IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received October 10, 2018, accepted October 28, 2018, date of publication November 9, 2018, date of current version December 19, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2880309

Research on the Algorithm and Test of Transmission Line Voltage Measurement Based on Electric Field Integral Method

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This work was supported by the National Natural Science Foundations of China under Grant 51677009.

ABSTRACT The non-contact voltage measurement of the transmission line is of importance to the operation and intellectualization of the electrical power system. Presently, the non-contact measurement of the transmission line voltage based on the field sensor has been widely studied. The methods of obtaining the voltage by solving the electric field inverse problem have difficulties in solution and calibration. This problem can be effectively solved by adopting the numerical integral algorithm of electric field. In this paper, the voltage measurement by using the Chebyshev piecewise integral algorithm, Gauss-Legendre integral algorithm and Gauss-Legendre improved algorithm was analyzed and the integral intervals of the algorithms were optimized. The multi-index comprehensive evaluation model was established for evaluating the measurement effect, adopting improved subjective weighting method. The finite element simulation model of the 10-kV transmission line was built with the Maxwell software platform to carry out the simulation test. The measurement effects of different voltage measurement methods were compared and it was proposed to apply the Chebyshev piecewise integral algorithm to the voltage measurement system of the transmission line. Finally, the transmission line voltage measurement test platform based on D-dot sensor was built and the measurement safety and accuracy of the Chebyshev piecewise integral algorithm was verified.

INDEX TERMS Algorithms, electric field integral, Gauss-Legendre, non-contact, piecewise Chebyshev, transmission lines, voltage measurement.

I. INTRODUCTION

The effective and accurate measurement of the transmission line voltage is of great significance to ensuring the safe operation of the power grid. Presently, traditional voltage transformers are becoming more and more difficult to adapt to the requirements of modern power grid development and the non-contact voltage measurement method based on field sensors [1]–[4] has become a research hotspot, which has been carried out mainly in two directions.

Firstly, the electric field sensor measures the electric field near the transmission line to be measured through a certain way of arrangement, and the transmission line voltage is obtained by the inverse problem of electric field. Inverse problem solving has generalized cross-validation method (GCV) [5] , third-order convergence iterative method [6], quasi-Newton method and two-parameter algorithm, statistical approximation model (such as radial basis function model) [7]–[10], stochastic class optimization algorithms (such as simulated annealing algorithm) and deterministic class search algorithms (such as gradient class method) [11]. Besides calculation complexity, the method often has no solution, multiple solutions or wrong solutions, resulting in inaccurate measurement results [12]–[14].

Secondly, according to the theorem of electric field integral, the electric field sensor measures the electric field intensities of several nodes, and the transmission line voltage is calculated based on the numerical integral algorithm. At present, the method has many disadvantages, such as inaccurate measurement results, failure to realize non-contact measurement and sensor breakdown. In overseas, Nicolas A.F. Jaeger has designed the optical voltage transformer based on the distributed sensing head, and realized the measurement of line voltage by the numerical integral algorithm. However, it did not realize the non-contact measurement actually [15]. Patrick P. Chavez et al. tested the designed optical voltage sensor without considering the complex transmission line environment and the insulation situation. The measurement accuracy met the requirements of IEC Standard Level 0.2 [16]. Literature [17] applied the Gauss-Legendre integral algorithm and calculated the voltage of the transmission line through calculation. Literature [18] divided the integral path into at least two sub-integral intervals, calculated the integral of each of them by using the Gauss Legendre integral algorithm, and summed up them to obtain the voltage of the transmission line. However, it did not propose the reason of the integral interval division and its optimization method.

The voltage measure method of the transmission line based on the electric field integral algorithm is discussed, and the voltage measurement methods of the transmission line based on the Chebyshev piecewise integral algorithm, Gauss-Legendre integral algorithm, Gauss-Legendre improved algorithm are analyzed. The simulation measurement results of three algorithms were compared. The measurement safety and accuracy was taken into account to obtain the appropriate electric field integral algorithm. The D-dot electric field sensor [19]–[25], which has high precision, simple structure and easiness to be distributed in large area, was selected to set up the transmission line voltage measurement system and then verify the voltage measurement effect.

