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ERROR ANALYSIS OF THE THREE-PHASE ELECTRICAL ENERGY CALCULATION METHOD IN THE CASE OF VOLTAGE-LOSS FAILURE

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Abstract

The single-phase voltage loss is a common fault. Once the voltage-loss failure occurs, the amount of electrical energy will not be measured, but it is to be calculated so as to protect the interest of the power supplier. Two automatic calculation methods, the power substitution and the voltage substitution, are introduced in this paper. Considering the lack of quantitative analysis of the calculation error of the voltage substitution method, the grid traversal method and MATLAB tool are applied to solve the problem. The theoretical analysis indicates that the calculation error is closely related to the voltage unbalance factor and the power factor, and the maximum calculation error is about 6% when the power system operates normally. To verify the theoretical analysis, two three-phase electrical energy metering devices have been developed, and verification tests have been carried out in both the lab and field conditions. The lab testing results are consistent with the theoretical ones, and the field testing results show that the calculation errors are generally below 0.2%, that is correct in most cases.

Keywords: three-phase electrical energy meter, voltage-loss failure, voltage substitution, three-phase voltage unbalance, calculation error.

1. Introduction

Three-phase electricity meters have been widely applied as the devices for measuring the electric energy consumed by three-phase loads [1–2]. For an arbitrary phase of a three-phase electricity meter, if the load current is greater than the start current and the voltage is lower than 78% of the rated voltage, it can be referred to as a phase-voltage loss. In the practical operation, the phase-voltage loss is a common failure due to a fault of voltage transformers [3–5]. Once the voltage-loss failure occurs, a considerable amount of electrical energy will not be measured. However, the amount of the electrical energy loss has to be calculated so as to protect the legitimate rights and interest of the electric power supplier. According to the monthly average

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power consumption, the conventional calculation method evaluates the entire electrical energy loss artificially, which is time-consuming and laborious. What is worse, the evaluation result might cause a great dissension between the power suppliers and the consumers over compensation.

Nowadays, with the development of technology, the power grid is becoming more and more automated. As an important part of power grid, the electrical energy metering system also needs to be improved [6, 7]. However, the traditional artificial calculation method does not meet the requirements of automation. Considering the lack of a unified calculation method, research on the automatic calculation methods is necessary.

A calculation method called the power substitution has been first proposed in [8]. Basing on the said calculation method and the power user electric energy data acquiring system, a module has been developed with the function of automatic calculation of the electrical energy loss [9]. When using the calculation method, the three-phase voltages and currents are supposed to be critically symmetrical, which is hard to achieve in the practical operation of a power system, especially in distribution networks. Thus the error of this method may be enormous because of the asymmetries of phase voltages and currents. To overcome the disadvantage, a new calculation method, namely the voltage substitution, has been proposed [10]. In this method, three-phase loads do not need to be symmetrical any more, resulting in a significant reduction of the calculation error. Basing on this idea, smart meters and terminals equipped with the automatic calculation function have been developed and experimentally applied in some provinces of China [11]. Nevertheless, the new method cannot be popularized and applied on a large scale because of the absence of quantitative error analysis which is crucial to directly determine whether power suppliers or consumers can accept the calculation results.

In this paper, the quantitative error analysis of the new calculation method is presented. In the process of analysis, symmetric components and simulation analysis methods are employed. The result of theoretical analysis indicates that the maximum calculation error is about 6%. The lab testing results are consistent with the results of theoretical analysis, whereas the result of practical field testing shows that the calculation error is generally below 0.2%. This work provides the theoretical and practical support for the popularization and application of the new method.

2. Introduction of calculation methods

2.1. Conventional method: power substitution

The conventional calculation method is named the power substitution [8]. The basic idea of the method is to replace the power of the phase whose voltage is lost with the average power of the other two normal phases.

