proposed for reactive power and voltage optimization in distribution systems [6-9]. The fuzzy-based method [10-13] and expert system [14, 15] have also been used in voltage control. A probabilistic load flow analysis based voltage and reactive power control algorithm has been employed as well [16]. In addition, a normalized weighting method has been presented, taking into account four important objectives including reactive power, feeder loss, voltage deviation, and voltage profile [17]. Of course, each method has its strengths and weaknesses [18]. According to the rapid development of information technology (IT), communication and control technologies, many intelligent devices have been extensively developed such as communication devices, remote control and monitoring devices, etc. In the modern distribution automation system (DAS), feeder remote terminal units (FRTUs) are widely used to collect data. Therefore, a DAS-based voltage control algorithm is needed.

In this paper, a new voltage control algorithm is proposed for DAS through the modification of ULTC, SVR, and shunt condenser. But at present, the measurement data from FRTUs such as voltage magnitudes contain many errors, and so a distributed load modeling based load flow algorithm has been introduced to solve this problem. If the voltage magnitudes are not within an acceptable range, the voltage control algorithm is performed to reset those control devices. The remainder of the paper is organized in five sections: Sections 2 and 3 formulate a network modeling and a new load flow algorithm for estimating voltage profiles, Section 4 provides the proposed voltage control algorithm, and Section 5 presents the test results to verify its effectiveness. The conclusion is reached in Section 6.

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2. Network Modeling

2.1 Characteristics of DAS

DASt enables an electric utility to remotely monitor, coordinate, and operate distribution components, in a real-time mode from remote locations. It also involves collecting data and analyzing information to make control decisions. Feeder Remote Terminal Units (FRTUs) play a critical role in measuring and acquiring the magnitude and phase angle of the voltage and current at each node. Unfortunately, the problem is that the voltage magnitude has much error whereas the phase angle of voltage, current magnitude, and phase angle of the current are very reliable. The proposed algorithm can solve this issue to get an accurate value of the voltage profile [19].

2.2 Problem of Voltage Control

Voltage control can be a difficult task in distribution systems due to the lack of voltage monitoring points, irregularity of load patterns, unbalance conditions, etc. Fig. 1 shows the voltage control in a Distribution Automation System (DAS), in which there are three voltage control devices such as ULTC, SVR, and a shunt condenser. The DAS server can connect all FRTUs and all control devices.

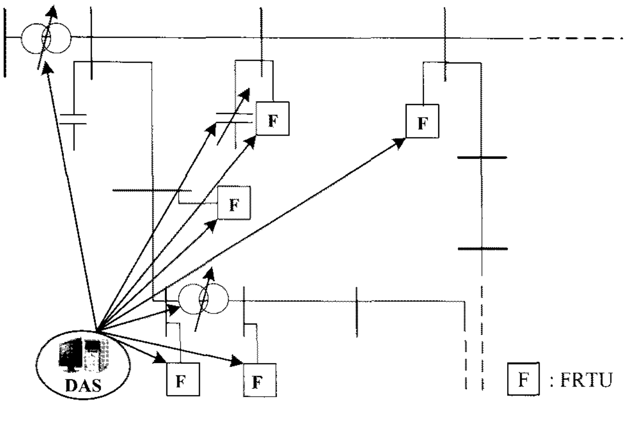

Fig. 1. Voltage Control in DAS

FRTUs collect such data including voltage magnitude. However, the problem is that the data of voltage magnitude contain significant errors. Thus, the voltage control scheme would have a big error with the contribution by those incorrect data. So an accurate load flow algorithm is required to estimate the value of the voltage profiles along the feeders. On the other hand, the coordination of the voltage control devices is required. But the coordination between various devices for voltage control is a complicated task. A fixed coordination strategy cannot provide optimal operation of these devices in all situations due to randomness of the load pattern [20]. The proposed method can be used as an online program for monitoring voltage drop, but it is implemented based on periodically measured polling data. Note that the data synchronization requires the setup of GPS. In this paper, this data synchronizing issue is purposefully omitted.