II. TRANSMISSION LINE VOLTAGE CALCULATION MODEL

When measuring the phase voltage of a three-phase transmission line, factors such as the positional relationship of the transmission line and the measurement environment affect the three-phase synthetic electric field in the calculation area, but the potential of the transmission line is not affected by the above factors. The phase line voltage can be obtained by electric field integration.

The theorem of electric field integral to measure voltage was to take the field strength between the transmission line and the ground as the calculation area. According to the integral relation between the electric field strength and the transmission line voltage, the phase voltage of the transmission line to be measured can be calculated by the method of numerical integral.

The transmission line was the power frequency voltage, and the ground potential was used as the reference potential. A electric field region was formed between the transmission line and the ground, which can be regarded as a quasi-static field. The electric field strength vector $\vec{E}$ conformed to Maxwell's equation:

$$\nabla \times \vec{E} \approx 0 \tag{1}$$

The above formula showed that the electric field below the transmission line can be regarded conservative. Due to the conservative nature of the electric field, the potential difference was independent of the integral path. As long as the projection of the electric field strength in the direction of the integral path was accurately measured, the integral result was necessarily the potential of the transmission line. For the sake of convenience, Integral path perpendicular to the ground (0 potential reference) was constructed in the calculation area, and the integral formula is as follows:

$$V_d = \int_0^d E(x)dx \tag{2}$$

Where V_d was the voltage of the transmission line to be measured, d was the vertical distance from the transmission line to the ground, and $E(x)$ was the component of the electric field intensity vector at the distance x from the ground in the integral path (the direction pointing to the ground is positive).

Since $E(x)$ was not an explicit function, this definite integral cannot be calculated using the basic theorem of calculus Newton-Leibnitz formula. With numerical integration method, the definite integral was constructed by using the function values of several discrete points. The approximate formula was as follows:

$$V_d = \int_0^d E(x)dx \approx \sum_{j=0}^{n} A_j E(x_j) \tag{3}$$

where A_j was the first quadrature coefficient; $E(x_j)$ was the intensity of the electric field along the plumb direction of the discrete integral point x_j on the integral path; m was the total number of integral points, namely, the total number of used electric field sensors.

A. VOLTAGE MEASUREMENT ALGORITHM BASED ON THE CHEBYSHEV PIECEWISE INTEGRAL ALGORITHM

Three kinds of typical structural transmission line simulation models were established by Maxwell software, which were horizontal arrangement, regular triangle arrangement, and double-circuit arrangement. Fig. 1 presented the spatial distribution curve of the electric field on the integral path of A phase line of horizontally arranged transmission lines under 10kV voltage.

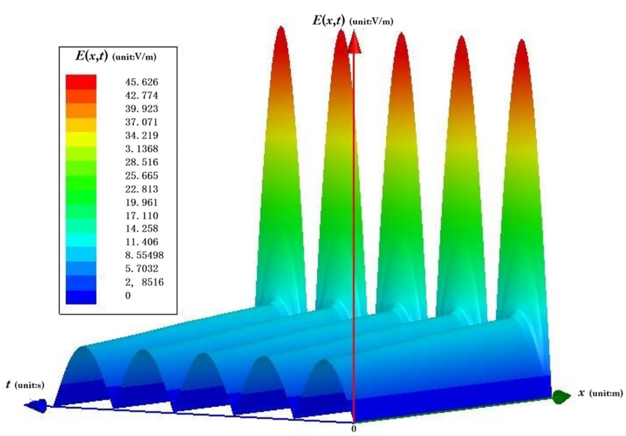

FIGURE 1. Electric field distribution curve below the transmission line.

