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A Modified Back/Forward Sweep Method Based on the Electricity Consumption Data

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Abstract

With the development of distribution automation system, the centralized meter reading system has been adopted more and more extensively, which provides real-time electricity consumption data of end-users, and consequently lays foundation for operating condition on-line analysis of distribution network. In this paper, a modified back/forward sweep method, which directly uses real-time electricity consumption data acquired from the centralized meter reading system, is proposedto realize voltage analysis based on 24-hour electricity consumption data of a typical transformer district. Furthermore, the calculated line losses are verified through data collected from the energy metering of the distribution transformer, illustrating that the proposed method can be applied in analyzing voltage level and discovering unknown energy losses, which will lay foundation for on-line analysis, calculation and monitoring of power distribution network.

Keywords

Low-Voltage Distribution Network, Back/Forward Sweep Method, Electricity Consumption Data, On-Line Analysis and Calculation

1. Introduction

The existing data acquisition system of low-voltage distribution network is capable of collecting electricity consumption data from end-users within a certain interval, which serves as a fundamental part in on-line analysis and calculation for distribution network, however, there still exists limitations on collecting load power consumption data. There have been large amounts of researches making use of electricity consumption data for distribution network analysis and calculation. Research [1] created a mathematical model regarding theoretical line losses as a variable in adoption of equivalent resistance method and load shape coefficients. Similarly, improved algorithms for theoretical line losses calculation were put forward on the foundation of equivalent resistance method and back/ forward sweep method [2] [3]. But it should be noted that these methods only concentrated on line losses calculation, which cannot satisfy the need of on-line analysis or calculation for distribution network. In order to deal with the information obtaining problems of non-measured nodes for distribution network, [4] estimated the electricity consumption data of non-measurement nodes in accordance to those measurement ones, completing quasi-real-time data for line losses calculation adopting backward/forward sweep method. Alternatively, taking the concept of distribution system state estimation and load forecasting for reference, [5] calculated line power flow and theoretical line losses based on partial real-time measurement information of 10 kV distribution system. Nonetheless, none of these researches is applicable to the general condition that the end-users of low-voltage distribution network are lack of load power measurement data. From another aspect, previous researches have created various load modellings to perform analysis for distribution network, [6] proposed a power flow calculation algorithm employing constant impedance load model and [7] analyze voltage quality based on probabilistic power flow calculation, while the uncertain modelling of fluctuating load had been completed to obtain probabilistic density distribution function of load flow. However, there tends to be some differences between these load modellings and the actual load, resulting that the realistic operating condition of distribution network cannot be reflected appropriately.

Therefore, a modified back/forward sweep method based on real-time electricity consumption data is proposed. On the basis of electricity consumption data acquired by remote concentrated meter reading system, a transformer district is taken as a research example to realize voltage and theoretical line losses analysis. Furthermore, the results of line losses are verified through electricity consumption data collected by the energy metering of the distribution transformer, illustrating that the proposed method can be applied in analyzing voltage level and discovering unknown energy losses, which will lay foundation for on-line analysis, calculation and monitoring of power distribution network.

2. Modified Back/Forward Sweep Method Based on Electricity Consumption Data

2.1. Algorithm Description

Within a certain time period, electricity consumption data are collected from the low voltage side of the distribution transformer and all the end-users of the transformer district, represented symbolically by A and A_k as **Figure 1** shows.

Considering that the time intervals of data acquisition might differ within various measuring points, or the data acquired have non-synchronous problems, it's necessary to reduce and calculate the electricity consumption data. Given the condition that the load power flow holds steadiness within each time interval of

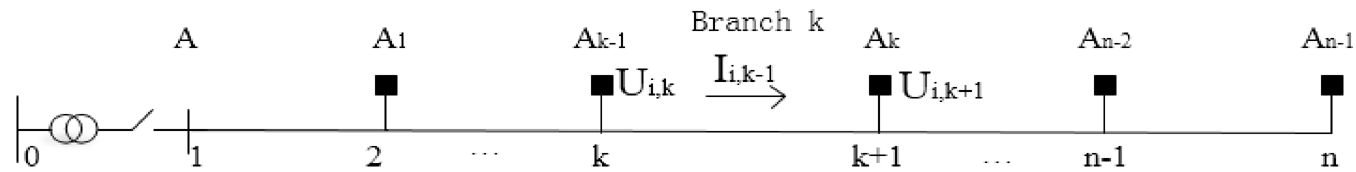

Figure 1. Typical model of low-voltage distribution network with n nodes.

data acquisition, the per unit value of load power can be calculated based on electricity consumption data and power factor of each node.