2.3 Distributed Load Modeling

In DAS, Feeder Remote Terminal Units (FRTUs) play the critical role of measuring and acquiring the magnitude and phase angle of the voltage and current at each node. However, the problem is that the voltage data is incorrect with a significant amount of error whereas the current data is near true value. Therefore, the proposed algorithm contributes to solve this issue based on a new load modeling.

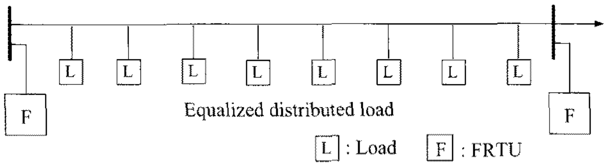

Fig. 2. Distributed load modeling in one-section feeder

Fig. 2 presents a new modeling of a distribution system which considers that the load is uniformly distributed along the line.

The load information is very important for load flow analysis, especially when it comes to a complicated radial distribution system, where the different loads are distributed in different lines. The consumption of electric power for loads varies with the voltage level, so the load can affect the voltage magnitude. In the proposed algorithm, the modeling of the distributed load and the distributed current is utilized.

2.4 Constants of Four Terminals

In a complicated radial system, it is very hard to get the solution of load flow for each node. Thus, the method of constants of four terminals has been used to simplify the process of load flow calculation.

$$\begin{pmatrix} V_q \\ I_q \end{pmatrix} = \begin{pmatrix} A_k & B_k \\ C_k & D_k \end{pmatrix} \begin{pmatrix} V_p \\ I_p \end{pmatrix} \tag{1}$$

$$\begin{pmatrix} A_k & B_k \\ C_k & D_k \end{pmatrix} = \begin{pmatrix} \cosh\beta_k & -Z_k \sinh\beta_k \\ -\frac{1}{Z_k}\sinh\beta_k & \cosh\beta_k \end{pmatrix} \tag{2}$$

The coefficient matrix (2) is called the constants of four terminals, which is a basic form. In radial distribution networks, there are many different configurations at different nodes, so the extensional forms of constants of four terminals should be analyzed.

2.4.1 Node with outgoing current

Fig. 3 displays the case of a node with outgoing current. I_q is an incoming current and I_{qq} is an outgoing current at the node q. The extensional form of four terminal constants is expressed in (3).

$$\begin{pmatrix} A_l & B_l \\ C_l & D_l \end{pmatrix} = \begin{pmatrix} \cosh\beta_l + Y_{qq}Z_l \sinh\beta_l & -Z_k \sinh\beta_l \\ -\dfrac{1}{Z_l}\sinh\beta_l - Y_{qq}\cosh\beta_l & \cosh\beta_l \end{pmatrix} \qquad (3)$$

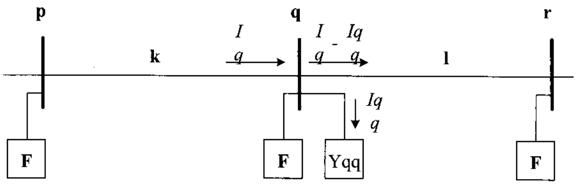

Fig. 3. Node with outgoing current

2.4.2 Node with lateral

In radial distribution networks, a node with lateral is a common case as shown in Fig. 4. Where, I_p is the incoming load current; I_{pA} is the load current flowing in section k; I_{pB} is the load current flowing in branch section l; k_{pq} is the current distribution factor in section k; and k_{pr} is the current distribution factor in section l. The extensional form of constants of four terminals is shown in (4).

$$\begin{pmatrix} A_k & B_k \\ C_k & D_k \end{pmatrix} = \begin{pmatrix} \cosh\beta_k & -k_{pq}Z_k \sinh\beta_k \\ -\dfrac{1}{Z_k}\sinh\beta_k & k_{pq}\cosh\beta_k \end{pmatrix} \qquad (4)$$

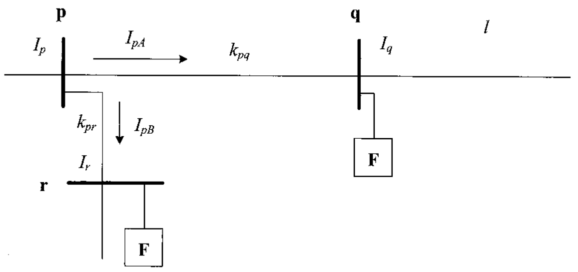

Fig. 4. Node with lateral

2.4.3 Node with transformer

The equivalent circuit modeling of SVR is shown in Fig. 5, where z is the impedance of the transformer and the ratio of the transformer is 1:a. So the extensional form of constants of four terminals is achieved below.