The simulation results represent the similar distribution characteristics that the electric field distribution near the side of the transmission line showed a fast attenuation state. In the part with slow change of the electric field, the electric field values in different positions of the integral path had little difference, and the information contained was little, so the excessive distribution of integral nodes in this interval would cause the waste of resources. Therefore, the integral interval was divided into the non-mutation integral interval and mutation integral interval of electric field, as shown in Fig. 2. The integral results of the electric field were V_1 and V_2, so the voltage calculation model of the transmission line voltage was:

$$V_d = V_1 + V_2 \tag{4}$$

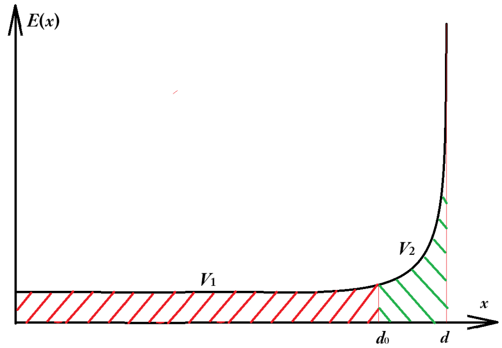

FIGURE 2. Integral interval segmentation diagram of the electric field.

1) VOLTAGE CALCULATION MODEL OF THE NON-MUTATION INTEGRAL INTERVAL OF THE ELECTRIC FIELD

It was assumed that the integral interval segmentation point was determined to be at d_0 from the ground, and the transmission line to be measured was d from the ground. The non-mutation interval of the electric field was $[0, d_0]$.

In the non-mutation interval of electric field, one integral node was set up. The electric field integral was calculated by the rectangle formula. The electric field sensor was set up at the place $d_0/2$ away from the ground. The electric field integral formula of the non-mutation interval of the electric field was as follows:

$$V_1 = \int_0^{d_0} E(x)dx \approx A_0 E(x_0) \approx d_0 E(d_0/2) \tag{5}$$

2) VOLTAGE CALCULATION MODEL OF THE MUTATION INTEGRAL INTERVAL OF THE ELECTRIC FIELD

Chebyshev integral has been widely used in engineering technology calculation, characterized by fast calculation and high accuracy. Therefore, Chebyshev algorithm was used to calculate the integral value of the mutation section of electric field.

There are n integral nodes were set up on the mutation integral interval $[d_0, d]$ of the electric field. The integral formula of the electric field in this interval was:

$$V_2 = \int_{d_0}^{d} E(x)dx \approx \sum_{j=1}^{n} A_j E(x_j) \tag{6}$$

It was substituted in the normalization formula $t = \frac{2}{d-d_0}(x - \frac{d+d_0}{2})$ to normalize the integral interval $[d_0, d]$ of the integral formula, as shown in Fig. 3.

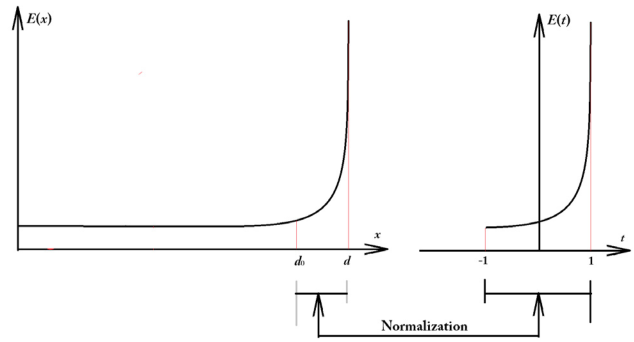

FIGURE 3. Integral interval normalization diagram of the integral interval in the mutation section of the electric field.

The function $E(x)$ of x was transformed into a function $E(t)$ of the temporary variable t. Formula (3) was rewritten as:

$$V_2 = \frac{d-d_0}{2} \int_{-1}^{1} E(t)dt \tag{7}$$

The Chebyshev algorithm was used to calculate the $\int_{-1}^{1} E(t)\,dt$ part of formula (7). The integral formula was as follows:

$$\int_{-1}^{1} E(t)dt \approx B_n \sum_{j=1}^{n} E(t_j) \tag{8}$$

where $E(t)$ was the function of the temporary variable t for the quadrature coefficient of the electric field intensity; B_n was the second quadrature coefficient of the Chebyshev algorithm.

