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Research on Transmission Line Voltage Measurement Method Based on Improved Gaussian Integral

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ABSTRACT Currently, there are two non-contact measurement methods of the transmission line voltage based on field sensor: one is calculation with the inverse problem of electric field for the solution, and the other is to solve by the numerical integration algorithm. In general, the first one is confronted with data equation solving problems and difficulties in accurate calibration as well as low precision, while the second one is troubled by the complexity of algorithm equation and unsatisfactory integration node. In view of the above problems, this paper improves on the basis of the Gaussian integral algorithm to seek better nodes, in order to reduce the difficulty of solving and improve the measurement accuracy of the integral algorithm. First, starting from the Gaussian integral algorithm and making research to improve the Gaussian integral algorithm theory. Then, the finite element simulation of three-phase transmission line through Maxwell software is built, and the space electric field distribution data is acquired to calculate an integral node as well as its corresponding weights. Finally, the three-phase transmission line voltage measurement test platform with D-dot sensor voltage measurement system is built to test verification. The text results show that the voltage measurement method based on the improved Gaussian Integral has characteristics of a simple solution, better integral node, and higher precision, and all the measured voltage errors are less than 0.45%.

INDEX TERMS Non-contact measurement, improved Gaussian integral, Maxwell software, D-dot sensor.

I. INTRODUCTION

With continuous improvement of transmission line voltage level in the power system, the transmission line voltage measurement method based on inverse problem has become one of the hot issues in the field [1]–[3]. At present, the existing voltage measurement system based on field sensor has a simple measurement principle: the electric field coupling is adopted to measure the spatial electric field value and the line voltage is obtained by solving the inverse problem [4]–[7]. This method has advantages of being non-contact and with low insulation strength requirements, but due to solution method limitations, it is difficult to solve the equation in the process of solving the inverse problem and to calibrate, and the solution precision is not high enough [8]–[10]. Therefore, a numerical integration algorithm that is simple, easy to calibrate and with higher precision to solve the transmission line voltage is explored. The existing numerical integral algorithms are mainly the Gauss–Legendre Algorithm, the Gaussian Integral and Chebyshev Algorithm [11]–[13], which all calculate line voltage by integral node and corresponding weights, and encounter problems that the integral node is not optimal, and the main node being too close to power lines, leading to sensor installation difficulty and increasing electric field measurement error. In order to solve those problems, this paper improves the Gaussian Integral method to optimize the integral nodes and improve the voltage measurement accuracy.

At present, solving the voltage value of transmission lines by combining numerical integration algorithm with optical voltage sensor has been widely studied [14]–[16]. On the basis of optical sensors for voltage measurement, many experts have used the numerical integration method to perform weighted summation on several integral nodes to

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achieve voltage measurement, and the measurement accuracy is very high [17]–[19]. However, the optical voltage transformer is a kind of precision instrument with high cost and easy damage in transportation, so its application scope is limited [20]–[23]. While compared with the measurement of voltage by optical sensor, the D-dot sensor has advantages of simple structure, low cost and wide dynamic range etc, apart from meeting the basic requirements. So it is more conveniently and widely used [24]–[27]. Moreover, under the condition that a number of integrating nodes are reasonably fixed [28], the improved Gaussian integral algorithm can obtain other integrating nodes that far away from the wire, so that the sensor can be installed far away from the wire, thus reducing the measurement error and improving the voltage accuracy. At the same time, the equation can be reduced order to simplify the calculation.

Therefore, this paper first studies Gaussian integral algorithm and proposes the improved Gaussian Integral algorithm of transmission line voltage calculation method. Then a simulation model of three-phase transmission line space electric field is built for simulation analysis of 20kV, 10kV, 5kV to acquire space electric field distribution data. And the positions of the remaining nodes and the corresponding integral weights are obtained by combining the simulation data with the algorithm when different nodes are fixed, and they are compared and analyzed with the integral node obtained by the Gaussian integral method. Finally, the test platform is built to verify the advantages of the proposed improved Gaussian method.