1) Taking the high voltage side of distribution transformer as slack node, current of each branch can be derived from the terminal of power lines to the head based on load power under the assumption that the voltage value of each node of the whole power grid set as rated voltage in the initial iteration, as Equation (1) shows, where $I_{i,k-1}$ is current of branch k in the ith iteration, Δt is the time interval of data acquisition of remote centralized meter readying system, S_b is the reference capacity of power distribution system, A_{k-1} is the electricity consumption data of end-user k within time interval Δt, $\cos\varphi$ is load power factor, $U_{i,k-1}$ is the voltage value of node k in the $(i-1)$th iteration, and so on, $\sum I'_{i,k-1}$ is the sum of current of all the branches of branch k in the ith iteration.

$$I_{i,k\text{-}1} = A_{k\text{-}1}\left(1 + j\sin\left(\arccos\varphi\right)\right)/S_b\Delta tU_{i\text{-}1,k} + \sum I'_{i,k\text{-}1}\,. \tag{1}$$

2) Voltage value of each node can be modified from the head of power line to the terminal according to the value of slacking node, after obtaining current of the first branch, shown in Equation (2), where R_{k-1}, X_{k-1} is per unit equivalent impedance of branch k.

$$U_{i,k+1} = U_{i,k} - I_{i,k\text{-}1}\left(R_{k\text{-}1} + jX_{k\text{-}1}\right). \tag{2}$$

3) Perform iterative calculation until errors of all the nodes of power distribution between the last two iterations meet the requirement of precision, as Equation (3) shows, where ε represents error precision of iteration.

$$\left|U_{i,k+1} - U_{i\text{-}1,k}\right| \le \varepsilon\,. \tag{3}$$

4) Based on the result of modified back/forward sweep method, excluding distribution transformer losses, theoretical line losses can be calculated as Equation (4) shows, where *Sloss* is sum of theoretical line losses of the whole transformer district, n is number of branches in power distribution network.

$$Sloss = \sum_{k=2}^{n-1} I_{i,k\text{-}1}\overline{I_{i,k\text{-}1}}\left(R_{k\text{-}1} + jX_{k\text{-}1}\right). \tag{4}$$

3. Case Application

Figure 2 shows a transformer district, a radial connected network supplied by a S9 series 160-kVA 10/0.4 kV transformer with 3 types of loads.

3.1. Calculation Results

1) Assuming that the electric meter freezes the electricity consumption data

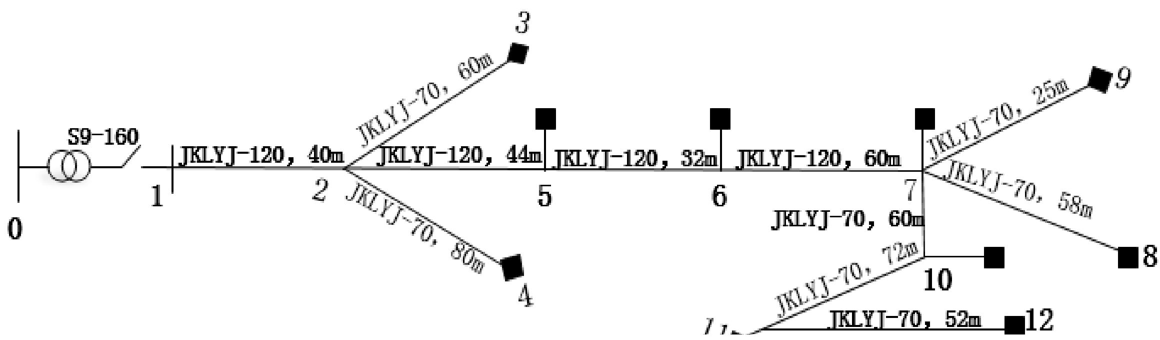

Figure 2. Grid structure of transformer district.

every hour, the electric meter readings of all the measuring points of the transformer district at 18:00 are given in **Table 1**. Power flow calculation converges after 4 iterations by adopting modified back/forward sweep method with the error precision set as 10^{-6}. Calculated theoretical line losses energy within measuring time is 0.68 kilowatt hours.