Regard $E(t)$ as the polynomial not higher than n, the second quadrature coefficient B_j and integral points t_j meeting the following constraints:

$$B_n = 2/n \tag{9}$$

$$\sum_1^n t_j = 0 \quad \sum_1^n t_j^2 = \frac{n}{3} \quad \sum_1^n t_j^3 = 0 \quad \sum_1^n t_j^4 = \frac{n}{3} \cdots \tag{10}$$

The first quadrature coefficient of the mutation interval of the electric field A_j was obtained according to the definition:

$$A_j = \frac{d-d_0}{2} B_n = \frac{d-d_0}{n}, \quad j = 1, 2, 3, \ldots n \tag{11}$$

The integral points $t_1, t_2, t_3, \ldots t_n$ were obtained according to formula (10). When the number of integral points was 1 to 6, the position of Chebyshev integral points was shown in Table 1.

TABLE 1. Integral point location of the mutation interval of the electric field by the chebyshev piecewise integral algorithm.

Number of Integral Points n	t_1	t_2	t_3	t_4	t_5
1	0				
2	-0.577	0.577			
3	-0.707	0	0.707		
4	-0.795	-0.188	0.188	0.795	
5	-0.832	-0.375	0	0.375	0.832

The integral interval is [-1, 1].

According to the transformation relation, the integral point t_j was transformed into the electric field measurement position $x_j(j = 1, 2, 3, .., n)$, which is the distance from the electric field measurement point to the ground. The electric field integral of the mutation section V_2 was calculated according to the formula (6).

$$V_2 \approx \sum_{j=1}^{n} A_j E(x_j) \tag{12}$$

The sum of it and the electric field integral V_1 of the non-mutation integral interval was the voltage of the transmission line.

According to the electric field distribution simulation result of horizontally arranged transmission line with different voltage levels obtained, the electric field integration results of different integration intervals were obtained by Matlab programming. The voltage measurement accuracy reached a high value when the integral interval segmentation point was around $0.7d$ (under the premise of sensors is not broken down).

B. VOLTAGE MEASUREMENT ALGORITHM BASED ON THE GAUSS-LEGENDRE INTEGRAL ALGORITHM

The calculation formula of transmission line voltage based on Gauss-Legendre integral algorithm [26], [27] was as follows:

$$V_d = \int_0^d E(x)dx \approx \sum_{j=0}^{n} A_j E(x_j) \tag{3}$$

The formula $t = \frac{2}{d}(x - \frac{d}{2})$ was substituted into formula (3) to normalize the integral interval, as shown in Fig. 4.

The function $E(x)$ of x was transformed into a function $E(t)$ of t. Therefore, the electric field integral formula (3) was rewritten as:

$$V_d = \frac{d}{2}\int_{-1}^{1} f\left(\frac{d}{2}t + \frac{d}{2}\right)dt = \frac{d}{2}\int_{-1}^{1} f(t)\,dt \tag{13}$$

For the part $\int_{-1}^{1} E(t)\,dt$ in formula (13), the Gauss-Legendre integral algorithm was used for calculation. The formula was as follows:

$$\int_{-1}^{1} E(t)dt \approx \sum_{j=0}^{n} C_j E(t_j) \tag{14}$$

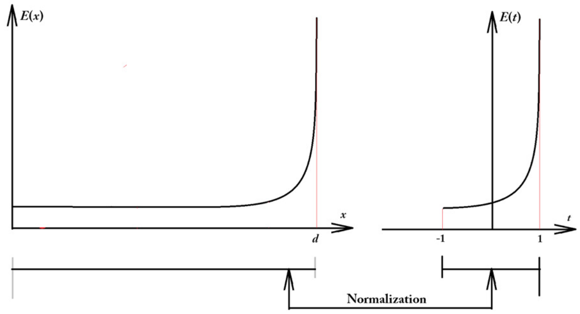

FIGURE 4. Integral interval normalization diagram by the Gauss-Legendre Algorithm.

where C_j was the second quadrature coefficient of the Gauss-Legendre integral algorithm, meeting the following constraint:

$$C_j = \frac{2}{\left(1 - t_j^2\right)\left[\prod_{i=0, i\neq j}^{n}\left(t_j - t_i\right)\right]^2} \tag{15}$$

According to the constraint, the position of the integral point t_j and the second quadrature coefficient C_j of the Gauss-Legendre integral algorithm with the total number of integral points of 2 to 5 were obtained, as shown in Table 2.