II. GAUSSIAN INTEGRAL METHOD

Currently the Gaussian numerical integration method is widely used in voltage measurement of transmission lines. In space, the electric field distribution is a continuous function, but it is impossible to measure the continuous value of electric field intensity in practical application. Therefore, numerical integration is adopted to discretize the integral of continuous function. When measuring the voltage of power lines, the D-dot sensor is installed on different integrating nodes to collect the node electric field value, and calculation is carried out by numerical integral accumulation and summation. The Gaussian numerical integration formula is adopted as follows:

For any continuous function $f(x)$, the general form of Gaussian integral is:

$$I(f) = \int_a^b \omega(x) f(x)dx \approx \sum_{k=1}^{n} A_k f(x_k) \tag{1}$$

The above $\omega(x)$ is called the weight function on the integral interval $[a, b]$, and $\omega(x) \geq 0$. Integral node x_k (k = 1, 2, 3. . . . .n) is the Gaussian integral node over interval $[a, b]$. The electric field integral can be equivalent to:

$$U_{ba} = -\int_a^b E_x(x)dx \approx -\sum_{i=1}^{N} \alpha_i E_x(x_i) \tag{2}$$

In formula (2), N is the number of integrating nodes, α_i is the weighted coefficient when summing, and $E_x(x_i)$ is the electric field intensity at the integral node x_i. Because the electric field to be measured $E_x(x)$ is formed under external interference, which is different from the ideal electric field produced during simulation, so it is described by formula $E_x(x) = \omega(x)E_x^{unp}(x)$ when solving. Where $\omega(x)$ is the weight function, $E_x^{unp}(x)$ is the electric field intensity without interference, and can be obtained by means of simulation.

Let $\alpha_i = \beta_i/E_x^{unp}(x_i)$ and it can be derived from formula (2):

$$-\int_a^b E_x^{unp}(x)\omega(x)dx \approx -\sum_{i=1}^{N} \beta_i \omega(x_i) \tag{3}$$

For special $\omega(x) = 1, x, x^2, x^3, \cdots, x^{2N-1}$, we can conclude with formulas:

$$\begin{cases} m_0 = \beta_1 + \beta_2 + \cdots + \beta_N \\ m_1 = \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_N x_N \\ m_2 = \beta_1 x_1^2 + \beta_2 x_2^2 + \cdots + \beta_N x_N^2 \\ \cdots\cdots \\ m_{2N-1} = \beta_1 x_1^{2N-1} + \beta_2 x_2^{2N-1} + \cdots + \beta_N x_N^{2N-1} \end{cases} \tag{4}$$

In the formula (4),

$$m_k = \int_a^b E_x^{unp}(x)x^k dx = \sum_{i=1}^{n} E_x^{unp}(x_i)x_i^k \Delta x \tag{5}$$

Let the characteristic term of the integral node be:

$$P(x) = \prod_{i=1}^{n}(x - x_i) = \sum_{k=0}^{n} c_k x^k, \quad c_n = 1 \tag{6}$$

c_k is the coefficient of the characteristic polynomial, which can be obtained according to the corresponding mathematical operation. Then, according to Maxwell simulation results and numerical integration theory, the integral nodes and corresponding integral weights can be obtained.

III. IMPROVED GAUSSIAN INTEGRAL METHOD

In order to get better integral nodes and improve the accuracy of voltage measurement, the Gaussian integral method is improved. The following is an improved Gaussian integral formula, that is, a Gaussian integral formula with several predetermined nodes, the general form of which is as follows:

$$\int_a^b \omega(x) f(x)dx \approx \sum_{k=1}^{m} a_k f(z_k) + \sum_{k=1}^{n} \omega_k f(x_k) \tag{7}$$

where, z_k is the fixed node mentioned above, and m + 2n constants of a_k ω_k, and x_k are established according to the requirement that the integral rule is accurate for polynomials with the highest degree possible (that is m + 2n − 1).