Normally, the value of total three-phase electrical power P_0 can be calculated as:

$$P_0 = P_A + P_B + P_C\,, \tag{1}$$

where P_A, P_B and P_C are the electrical power of phase A, phase B and phase C, respectively. Assuming that the voltage of phase A is lost, the value of total three-phase electrical power P_0' can be calculated as follows:

$$P_0' = \frac{1}{2}(P_B + P_C) + P_B + P_C\,. \tag{2}$$

Obviously, the error of the above method may be enormous because of asymmetries of phase voltages and currents.

2.2. New method: voltage substitution

The new calculation method is named the voltage substitution [10]. The basic idea of the new calculation method is to produce a virtual voltage by rotating a normal phase voltage instead of the lost voltage. Provided that the voltage of phase A is lost, the substitution voltage can be generated through rotating the voltage of phase B by 120 degrees counter-clockwise. The primary principle of the new method is shown in Fig. 1.

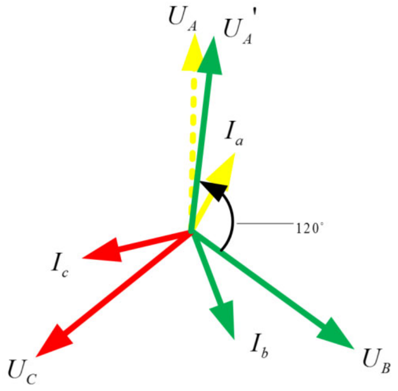

Fig. 1. The principle of the new method.

In Fig. 1 U_A, U_B, U_C, I_A, I_B and I_C are the voltage and current amplitudes of phase A, phase B and phase C, respectively; U_A' is generated by rotating U_B counter-clockwise by 120 degrees.

Formula (1) can be rewritten as:

$$P = U_A I_A \cos\varphi_A + U_B I_B \cos\varphi_B + U_C I_C \cos\varphi_C\,, \tag{3}$$

where φ_A, φ_B, and φ_C are the factor angles of phase A, phase B and phase C, respectively. In the case the voltage of phase A is lost, the value of total three-phase electrical power P' can be calculated as:

$$P' = U_A' I_A \cos\varphi_A' + U_B I_B \cos\varphi_B + U_C I_C \cos\varphi_C\,, \tag{4}$$

where $U_A' = U_B$, and φ_A' is the angle between U_A' and I_A.

In the new calculation method, three-phase currents do not need to be symmetrical any more. Therefore, under the same condition, the error of the new calculation method is much smaller than that of the conventional one.

3. Theoretical error analysis

In general, it is apparent that the exact voltage substitution error cannot be obtained when the voltage-loss failure occurs. Thus, the error analysis of the new calculation method is difficult to be performed. In this paper, the error is tried to be analysed under the restricting condition of three-phase voltage unbalance.

3.1. Unbalance factor of three-phase voltage

3.1.1. Symmetrical components

The three-phase voltages can be decomposed into symmetrical three-phase voltages by the symmetrical components' method, as shown in (5):

$$\begin{cases} \dot{U}_A = \dot{U}_{A(1)} + \dot{U}_{A(2)} + \dot{U}_{A(0)} \\ \dot{U}_B = \dot{U}_{B(1)} + \dot{U}_{B(2)} + \dot{U}_{B(0)} \\ \dot{U}_C = \dot{U}_{C(1)} + \dot{U}_{C(2)} + \dot{U}_{C(0)} \end{cases}, \tag{5}$$

where $\dot{U}_{A(0)}$, $\dot{U}_{B(0)}$, $\dot{U}_{C(0)}$, $\dot{U}_{A(1)}$, $\dot{U}_{B(1)}$, $\dot{U}_{C(1)}$, $\dot{U}_{A(2)}$, $\dot{U}_{B(2)}$, and $\dot{U}_{C(2)}$ are the three-phase zero sequence voltage vectors, positive sequence voltage vectors and negative sequence voltage vectors, respectively.