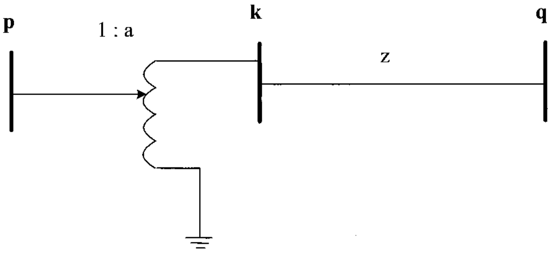

Fig. 5. Node with transformer

$$\begin{pmatrix} A_k & B_k \\ C_k & D_k \end{pmatrix} = \begin{pmatrix} a & -\dfrac{z}{a} \\ 0 & \dfrac{1}{a} \end{pmatrix} \qquad (5)$$

In complicated radial distribution networks, the extensional forms of constants of four terminals can be integrated due to the aforementioned three cases, thus the estimation of voltage profile could be greatly simplified.

3. Estimation of Voltage Profile along Feeder

The feeder under consideration serves a large number of relatively small customers, and detailed knowledge of these customer loads is not available. An innovative method has been proposed for estimating the voltage profile on the study radial distribution system from the measurements at the feeder head and at the other nodes, and the knowledge of the feeder parameters.

3.1 Overview

Fig. 6 presents a simple distribution system diagram which consists of 5 nodes with FRTU respectively. Given the magnitude and phase angle of voltage and current at node 0, those data at node 1 can be calculated through the proposed algorithm. Then the same process would be handled in the next section between nodes 1 and 2. By moving sections one by one, the magnitude and phase angle of the voltage and current at each node would be obtained.

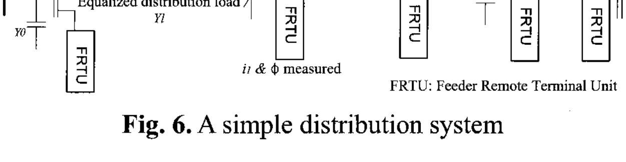

Fig. 6. A simple distribution system

The process in the first section between nodes 0 and 1 is taken out to be analyzed in detail.

At first, listing the given conditions below:

1. The phase of voltage and current at node 0;
2. Line impedance in the first section;
3. The current magnitude and the angle of power factor at node 1, with both data being measured by FRTU.

Then, the following data are supposed to be solved:

1. Distributed load admittance in the first section;
2. The magnitude and phase angle of voltage and current at node 1.

The magnitude and phase angle of voltage and current along the feeder can be calculated through the above-mentioned procedures using the measured data from FRTU and the known voltage and current at the feeder head.

3.2 A New Load Flow Algorithm in DAS

The one-section modeling between nodes p and q is shown in Fig. 7. Line impedance z_k and equalized load admittance y_k are distributed at every dx in the line. The basic equations of voltage drop and current drop are illustrated as follows:

$$dV(x) = -I(x)zdx \tag{6}$$

$$dI(x) = -V(x)ydx \tag{7}$$

Where, zdx is line impedance in the unit length, and ydx is load admittance in the unit length.

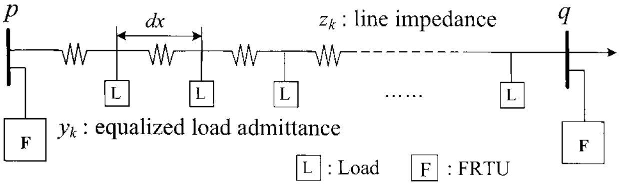

Fig. 7. A simple distribution system

Through a series of differential calculations, the solutions of (6) and (7) are obtained below.

$$V(x) = C_1 \cosh\gamma_k x + C_2 \sinh\gamma_k x \tag{8}$$

$$I(x) = C_3 \sinh\gamma_k x + C_4 \cosh\gamma_k x \tag{9}$$

Where, $\gamma_k = \sqrt{z_k y_k}$ is the characteristic constant of the line.