In the process of solving the transmission line voltage, the ground is taken as the reference potential, and the integral diagram is shown in Figure 1. In the figure, d represents the

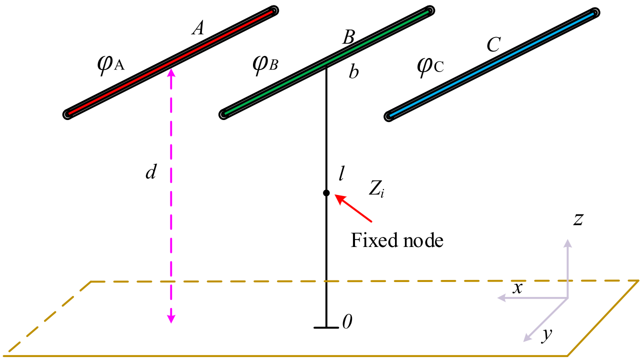

FIGURE 1. Schematic diagram of integral path.

distance between the transmission line and the ground, l is the integral path, and z_i represents the position of the fixed node.

At this point, the electric field integral formula can be equivalent to:

$$U_b = -\int_0^b E_x(x)dx \approx -(\sum_{i=1}^{M} \lambda_i E_x(z_i) + \sum_{i=1}^{N} \alpha_i E_x(x_i)) \quad (8)$$

where is the number of fixed integrator nodes, N is the number of integrator nodes to be evaluated, λ_i and α_i are the weight value of Gaussian integral sum, $E_x(z_i)$ and $E_x(x_i)$ are the field intensity along the z-axis at the integration node z_i and x_i.

Similarly, let $\lambda_i = \theta_i / E_x^{unp}(z_i)$ and $\alpha_i = \beta_i / E_x^{unp}(x_i)$, when substituted into equation (8), the voltage solution formula of the improved Gaussian algorithm can be obtained as follows:

$$-\int_0^b E_x^{unp}(x)\omega(x)dx \approx -(\sum_{i=1}^{M} \theta_i \omega(z_i) + \sum_{i=1}^{N} \beta_i \omega(x_i)) \quad (9)$$

To ensure the accuracy of formula(9), the weight function $\omega(x)$ is set as a series of polynomials with increasing degree. Considering that there are 2N + M unknown quantities to be solved, and when $\omega(x) = 1, x, x^2, x^3, \cdots, x^{2N+M-1}$ formula (9) is established as accurate. Since z_i is known, 2N + M order equations about θ_i, β_i and x_i can be obtained in the same way (10), as shown at the bottom of this page.

In the analysis of specific objects, solve m_k first. Firstly, divide the distance below the transmission line into n equal parts, and according to Maxwell simulation results we can find out the $E_x^{unp}(x_i)$ of these equal points below the transmission line. Then, the corresponding m_k can be obtained according to the above formula. After that, the characteristic polynomial coefficient of x can be solved by reducing the order of equation (10) according to the fixed node through mathematical operation, and the value of integral node x_i can be obtained. Finally, any M + N equations in equation (10) can be selected to get θ_i and β_i, as well as λ_i and α_i can be confirmed. According to this idea, the corresponding integral nodes and integral weights can be solved through MATLAB programming. In this way, the weighted sum of the node electric field measured by the D-dot sensor can obtain the wire voltage value.

IV. TRANSITION LINE SIMULATION AND INTEGRATION NODE SELECTION

A. ELECTRIC FIELD SIMULATION ANALYSIS OF TRANSMISSION LINE

As the algorithm described in this paper requires the support of simulation results, the spatial electric field value of the three-phase transmission wire without interference is obtained through simulation, and the corresponding m_k value is obtained. Here, the problem of solving the voltage of 20kV, 10kV and 5kV transmission lines by using the electric field integral method is taken as an example for simulation analysis. Since the transmission line under the actual working conditions is not straight. But for a long distance, we can think of the transmission wire as straight in a small range. And when the height is certain, the transmission lines voltage can be also calculated according to the space electric field. Therefore, the sensor installation position will correspond to different transmission line heights, and the measured electric field will be different, but the result calculated by numerical integration is the same, which is the transmission line voltage value. On this basis, for the 20kV, 10kV and 5kV voltage levels of transmission lines, in line with the test in the next chapter, the structure adopted in this paper is the horizontal equidistance distribution of three conductors, with the phase spacing is 0.6m, the height is 1.5m and 2.0m above the ground, and the span is set to 2m. The simulation model of the line is built by using the simulation software Ansoft Maxwell, as shown in figure 2.