The sequence voltages are:

$$\begin{cases} \dot{U}_{A(0)} = \dot{U}_{B(0)} = \dot{U}_{C(0)} = \dfrac{1}{3}\left(\dot{U}_A + \dot{U}_B + \dot{U}_C\right) \\ \dot{U}_{A(1)} = \alpha\dot{U}_{B(1)} = \alpha^2\dot{U}_{C(1)} = \dfrac{1}{3}\left(\dot{U}_A + \alpha\dot{U}_B + \alpha^2\dot{U}_C\right) \\ \dot{U}_{A(2)} = \alpha^2\dot{U}_{B(2)} = \alpha\dot{U}_{C(2)} = \dfrac{1}{3}\left(\dot{U}_A + \alpha^2\dot{U}_B + \alpha\dot{U}_C\right) \end{cases}, \tag{6}$$

where α is defined as the counter-clockwise rotation factor of 120 degrees. The complex exponent form of α is:

$$\alpha = e^{j120^\circ}. \tag{7}$$

3.1.2. Unbalance factors

The three-phase voltage unbalance factor has been defined in relevant standards such as the China national standard and the IEC standard [12, 13]. The value of unbalance factor can be determined by:

$$\begin{cases} \varepsilon_{\mathrm{U2}} = \dfrac{V_2}{V_1} \\ \varepsilon_{\mathrm{U0}} = \dfrac{V_0}{V_1} \end{cases}, \tag{8}$$

where $\varepsilon_{\mathrm{U2}}$ and $\varepsilon_{\mathrm{U0}}$ are respectively the unbalance factors of the negative and zero sequence voltages. V_0, V_1, and V_2 are the amplitude values of zero, positive and negative sequence voltages, respectively, and they are determined by:

$$\begin{cases} V_0 = \left|\dfrac{1}{3}\left(\dot{U}_A + \dot{U}_B + \dot{U}_C\right)\right| \\ V_1 = \left|\dfrac{1}{3}\left(\dot{U}_A + \alpha\dot{U}_B + \alpha^2\dot{U}_C\right)\right| \\ V_2 = \left|\dfrac{1}{3}\left(\dot{U}_A + \alpha^2\dot{U}_B + \alpha\dot{U}_C\right)\right| \end{cases}. \tag{9}$$

For a better explanation, Fig. 1 is redrawn as below.

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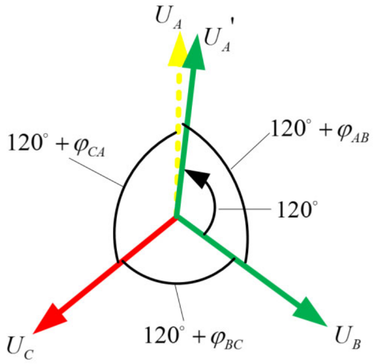

Fig. 2. Implementation of the new method.

In Fig. 2, the angle between phase A and phase B voltages is $120^\circ + \varphi_{AB}$; the angle between phase B and phase C voltages is $120^\circ + \varphi_{BC}$; the angle between phase C and phase A voltages is $120^\circ + \varphi_{CA}$. Following the definition of α, a set of rotation factors λ_a, λ_b, and λ_c are respectively defined as the counter-clockwise rotation factors of rotating by φ_{AB}, φ_{BC}, and φ_{CA}degrees. Then, the following equations are derived:

$$\begin{cases} \lambda_a = e^{j\varphi_{AB}} \\ \lambda_b = e^{j\varphi_{BC}} \\ \lambda_c = e^{j\varphi_{CA}} \end{cases} . \tag{10}$$

Taking the phase A voltage as reference, if it is defined that $U_C = yU_A$, $U_B = xU_A$, the three-phase voltage unbalance factor calculation formula can be ultimately transformed into the following complex exponent form by substituting (7), (9) and (10) into (8).

$$\begin{cases} \varepsilon_{\text{U2}} = \dfrac{|e^{j\varphi_{AB}} + xe^{j120^\circ} + ye^{j(240^\circ + \varphi_{CA})}|}{|e^{j\varphi_{AB}} + x + ye^{j(\varphi_{AB} + \varphi_{CA})}|} \\ \varepsilon_{\text{U0}} = \dfrac{|e^{j\varphi_{AB}} + xe^{j240^\circ} + ye^{j(120^\circ + \varphi_{AB} + \varphi_{CA})}|}{|e^{j\varphi_{AB}} + x + ye^{j(\varphi_{AB} + \varphi_{CA})}|} \end{cases} . \tag{11}$$