Taking account of the boundary conditions at the source side, (8) and (9) are able to be further expressed below.

$$V(x) = V_p \cosh\gamma_k x - \frac{\gamma_k}{y_k} I_p \sinh\gamma_k x \tag{10}$$

$$I(x) = -\frac{y_k}{\gamma_k} V_p \sinh\gamma_k x + I_p \cosh\gamma_k x \tag{11}$$

Assuming L_k is the length of one section, in terms of (10) and (11), the phase of voltage and current at the load side would be achieved in the case of $x = L_k$, which are shown in (12) and (13).

$$V_q = V_p \cosh\beta_k - Z_k I_p \sinh\beta_k \tag{12}$$

$$I_q = -\frac{V_p}{Z_k}\sinh\beta_k + I_p \cosh\beta_k \tag{13}$$

Where, $Z_k = \sqrt{z_k / y_k}$, $\beta_k = \gamma_k L_k$

In (12) and (13), except for the equalized load admittance y_k, the other unknown variables can be computed.

If y_k is obtained, V_q would be achieved easily. Thus, to get y_k, some information at the load-side node is needed.

i) The current magnitude is measured by FRTU.

ii) The phase angle difference between the voltage and the current is acquired by FRTU, and it is identical to the angle of power factor.

Moreover, there are two cases in the distribution line. The first case is the line connected with a feeder end; the second case is the line not connected with a feeder end. Two kinds of conditions should be respectively found out in accordance with both cases.

In the first case, the current at the end of the feeder is zero as given in (14).

$$I_q = -\frac{V_p}{Z_k}\sinh\beta_k + I_p \cosh\beta_k = 0 \tag{14}$$

Substituting (12) and (13) into (14), distributed load admittance y_k can be computed through the Newton-Raphson method.

In the second case, two equations as in (15) and (16) are found out:

$$i_q^{\,2} = I_q \cdot I_q^{\,*} \tag{15}$$

$$(V_q I_q^{\,*})^2 = v_q^{\,2} i_q^{\,2} \cos^2\varphi_q \tag{16}$$

Substituting (12) and (13) into (15) and (16), the following further equations can be obtained.

$$i_q^2 = (I_p \cosh\beta_k - \frac{V_p}{Z_k}\sinh\beta_k)(I_p \cosh\beta_k - \frac{V_p}{Z_k}\sinh\beta_k)^* \tag{17}$$

$$\begin{gathered} \left(\left(V_p \cosh\beta_k - Z_k I_p \sinh\beta_k\right) \cdot (I_p \cosh\beta_k - \frac{V_p}{Z_k}\sinh\beta_k) \right)^2 = \\ i_q^2 \left(\cos\varphi_q\right)^2 (V_p \cosh\beta_k - Z_k I_p \sinh\beta_k)(V_p \cosh\beta_k - Z_k I_p \sinh\beta_k)^* \end{gathered} \tag{18}$$

Where,

i_q is the current magnitude at load-side node q;

φ_q is the angle of power factor at load-side node q.

In the same way, y_k can be solved through the Newton-Raphson method in terms of (17) and (18).

For both cases, finally y_k is substituted into (12) and (13) to calculate V_q and I_q which are the magnitude and phase angle of voltage and current at the load-side node.

4. Proposed Voltage Control Algorithm

In the DAS, because the measured data of voltage magnitude contain significant errors, this paper first introduced a corresponding load flow algorithm to estimate the voltage profiles along the feeders. Following that there must be some means of regulating the voltage so that every customer's voltage remains within an acceptable level. The proposed voltage control algorithm is based on Gradient method, which is the most popular method in the optimization technique.