2) Typical per unit daily load curves of all the load types of the transformer district are given in **Figure 3**. With application of modified back/forward sweep method, voltage and theoretical line losses analysis of the transformer district is performed based on real-time electricity consumption data, obtaining 24-hour voltage variation trend of all the nodes as well as theoretical line losses changing tendency shown in **Figure 4**.

3.2. Result Verification

If there exist no unknown energy losses in power distribution network, such as electricity stealing or leakage, the theoretical line losses of distribution transformer area should be equivalent to the difference between electricity consumption data acquired from the low voltage side of distribution transformer and the sum of which collected from end-users of the whole area, shown as Equation (5). Otherwise, it indicates that there are some kind of unknown energy losses from the measuring point of the low voltage side of power distribution transformer to those of end-users. As such, result of modified back/forward sweep method can be verified, shown as Equations (5)-(7), where A_{sum} represents the sum of electricity consumption data collected from end-users of the whole electrical transformer district, ΔA denotes sum of theoretical line losses energy within time interval Δt.

$$A - A_{sum} - \Delta A = 0 . \tag{5}$$

$$A_{sum} = \sum_{k=1}^{n-1} A_k . \tag{6}$$

$$\Delta A = Sloss \Delta t . \tag{7}$$

With the verification of Equation (5), it can be indicated from the calculation result that there exists no unknown energy losses at 18:00 in the transformer district shown in **Figure 2**. Moreover, when the 24-hour electric meter reading at the low voltage side of the transformer are given, unknown energy losses

Table 1. Electric meter readings of all the users of the transformer district.

User Number	2	3	4	5	6	7	8	9	10	11	12
Electric Meter Reading (kilowatt hour)	11.67	13.76	3.54	4.51	4.49	3.74	4.2	3.12	6.66	7.31	6.86

a. Load power factor is 0.85. b. The electric meter at the low voltage side of the transformer reads 70.54 kilowatt hours. c. Number 2 - 3 are business users, number 4 - 9 are residential users, number 10 - 12 are agricultural users.

