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Practical impedance estimation in low-voltage distribution network

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Abstract: This paper proposes a method of estimating the impedances between nodes in a low-voltage distribution network. This method works without any information on the phase differences between nodes. It only requires measurements that can be easily obtained and shared from existing devices and communication technologies such as power line communication(PLC). In other words, it is not necessary to carry out synchronized real-time measurement for observing phase differences. From governing equations based on the basic circuit theory, the mathematical optimization problem is formulated to solve them and then obtain the estimates of the impedances among nodes. To find a solution to the nonconvex and nondifferentiable optimization problem, a representative metaheuristic algorithm, called the particle swamp optimization(PSO), is employed with a new biquadratic and linear hybrid cost function that is proper for fast convergence both far away from and near an optimal point.

Keywords: Impedance estimation, low-voltage distribution network.

1. INTRODUCTION

Recently, the control strategies for regulating voltages in low-voltage(LV) distribution network have been explored with centralized or decentralized approaches. Specially, voltage regulation schemes have been much developed by using switching control in Walling and Saint (2008), optimal reactive power dispatching scheme in Baran and El-Markabi (2007); Carvalho et al. (2008), and authenticated control framework in Rogers et al. (2010). In order to control voltages in LV distribution network, it is often required that the impedances among nodes are available. However, it is cumbersome to measure every impedances between nodes directly since the LV distribution networks are spread out over a wide area. Currently, most voltage controls are based on empirical knowledge and thus they are not accurate. It would be worthwhile to develop an algorithmic method of estimating the impedances with the given measurable information and existing communication technologies such as power line communications(PLC). Based on such estimation methods of obtaining the impedances between nodes automatically, more accurate and convenient voltage control schemes can be developed.

In this paper, we propose a practical method of estimating impedances between nodes by using measurements that can be easily obtained with inexpensive devices. The information on the phase difference between nodes is not required since it can be obtained with very expensive devices. To begin with, a simple module, a one layer, sharing the same bus is analyzed by using the basic circuit theory and providing a governing equation, and the impedance devices connected in parallel with that bus are estimated from these governing equations and several different energy consumption patterns. In order to solve the complicated simultaneous equations, the optimization scheme is proposed together with a specialized cost function that is proper for fast convergence both far away from and near an optimal point.

The rest of the paper is organized as follows: In Section 2, the optimization problem for estimating the impedances between nodes is formulated with an efficient cost function. The popular optimization algorithm, called the particle swarm optimization(PSO) in Rao (2009), is introduced to solve the proposed estimation problem in Section 3. Finally, the conclusion is drawn in Section 4.

2. IMPEDANCE ESTIMATION

Consider an LV distribution network as seen in Fig. 1. Such a distribution network has tree or radial structure. As a simple module sharing the same bus, we first analyze a dotted box in Fig. 1 that is depicted in detail in Fig. 2. Later on, we discuss how to make the use of the result for a basic module in Fig. 2 in order to extend it to the LV distribution network in Fig. 1. It is assumed that the complex power, S_i, $i = 1, 2, \cdots, N$ of each node is available. The voltage and the current, V_1, and I_1 are assumed to be measured in terms of phasers since they are obtained at the same place. The voltage and the current of other nodes, V_i, and I_i, $i = 2, \cdots, N$, are measured in terms of the magnitude, which means that their phase

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information is not available. To begin with, we consider the first two nodes indexed by 1 and 2. The complex power S

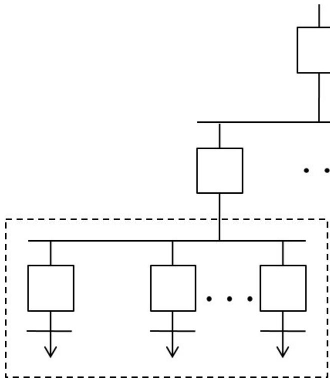

Fig. 1. An overall view of low-voltage distribution network (A dotted box appears in detail in Fig. 2)

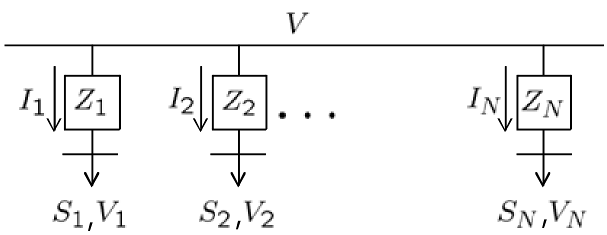

Fig. 2. A basic module of low-voltage distribution network

injected to the nodes 1 and 2 through impedances Z_1 and Z_2 can be computed to be

$$S = S_1 + Z_1|I_1|^2 + S_2 + Z_2|I_2|^2, \tag{1}$$

where $Z_1|I_1|^2$ and $Z_2|I_2|^2$ are the power losses of Z_1 and Z_2, respectively. The voltage V of the bus can be written down as follows:

$$V = V_1 + Z_1 I_1, \tag{2}$$

where $Z_1 I_1$ is the voltage drop in the impedance of Z_1.