TABLE 2. Integral point location of the mutation interval of the electric field by the chebyshev piecewise integral algorithm.

Number of Integral Points m	j	t_j	C_j
2	0	-0.58	1.00
	1	0.58	1.00
3	0	-0.77	0.56
	1	0	0.89
	2	0.77	0.56
4	0	-0.86	0.35
	1	-0.34	0.65
	2	0.34	0.65
	3	0.86	0.35
5	0	-0.91	0.24
	1	-0.54	0.48
	2	0.00	0.57
	3	0.54	0.48
	4	0.91	0.24

The integral interval is [-1, 1].

The measure point of the electric field x_j can be obtained with the temporary variable t_j.

The conversion relationship between the first quadrature coefficient A_j and the second quadrature coefficient C_j in the Gauss-Legendre integral algorithm was as follows:

$$A_j = \frac{d}{2}C_j \tag{16}$$

The voltage of the transmission line was calculated according formula (3):

$$V_d = \int_0^d E(x)dx \approx \sum_{j=0}^{n} A_j E(x_j) \tag{3}$$

C. VOLTAGE MEASUREMENT ALGORITHM BASED ON THE GAUSS-LEGENDRE IMPROVED ALGORITHM

According to the theorem of the Gauss-Legendre integral algorithm proposed by Literature [18] divides the integral path into at least two sub-integral intervals. The Gauss-Legendre algorithm was used to calculate the electric field integral in each sub-integral interval. The values were summed up to obtain the voltage of the transmission line.

Considering that it was not economical to construct too many sub-integral intervals, so three integral interval division points were set up.

The electric-field integral results of three intervals were V_1' V_2' and V_3', respectively. The expression of the voltage of the transmission line was:

$$V_d = V_1' + V_2' + V_3' \tag{17}$$

It was assumed that a total of $m = n' + 2$ electric field sensors were used for the measurement. With the great electric field spatial change rate on the integral path V_3', more integral points were distributed, therefore, n' sensors were used to measure the electric field, $n' > 1$. Each of V_1' and V_2' integral intervals uses one sensor to measure the electric field.

The integral formula of V_1' and V_2' integral intervals was:

$$V_1' = \int_0^{d_0'} E(x)dx \approx d_0' E(d_0'/2) \tag{18}$$

$$V_2' = \int_{d_0'}^{d_0''} E(x)dx \approx \left(d_0'' - d_0'\right) E\left(\frac{d_0' + d_0''}{2}\right) \tag{19}$$

V_3' was substituted into the normalization formula $t = \frac{2}{d-d''}(x - \frac{d+d''}{2})$ to normalize the integral interval, as shown in Fig. 5.

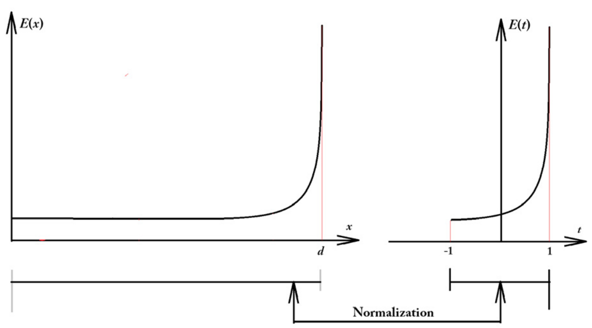

FIGURE 5. Integral interval normalization diagram by the Gauss-Legendre improved algorithm.