3.2. Objective function and restricting conditions

3.2.1. Objective function

The error of the new calculation method is related only to phase A. Comparing (3) with (4), the relative error of phase A, denoted by δ_{P_A}, is:

$$\delta_{P_A} = \frac{U_A' I_A \cos \varphi_A' - U_A I_A \cos \varphi_A}{U_A I_A \cos \varphi_A}, \tag{12}$$

where $\varphi_A' = \varphi_A - \varphi_{AB}$. Substituting $U_A' = U_B$ and $U_B = xU_A$ into (12), δ_{P_A} is determined by:

$$\delta_{P_A} = \left(\frac{\cos \varphi_{AB}}{\cos \varphi_A} + \tan \varphi_A \sin \varphi_{AB} \right) x - 1. \tag{13}$$

The emphasis of this paper is put on the analysis of δ_{P_A}, especially the maximum value of δ_{P_A} under the condition that the power grid is in the normal operation state.

3.2.2. Restricting conditions

When the power grid is in the normal operation state, the voltage unbalance factor should be less than a certain value. According to the relevant standards, the voltage unbalance factor at a common connection point of power system should be less than 2%. It should be noticed that only the unbalance factor of the negative sequence voltage is specified in existing standards.

However, since the zero sequence voltage may cause damage to electrical equipment, the zero sequence voltage is to be suppressed by some methods [14–16]. The unbalance factor of zero sequence voltage should also be less than 2% in practical operation [17, 18]. Therefore, the restricting condition is:

$$\begin{cases} \varepsilon_{\mathrm{U2}} \le 0.02 \\ \varepsilon_{\mathrm{U0}} \le 0.02 \end{cases} . \tag{14}$$

3.3. Solution

It can be seen from (13) that the value of δ_{P_A} is related to φ_{AB}, φ_A and x. Finding the maximum value of δ_{P_A} is a restricting optimization problem, but it is difficult to be solved by most optimization methods. As a result, the grid traversal method and MATLAB tool are alternatives to solve the problem.

3.3.1. Finding possible combinations of φ_{AB} and x

In order to obtain all solutions that conform to the restricting condition, the ranges of φ_{AB}, φ_{BC}, x, and y are initially set as below:

$$\begin{cases} -15^\circ \le \varphi_{AB} \le 15^\circ \\ -15^\circ \le \varphi_{BC} \le 15^\circ \\ 0.5 \le x \le 1.5 \\ 0.5 \le y \le 1.5 \end{cases} . \tag{15}$$

Calculation steps of φ_{AB}, φ_{BC}, x, and y are set to 0.2, 0.2, 0.01 and 0.01 degrees, respectively. Substituting the initial ranges into the restricting condition as well as using the grid traversal method and MATLAB tool, all the solutions can be obtained. Possible combinations of φ_{AB} and x are shown in Fig. 3.

In Fig. 3, there are 424 combinations of φ_{AB} and x. φ_{AB} ranges from −3.8 degree to 3.8 degree, and x ranges from 0.94 to 1.07.

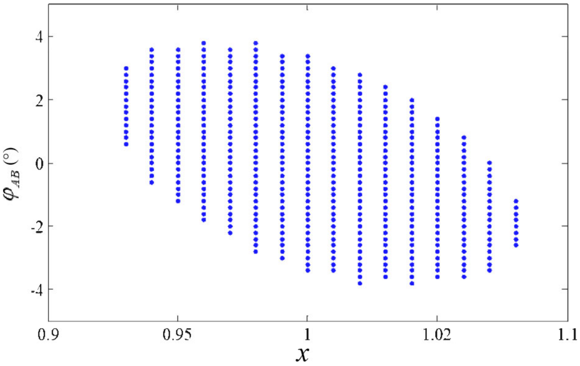

Fig. 3. Possible combinations of φ_{AB} and x.