4.1 Objective Function

Based on DAS, FRTU can collect data from the distribution network. All control devices can be remote controlled by commands and coordinates to keep the voltages within an allowable range. So the tap positions on the distribution transformer, the step voltage regulator, and shunt condenser should be changed. To take into account these three, the objective function with respect to X is found as follows. X represents both control variables A and state variables denoted as V, I.

$$\begin{aligned} J(X) &= \sum w_i (v_{ni} - |V_i|)^2 \qquad (19) \\ X &= [A, V, I]^T \\ A &= [a_1, a_2, \ldots a_p]^T \\ V &= [V_1, V_2, \ldots V_n]^T \\ I &= [I_1, I_2, \ldots I_n]^T \end{aligned}$$

where,

A is control variables;
V is node voltages;
I is node currents;
v_{ni} is rate voltage at each node;
V_i is estimated voltage at each node;
w_i is weighting factor at each section;
n is number of total nodes.

The weighting factor w_i is introduced in the objective function because the voltage control is more important in the section with the heavier load. Moreover, if the constant N and the deviation between the rate voltage and the estimated voltage are big, the impact of the objective function would be big. Also, the voltage control would be more important at the node with a big voltage deviation.

4.2 Constraints

The state variables V and I should meet the circuit equations. For example, in a distribution system, at section k between node p and q, the circuit equations are as follows.

$$f_k^V(X) = V_q - A_k V_p - B_k I_p = 0 \qquad (20)$$

$$f_k^I(X) = I_q - C_k V_p - D_k I_p = 0 \qquad (21)$$

The summary of all those circuit equations in all sections of the system is denoted as $F(X)$.

$$\begin{aligned} F(X) &= [F^V(X), F^I(X)]^T \qquad (22) \\ F^V(X) &= [f_1^V(X), f_2^V(X) \ldots, f_s^V(X)]^T \\ F^I(X) &= [f_1^I(X), f_2^I(X) \ldots, f_s^I(X)]^T \end{aligned}$$

If the control variables change, the state variables such as node voltage and node current would change as well.

4.3 Solution

In order to get the minimum value of the objective function, it should meet the following equation.

$$\frac{\partial J(X + \Delta X)}{\partial t} = 0 \qquad (23)$$

where,

$$\begin{aligned} \Delta X &= \sum_{k=1}^{p} \Delta X_k \\ \Delta X_k &= \frac{\partial X}{\partial a_k} \Delta a_k \\ \Delta a_k &= -t \frac{\partial J}{\partial a_k} \end{aligned}$$

t is acceleration factor;
k = 1, 2, …

The gradient of the objective function $J(X)$ is denoted by ∇J_k,

$$\nabla J_k = \frac{\partial J}{\partial a_k} = \left(\frac{\partial J}{\partial X}\right)^T \frac{\partial X}{\partial a_k} \qquad (24)$$

The gradient vectors of those state variables with respect to the control variables are denoted by ∇X_k, then

$$\nabla X_k = \frac{\partial X}{\partial a_k} \tag{25}$$

In (4), the partial derivatives of $F(X)$ with respect to the control variables a_k are as follows.

$$\frac{\partial F(X)}{\partial a_k} = \frac{\partial F(X)}{\partial X}\nabla X_k \tag{26}$$

Then ∇X_k can be determined as,

$$\nabla X_k = \left(\frac{\partial F(X)}{\partial X}\right)^{-1}\frac{\partial F(X)}{\partial a_k} \tag{27}$$

Substituting (24) – (27) into (23), the optimal setting can then be determined.

5. Case Study

5.1 Configuration of Study System

The configuration of the study system is illustrated in Fig. 8. There are a total of 11 nodes in this simple radial distribution system. ULTC is set up at node 1; A SVR is installed between node 7 and node 8; at node 2, there is a shunt condenser which is used for reactive power compensation.

The line parameters are shown in Table 1. In the DAS, FRTU collect the data such as the current magnitude and the angle of the power factor depicted in Table 2. But because there is much error with the measured voltage magnitude, it is unable to be used for the voltage control algorithm. The proposed load flow algorithm is dedicated for estimating the voltage profiles.