The integral formula of V_3' electric field was rewritten as:

$$V_3 = \int_{d_0''}^{d} E(x)dx = \frac{2}{d - d''} \int_{-1}^{1} E(t)\, dt \tag{20}$$

The $\int_{-1}^{1} E(t)\, dt$ part in formula (20) was calculated by the Gauss-Legendre integral algorithm. The formula was as follows:

$$V_3 = \frac{2}{d - d''} \int_{-1}^{1} E(t) dt \approx \frac{2}{d - d''} \sum_{j=0}^{n'-1} C_j E\left(t_j\right) \tag{21}$$

According to Table 2, the position t_j of the integral point of V_3' interval and the second quadrature coefficient C_j were obtained. They were substituted into the formula to obtain V_3'.

The integral results V_1' V_2' and V_3 were summed up to obtain the voltage of the transmission line.

III. MATHEMATICAL METHOD FOR THE VOLTAGE MEASUREMENT EFFECT

A. MULTI-INDEX COMPREHENSIVE EVALUATION MODEL OF VOLTAGE MEASUREMENT EFFECT

In order to quantitatively describe the measurement effect of the above three electric field integral algorithms, an evaluation model was established to determine the electric field integral algorithm with better measurement effect.

It was relatively easy to evaluate the single measurement of the voltage measurement effect, and it was difficult to evaluate the overall measurement effect. Considering the importance of the measurement accuracy and measurement safety for valuing the effect of measurement, the multi-index comprehensive evaluation model [28], [29] was established as follows:

$$R = 1 - s_1 L_1 - s_2 L_2 \tag{22}$$

where R was the voltage measurement effect; L_1 was the offset degree of voltage measurement; L_2 was the risk degree of voltage measurement; s_1 was the weight coefficient of the offset degree of voltage measurement; s_2 was the weight coefficient of the risk degree of voltage measurement.

The offset degree of voltage measurement was expressed by the relative error of voltage measurement:

$$L_1 = \left|V_d - V_{d,real}\right| / V_{d,real} \tag{23}$$

where $V_{d,real}$ was the actual voltage of the transmission line; V_d was the measured voltage of the transmission line.

The safety of the voltage measurement was related to the minimum distance between the measure point and the surface of the transmission line. The smaller the distance was, the greater the probability of the sensor being broken down was, and the worse the measurement security was. The risk degree of voltage measurement was defined as follows:

$$L_2 = d_{\max}/d \tag{24}$$

where $d_{\max}$ was the farthest distance from the measuring point of the electric field to the ground; d was the distance from the transmission line to be measured to the ground.

B. WEIGHT COEFFICIENT DETERMINATION OF VOLTAGE MEASUREMENT EFFECT

An important step in the multi-indicator comprehensive evaluation of the voltage measurement effect was the determination of weight coefficients, the offset degree of voltage measurement and the risk degree of voltage measurement.

There were many methods for determining the weight coefficient, which can be divided into three categories: subjective weighting method [30], objective weighting method [31], and combined weighting method. In this case, the offset degree of voltage measurement and the risk degree of voltage measurement were determined using a subjective weighting method.

According to the decision maker's subjective assessment of the measurement accuracy and safety of the voltage measurement application environment and its own knowledge and experience, the offset degree of voltage measurement and the risk degree of voltage measurement weight coefficient can be reasonably determined and be flexibly changed as the situation changes.

Since the general subjective weighting method had the disadvantage of being subjective, it usually required multiple decision makers to participate in the determination of weights, so the improved subjective weighting method was adopted.

The improved subjective weighting method was based on the subjective weighting method. Firstly, each decision maker made a judgment on the weight coefficient, and the decision level weights of each decision maker were assigned using the entropy value theorem [32], [33]. The weights given by the decision makers were multiplied by the decision maker's decision level weights, and the arithmetic mean was obtained, and the combined weights of the offset degree of voltage measurement and the risk degree of voltage measurement were obtained as the final weight coefficients.