3.3.2. Obtaining value of δ_{P_A}

In this paper, the application scenario includes substations of 110 kV and above. Considering that the power factor ranges from 0.9 to 0.99 and all of the 424 combinations of φ_{AB} and x are submitted into the objective function, δ_{P_A} can be calculated as shown in Fig. 4.

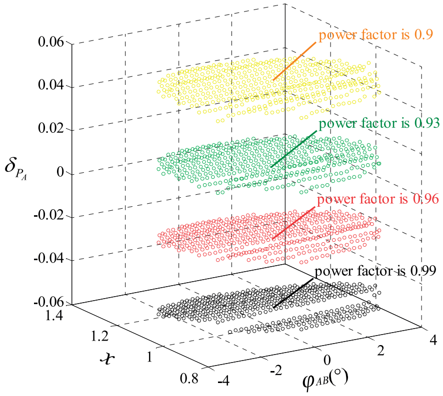

Fig. 4. Values of δ_{P_A} at different power factors.

As it is shown in Fig. 4:

- the relative theoretical errors are below 6% under the condition that the power system is in the normal operation state;
- as the power factor increases, the calculation error will vary from positive to negative.

4. Experimental test

4.1. Development of three-phase electrical energy metering equipment

In order to test the error of the new calculation method, the three-phase electrical energy metering equipment has been developed referring to typical applications [19, 20]. A block diagram of the designed metering equipment is shown below.

In Fig. 5, the designed three-phase electrical energy metering equipment is composed of several functional modules. Because the most universal design details such as a real-time clock, LCD display *et al.* can refer to the typical design of a three-phase electricity meter, this paper mainly introduces the key points. The signal transducers consist of resistor networks, which

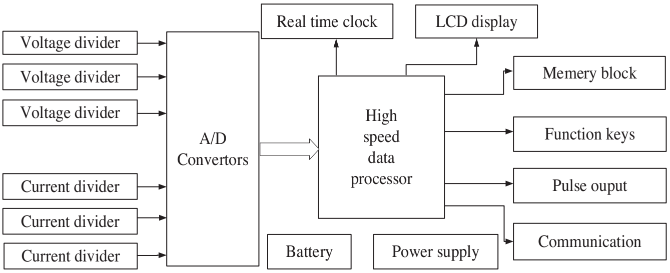

Fig. 5. A block diagram of the designed metering equipment.

convert (0–57.7) V or (0–5) A to (0–2.5) V. Since a special metering integrated circuit such as ADE7758 produced by Analog Devices is not flexible enough, an *analogue-to-digital convertor* (ADC) and a high-speed data processor are applied in the design. The ADS1278 employed in the design is a 24-bit, delta-sigma analogue-to-digital converter with data rates up to 144 k samples per second, enabling simultaneous sampling of eight channels. The STM32F407 microcontroller employed in the design is able to process the voltage and current sampling data easily and flexibly due to the DSP instructions and the floating point unit.

The software design focuses on two points, one is the electrical energy calculation method, and the other is the voltage substitution strategy. To measure the electrical energy accurately, a weighted digital signal processing algorithm proposed by W. J. Wu *et al.* is used in the design [21]. Compared with traditional algorithms, this algorithm has favourable effects on reducing the impact of frequency fluctuations on the power measurement error. The voltage substitution strategy is developed, and a flowchart of the designed metering equipment is shown above.

In Fig. 6, the designed metering equipment first measures voltage and current, and then detects a voltage-loss fault once it occurs. In the normal conditions, the designed metering equipment calculates the electrical energy normally. But once a voltage-loss failure occurs, the lost phase voltage will be replaced with a normal phase voltage before calculating the electrical energy. The regulation of voltage substitution is specified as follows: a) if the phase A voltage is lost, replace it with the phase B voltage; b) if the phase B voltage is lost, replace it with the phase C voltage; and c) if the phase C voltage is lost, replace it with the phase A voltage.