Table 1. Line Parameters and Current Distribution Factor

Section Number	Node Number	Resistance (p.u.)	Reactance (p.u.)	Current Distribution Factor
1	1 - 2	0.0058	0.0029	0.5
2	2 - 3	0.0308	0.0157	1.0
3	3 - 4	0.0228	0.0116	0.5
4	4 - 9	0.0238	0.0121	1.0
5	3 - 5	0.0511	0.0441	0.5
6	5 - 10	0.0117	0.0386	1.0
7	1 - 6	0.1068	0.0771	0.5
8	6 - 7	0.0643	0.0462	1.0
9	7 - 8	0.0010	0.0400	1.0
10	8 - 11	0.0123	0.0041	1.0

Table 2. Data from FRTU at Each Node

Node Number	Current Magnitude (p.u.)	Angle of Power Factor (rad)
1	1.000	pi/8
2	0.400	pi/8
3	0.225	pi/8
4	0.075	pi/8
5	0.050	pi/8
6	0.400	pi/8
7	0.200	pi/8
8	0.250	pi/8
9	0	pi/8
10	0	pi/8
11	0	pi/8

In addition, the ratio of the transformer is 1 : 0.8, and the compensation factor of the shunt condenser is 0.03.

5.2 Test Results

Based on the study system, the objective function is expressed in (28).

$$J(X) = \sum(v_{ni} - |V_i|)^2 \tag{28}$$

where, the weighting factor is set as 1.

$$X = [A, V, I]^T$$
$$A = [a_1, a_2, a_3]^T, V = [V_1, V_2, \dots V_{11}]^T, I = [I_1, I_2, \dots I_{11}]^T,$$

It is assumed that a_1 denotes the control variable of ULTC at node 1; a_2 denotes the control variable of the shunt condenser at node 2; and a_3 denotes the control variable of SVR at node 7.

At the initial settings, a_1 = 1.0, a_2 = 1.0, and a_3 = 0.8. The estimation results are tabulated in Table 3.

Table 3. Estimation of Voltage and Current at Initial Setting of Control Variables

Control Variables	$a_1 = 1.0$, $a_2 = 1.0$, $a_3 = 0.8$			
Node Number	Voltage (p.u.)		Current (p.u.)	
	Magnitude	**Phase Angle**	**Magnitude**	**Phase Angle**
1	1.0000	0	1.0000	-0.3927
2	0.9971	-0.0003	0.4000	-0.3052
3	0.9749	0.0212	0.2250	-0.2837
4	0.9726	0.0208	0.0750	-0.2841
5	0.9698	0.0191	0.0500	-0.3736
6	0.9425	-0.0141	0.4000	-0.4068
7	0.9194	-0.0200	0.2000	-0.4127
8	0.7315	-0.0325	0.2500	-0.4127
9	0.9716	0.0207	0.0000	-0.1244
10	0.9692	0.0183	0.0000	0.5148
11	0.7299	-0.0323	0.0000	-0.4461

Note that the results converge into 5 or 6 iterations in the proposed load flow algorithm.

The proposed voltage control strategy is determined to keep the voltage levels along the feeders within an allowable range. Modifications of the transformer under load tap changers (ULTC), step voltage regulator (SVR), as well as shunt condenser are as $a_1 = 1.0394$, $a_2 = 0.9742$, and $a_3 = 1.0764$, respectively. The estimation results are listed in Table 4.

Table 4. Estimation of Voltage and Current with Resetting of Control Variables using Voltage Control Algorithm

Control Variables	$a_1 = 1.0394$, $a_2 = 0.9742$, $a_3 = 1.0764$			
Node Number	Voltage (p.u.)		Current (p.u.)	
	Magnitude	**Phase Angle**	**Magnitude**	**Phase Angle**
1	1.0394	0	1.2014	-0.4289
2	1.0363	-0.0001	0.4277	-0.3939
3	1.0133	0.0215	0.2321	-0.2818
4	1.0108	0.0211	0.0779	-0.2838
5	1.0080	0.0194	0.0520	-0.3733
6	0.9605	-0.0182	0.5645	-0.4145
7	0.9252	-0.0269	0.3602	-0.4193
8	0.9905	-0.0393	0.3347	-0.4193
9	1.0098	0.0209	0.0000	-0.1244
10	1.0073	0.0186	0.0000	0.5148
11	0.9868	-0.0391	0.0000	-0.4461

The voltage magnitude determined by the proposed method has been greatly improved since there is a big voltage drop at node 8 and node 11.