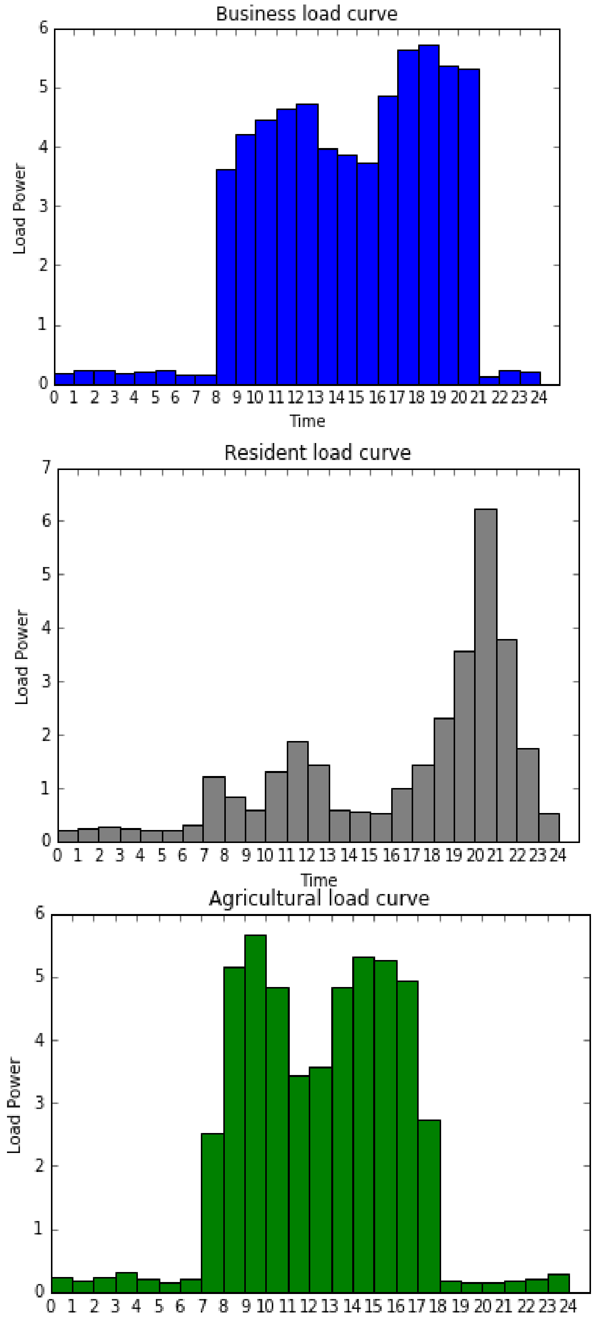

Figure 3. Typical per unit daily load curves of all the load types of the transformer district.

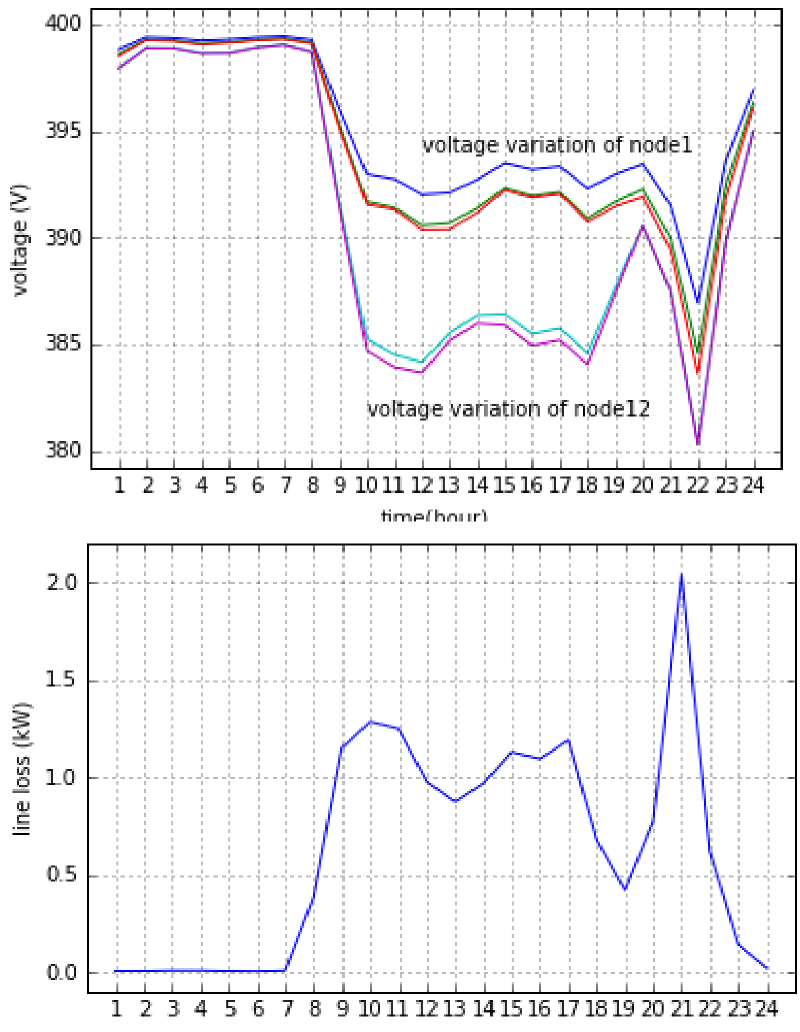

Figure 4. 24-Hour voltage variation and theoretical line losses tendency diagram of the transformer district.

within any hour during the measuring time can be discovered through the verification of Equation (5).

4. Conclusion

This work demonstratesamodified back/forward sweep method using the real-time electricity consumption data acquired by remote concentrated meter reading system. The proposed method, which owns fast calculation speed and high convergence reliability, can be applied in voltage level analysis and unknown energy losses discovery in the proof of the research case, serving to make practical meaning to on-line analysis, monitoring and calculation for power distribution network.

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