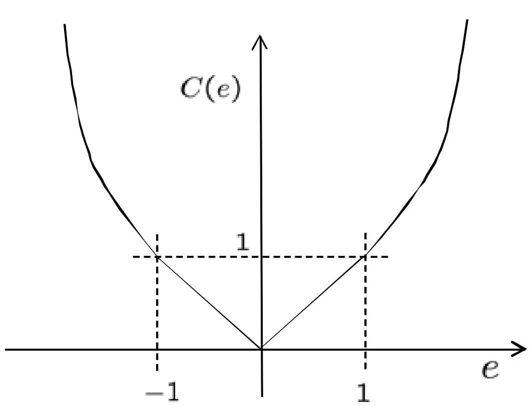

Fig. 3. The plot of $C(e)$

Using (1) and (2), we have

$$\begin{aligned} I_2 &= \left(\frac{S}{V}\right)^* - I_1 \\ &= \left(\frac{S_1 + Z_1|I_1|^2 + S_2 + Z_2|I_2|^2}{V_1 + Z_1 I_1}\right)^* - I_1 \\ &= \left(\frac{S_2 + Z_2|I_2|^2}{V_1 + Z_1 I_1}\right)^*. \end{aligned} \tag{3}$$

Note that since S_2, $|I_2|$, V_1, and I_1 are known, I_2 can be available in terms of phasers if Z_1 and Z_2 are estimated. The voltage of the node 2 can be represented as

$$\begin{aligned} V_2 &= V - Z_2 I_2, \\ &= V_1 + Z_1 I_1 - Z_2 I_2, \\ &= V_1 + Z_1 I_1 - Z_2\left(\frac{S_2 + Z_2 I_2^2}{V_1 + Z_1 I_1}\right)^*. \end{aligned} \tag{4}$$

Multiplying both sides by $V_1 + Z_1 I_1$ yields

$$V_2(V_1 + Z_1 I_1)^* = |V_1 + Z I_1|^2 - |Z_2|^2 |I_2|^2 - Z_2 S_2^*. \tag{5}$$

It is noted that the complex phaser V_2 is not available, but its magnitude is known. In order to use the known quantity, we take the abstract value on both sides of (5) as follows:

$$|V_2||V_1 + Z_1 I_1| = \big||V_1 + Z I_1|^2 - |Z_2|^2 |I_2|^2 - Z_2 S_2^*\big|. \tag{6}$$

Totally, there are four unknown real variables, or real and imaginary parts of Z_1 and Z_2. These four variables cannot be determined by a single equation (6). In order to estimate Z_1 and Z_2, we need to have 4 equations. It means that 4 different power consumption patterns are required for obtaining 4 equations. Indexing four different power, and voltage, current as $S_1^{(i)}$, $V_1^{(i)}$, and $I_1^{(i)}$, we propose the following cost function:

$$f(Z_1, Z_2) = \max(C(e_1), C(e_2), C(e_3), C(e_4)), \tag{7}$$

where e_i is defined by

$$\begin{aligned} e_i = &|V_2^{(i)}||V_1^{(i)} + Z_1^{(i)} I_1^{(i)}| \\ &- \big||V_1^{(i)} + Z I_1^{(i)}|^2 - |Z_2^{(i)}|^2 |I_2^{(i)}|^2 - Z_2^{(i)} (S_2^*)^{(i)}\big|, \end{aligned}$$

and $C(e)$ is given as

$$C(e) = \begin{cases} |e|, & -1 \le e \le 1, \\ e^4, & \text{otherwise.} \end{cases} \tag{8}$$

The plot of $C(e)$ in (8) is drawn in Fig. 3. The byquadratic part of $C(e)$ puts more weight on the large error. The linear part of $C(e)$ makes the cost function still sensitive near zero. The cost function (7) consisting of two parts plays a role in finding a solution fast and accurately.

The cost function (7) will be minimized until it is smaller than ϵ that is a given specified tolerance. Ideally, if the optimal value of the cost function (7) is zero, we can say that the corresponding solution is the perfect one satisfying 4 equations simultaneously. For faster convergence and more correct solution, it may be recommended that more than 4 power consumption patterns can be used.

In the same way, Z_3, Z_4, $\cdots$, and Z_N can be estimated by using the reference node 1. If Z_1 and Z_2 are available, the current I_2 in (3) is known. When Z_3, Z_4, $\cdots$ are estimated, the currents I_3, I_4, $\cdots$ can also be computed. Finally, the total current $I_1 + I_2 + \cdots + I_N$ can be found in terms