The formula for calculating the weight of the offset degree of voltage measurement s_1 was as follows:

$$s_1 = \frac{\sum_{i=1}^{q} \left(s_{1,i} \cdot w_{1,i}\right)}{q} \tag{25}$$

where q was the total number of decision makers participating in the determination of the offset degree of voltage measurement and the risk degree of voltage measurement, and $s_{1,i}$ was the i-th decision maker's weight determination for the offset degree of voltage measurement, and $w_{1,i}$ was the decision level weight of the decision maker's evaluation of the voltage measurement offset.

Similarly, the composite weight of the risk degree of voltage measurement s_2 is:

$$s_2 = \frac{\sum_{i=1}^{q} \left(s_{2,i} \cdot w_{2,i}\right)}{q} \tag{26}$$

where $s_{2,i}$ was the i-th decision maker's weight determination for the risk degree of voltage measurement, and $w_{2,i}$ was the decision level weight of the decision maker's evaluation of the voltage measurement risk.

The combined weight of the offset degree and the risk degree of voltage measurement was used as the final weight coefficients of the decision, which were used to indicate the importance of measurement accuracy and safety. They were determined according to the actual voltage measurement application requirements.

IV. SIMULATION TEST OF VOLTAGE MEASUREMENT BY DIFFERENT ELECTRIC FIELD INTEGRAL ALGORITHMS

In order to compare the voltage measurement methods based on the theorem of electric field integral under different weight coefficients of voltage measurement offset degree and risk degree, the simulation measurement test of the voltage of the transmission line was carry out, Chebyshev piecewise integral algorithm, Gauss-Legendre integral algorithm and Gauss-Legendre improved algorithm were tested respectively.

To compare the measurement effect of three kinds of voltage measurement methods, the A phase voltage peak measurement was carried out. Maxwell electromagnetic field simulation software was used to obtain the electric field distribution data on the integral path. The parameters of the 10kV transmission line were shown in Table 3.

TABLE 3. Parameters of the simulation model of 10kV transmission line.

Parameter	Content
Effective Value of Phase Voltage U/kV	10
Material	Copper
Radius R/mm	5.0
Length L/m	2.0
Distance from the Ground d/m	1.5
Interphase Distance D/m	>0.6

The sag problem of the wire was ignored. Its local straight line was used to simulate the situation of actual transmission lime. The three-dimensional finite element model of the three-phase transmission in the way of horizontal arrangement was established by using Maxwell software, as shown in Fig. 6.

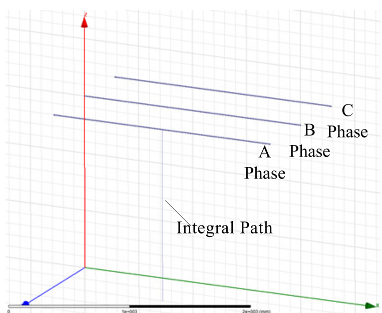

FIGURE 6. Simulation model of the test transmission line.

The duration of the simulation was set to 20 ms, and the time step was set to 0.25 ms. The plumb electric field on the integral path were extracted by the field calculator within Maxwell software. It is assumed that there were no special requirements for measurement safety or measurement accuracy.

The integration interval was determined as 0.7d, when the measurement simulation test was carried out by using the Chebyshev piecewise integral algorithm. As for the Gauss-Legendre improved algorithm, literature [18] does not propose the interval division standard, the first and second segmentation points of the intervals were set to be at $d_0'' = 7d/8$ and $d_0' = d/2$ from the ground in the test, respectively.

Combined with the mathematical model of voltage measurement offset degree and voltage measurement risk, the simulation results were shown in Table 4 below.

TABLE 4. Comparison of the simulation results of voltage measurement.

Voltage Measurement Method	Number of Integral Points	Deviation Degree of Voltage Measurement	Risk Degree of Voltage Measurement
Piecewise Chebyshev Integral Algorithm	2	0.6441	0.85
	3	0.5968	0.9366
	4	0.0299	0.9561
	5	0.0473	0.9692
Gauss Legendre Integral Algorithm	2	0.5428	0.7900
	3	0.46883	0.8850
	4	0.5411	0.9300
	5	0.1068	0.9550
Gauss Legendre Integral Improved Algorithm	3	0.6256	0.9375
	4	0.0745	0.9738
	5	0.1348	0.9856

TABLE 5. Voltage test results measured by the chebyshev piecewise integral algorithm.