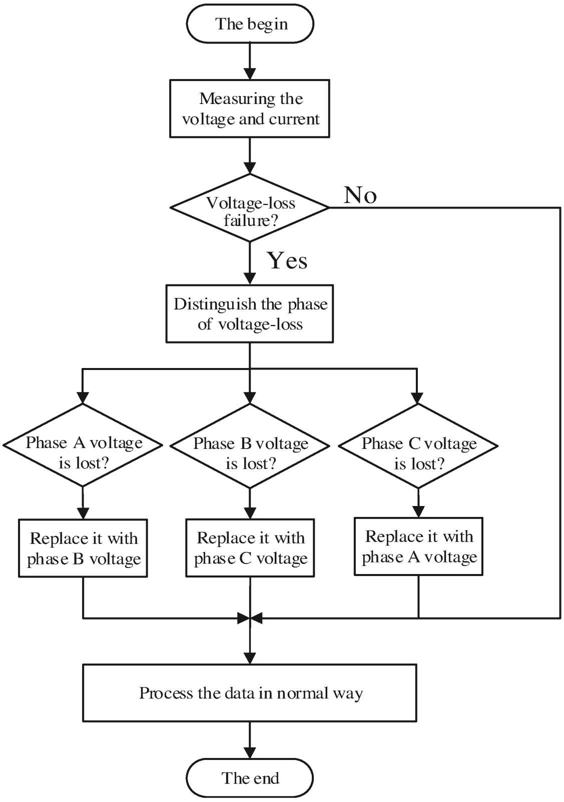

Fig. 6. A flowchart of the designed metering equipment.

4.2. Lab testing and analysis of results

The lab testing system mainly consists of a three-phase power source and a standard electricity meter. A block diagram of the lab testing system is shown in Fig. 7.

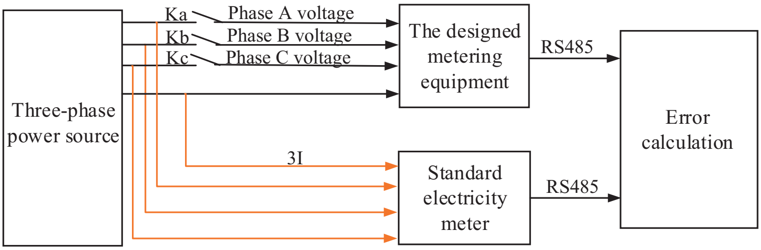

Fig. 7. A block diagram of the lab testing system.

In Fig. 7, the switches Ka, Kb and Kc are used to select the phase whose voltage is lost. In this paper, it is always assumed that the phase A voltage is lost. To verify the correctness of the theoretical analysis, the test parameters are chosen optionally as follows: a) the rated voltage is 220 V; b) the rated current is 5 A; c) $U_B = U_C = 0.98U_A = 220$ V; d) $I_B = I_C = 0.95I_A = 5$ A; e) $\cos\varphi_A = 1.0$, $\cos\varphi_B = 0.98$, $\cos\varphi_C = 0.96$; f) $\varphi_{AB} = \varphi_{BC} = 2°$. Under the set conditions, the negative and zero sequence voltage unbalance factors are respectively 1.8% and 1.3%. The test period is set to 30 minutes.

Assuming that the electrical energy of phase A measured by the designed metering device and the standard electricity meter are respectively W_{A1} and W_{A0} in 30 minutes, the measurement error δ_{W_A} can be calculated by:

$$\delta_{W_A} = \frac{W_{A1} - W_{A0}}{W_{A0}} \times 100\%. \tag{16}$$

The lab testing results are shown in Table 1.

Table 1. Results of lab testing and theoretical analysis.

The new method		**The conventional method**	
Testing error	Theoretical error	Testing error	Theoretical error
−1.98%	−2.06%	−9.72%	−9.64%

As shown by the testing, the results of theoretical analysis are consistent with those of the actual test, and the error of the new method is much smaller than that of the conventional calculation method.