6. Conclusion

Due to the required measurement data from FRTU at each node along feeders in DAS, the proposed voltage control strategy is determined to keep the voltage levels within the allowable range through the modification of the ULTC, SVR, and shunt condenser. In the mean time, this paper presents a fairly precise load flow algorithm to estimate the voltage profiles in a distribution system. The test results have verified its effectiveness based on a simple radial distribution system with 11 nodes.

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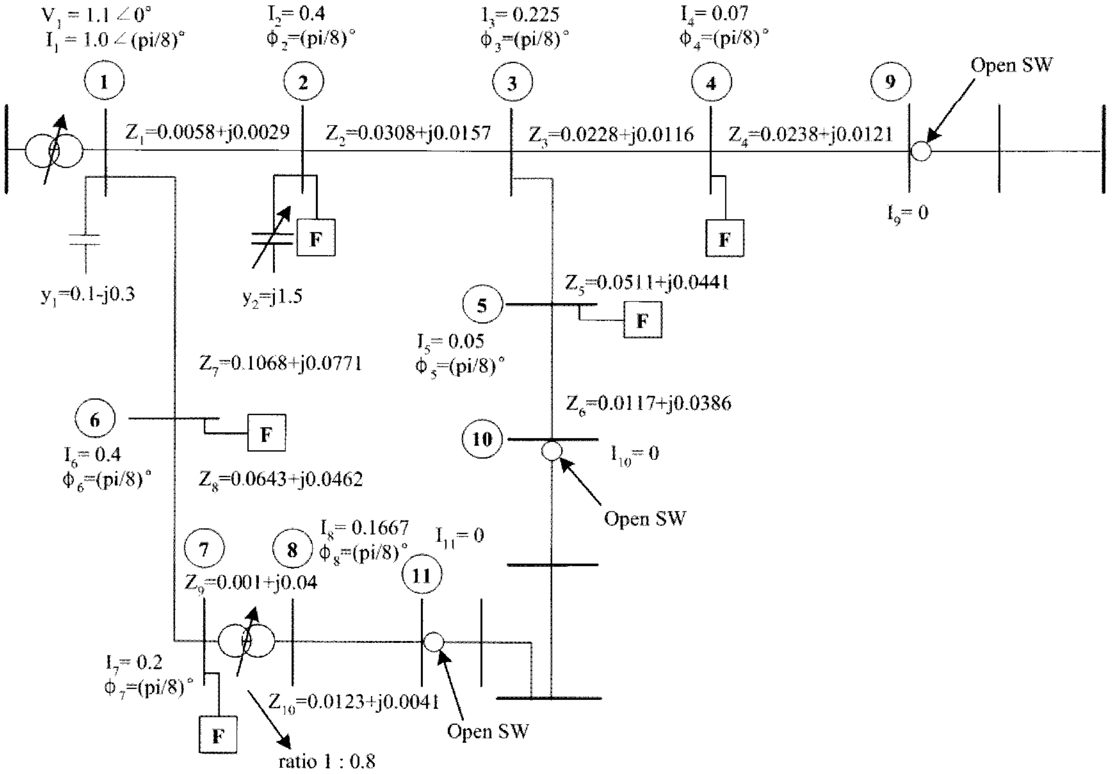

Fig. 8. An example of a radial distribution network

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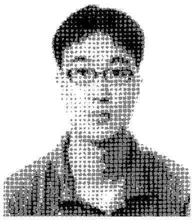

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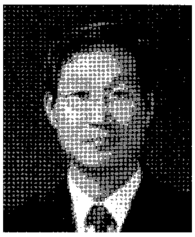

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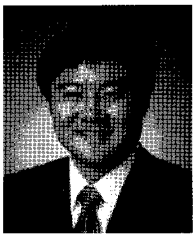

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