Peak Voltage of Transmission Line V_{real}(kV)	Measured Peak Voltage V_{test}(kV)	Voltage Measurement Deviation Degree L_1
5.00	4.90	0.02
5.98	5.86	0.0200
7.00	6.91	0.0128
8.02	7.87	0.0187
9.00	8.89	0.0122
10.0	9.87	0.013

The following conclusions could be drawn:

1) When the number of integral points was 2 and 3, the offset degrees of the transmission line voltages measured by three measurement methods were all larger than 50%, therefore, the application value was small.

2) Using the Chebyshev piecewise integral algorithm, a small number of sensors could achieve both high calculation accuracy and high measurement safety.

3) For some measuring environments where measurement safety was particularly important, if the weight coefficient of the voltage measurement risk degree was more than 70 times of that of the voltage measurement offset degree, it was proposed to adopt the Gauss-Legendre integral algorithm based on 5 points.

Similar results were obtained by repeating the voltage measurement tests of the transmission lines of other grades of voltage and other typical structural transmission line.

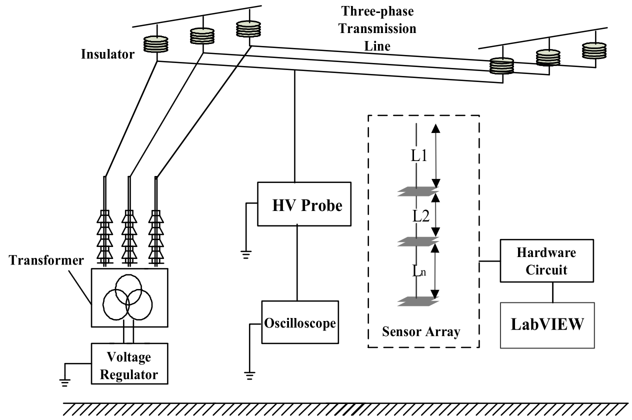

FIGURE 7. Diagram of the voltage measurement system of the test transmission line.

V. VOLTAGE MEASUREMENT TEST BY USING THE Chebyshev piecewise integral ALGORITHM

According to the simulation results of the transmission line voltage measurement, method based on the Chebyshev algorithm the effect can achieve better measurement effort. The 10 kV voltage measurement system was designed and built by adopting the D-dot sensor as the electric field measurement device. The voltage measurement method based on the Chebyshev piecewise integral algorithm was used to measure the line voltage, so as to verify the voltage measurement effect.

The built voltage measurement system of the transmission line was shown in Fig. 7. The platform devices included voltage regulator, transformer, analog transmission conductor, high voltage probe and oscilloscope.

The electric field sensor array was placed below the A phase transmission line through an insulated support rod. The output signal of the sensor was sent to the LabVIEW software of the computer to obtain the integral results, which is the measured voltage of the transmission line, V_{test}.

The peak voltage of the transmission line was obtained by the high voltage probe through the oscilloscope, which is considered to be the actual voltage of the transmission line, V_{real}.

The results of voltage measurement were as follows:

The offset degree of the peak voltage measurement results were less than 0.02, indicating that the voltage measurement method based on the Chebyshev piecewise integral algorithm had high accuracy. The minimum distance between the measure point and the surface of the transmission line was around 10 cm, where the possibility of sensor breakdown is small.

VI. CONCLUSION

The electromagnetic field simulation and voltage measurement test were carried out with the 10kV transmission line as the object. The voltage measurement effect of different integral algorithms was analyzed by combining the voltage measurement offset degree, voltage measurement security and other factors. According to the analysis, the 4-point

Chebyshev piecewise integral algorithm was more suitable for the integral algorithm of the D-dot electric field sensor voltage measurement system. The research work provided an idea for the selection of the integral algorithm of the transmission line voltage measurement and the integral interval optimization based on the electric field integral. It also provided the algorithm basis for the non-contact measurement of the transmission line voltage.

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