4.3. Field testing and results

Further, to verify the error of the new calculation method in a practical application, a field comparison test is designed. In an intelligent substation, since the data are shared by the switches, the field comparison test is easier to be implemented by employing a digital input electricity meter [22, 23]. The practical application test has been carried out in a 220 kV intelligent substation for a month. A diagram of the field testing is shown in Fig. 8.

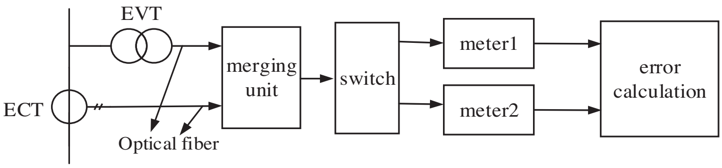

Fig. 8. A diagram of the field testing.

In Fig. 8, meter1 and meter2 receive the same voltage and current sampling values from the switch. The calculation program of meter2 has been modified to make the digital electrical energy meter2 ignore the sampling values of phase A voltage so as to simulate the voltage-loss failure of phase A. The field testing results are shown in Fig. 9.

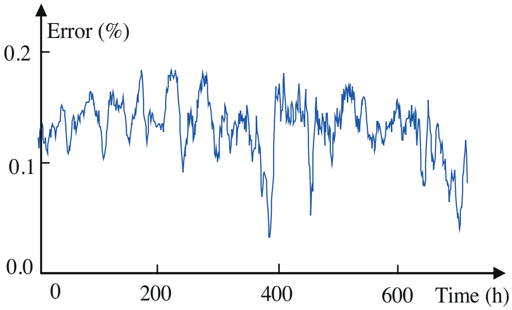

Fig. 9. Results of the field testing.

In Fig. 9, the period of error test is 1 hour, and only phase A is considered. It shows that the relative errors are generally below 0.2%. To verify the validation in most cases, a set of data measured in another substation is shown in Table 2.

Table 2. Results measured in a substation.

	Maximum value	**Minimum value**	**Average value**
Three-phase voltage unbalance	0.11%	0.02%	0.06%
Three-phase current unbalance	8.2%	2.3%	4.6%
Power factor of phase A	0.965	0.953	0.958

In Table 2, the voltage unbalance factor is very small, and the power factor is around 0.96. Actually, the voltage unbalance and power factors most closely are at this level in most substations. Therefore, in most cases the calculation error is below 0.2%, which is in conformance with the field testing results. Furthermore, since the three-phase current unbalance factor is around 4.6%, the power substitution error is obviously larger than the voltage substitution error.

5. Conclusions

In the practical operation, when a voltage-loss failure occurs, a considerable amount of electrical energy will not be measured, therefore an appropriate method is required to protect the interest of the power supplier. A new calculation method, the voltage substitution, has been proposed and experimentally applied in some places. However, a detailed error analysis of this method so far did not exist. In this paper, the theoretical analysis and experimental testing have been carried out. The following conclusions can be reached:

1. Compared with the conventional calculation method, the new method intuitively performs better since it is able to reduce the error caused by the unbalanced three-phase current.
2. In addition to the voltage unbalance factor, the error is also related to the power factor. As the power factor increases, the calculation error will obviously vary from positive to negative. When analysing the calculation error, attention should be paid to the three-phase voltage unbalance factor as well as the power factor.
3. For the application in substations of 110 kV and above, since the monthly average power factor is generally required to be greater than 0.9, the theoretical calculation error is below 6% under the condition that the power system is in the normal operation state. Additionally, the lab testing results are consistent with the aforesaid theoretical analysis ones.
4. The results of a long-term field testing in a substation indicate that the calculation error is below 0.2%. A set of data measured in another substation show that the voltage unbalance factor is very small and the power factor is around 0.96, so it is believed that this conclusion is correct in most cases.

Basing on the research presented in this paper, if the three-phase unbalance factor and the power factor are available, the electrical energy calculation error can be evaluated quantitatively. Although the calculation error is not definitely below 0.2% in all practical applications, it is always correct in most cases. Therefore, it is believed that the new method can be extended to the large-scale applications in substations.

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