The distribution diagram of spatial electric field intensity around the transmission line with 20kV voltage level and 1.5m height obtained by simulation as shown in Figure 3.

It can be seen from Figure 3 that the electric field which is near to the conductor changes rapidly, while that far away from the conductor changes slowly. Here, the simulated electric field data is imported into the Origin software to obtain the electric field distribution curve as shown in Figure 4 below. In the figure, the horizontal axis represents the vertical distance from the ground and the vertical axis represents the electric field value in the vertical direction of

$$\begin{cases} m_0 = \theta_1 + \cdots + \theta_M + \beta_1 + \cdots + \beta_N \\ m_1 = \theta_1 z_1 + \cdots + \theta_M z_M + \beta_1 x_1 + \cdots + \beta_N x_N \\ m_2 = \theta_1 z_1^2 + \cdots + \theta_M z_M^2 + \beta_1 x_1^2 + \cdots + \beta_N x_N^2 \\ \cdots\cdots \\ m_{2N+M-1} = \theta_1 z_1^{2N+M-1} + \cdots + \theta_M z_M^{2N+M-1} + \beta_1 x_1^{2N+M-1} + \cdots + \beta_N x_N^{2N+M-1} \end{cases} \quad (10)$$

TABLE 1. Gaussian algorithm integral node and weight calculation results.

Integral Algorithm	Line Height(m)	Voltage Level(kV)	Integral Node Coordinates x_i (m)			Corresponding Integral Node Weight		
Gaussian Integral	2.0	20	1.174	1.931	0.259	1.1634	0.3099	0.3290
	1.5	20	0.854	1.440	0.189	0.7699	0.2600	0.4684
		10	0.855	1.440	0.189	0.7672	0.2602	0.4698
		5	0.854	1.440	0.189	0.7717	0.2602	0.4693

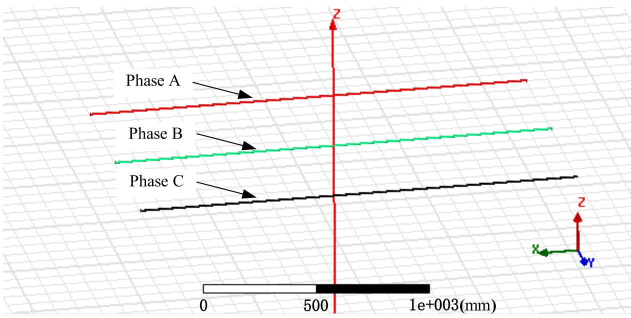

FIGURE 2. Simulation models of 20kV, 10kV and 5kV transmission lines.

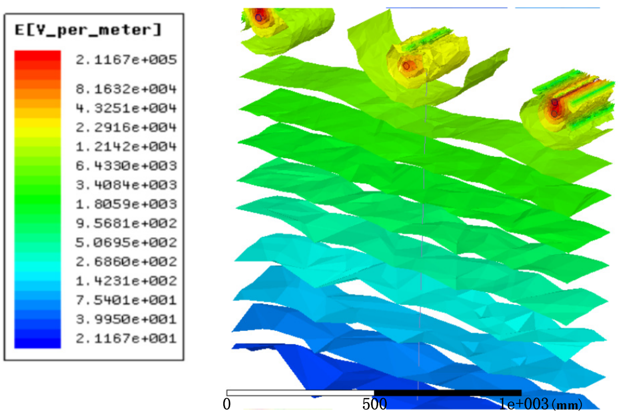

FIGURE 3. Electric field distribution diagram of 20kV, 1.5m transmission line.

the position. According to the electric field distribution, and to better explain the distribution mechanism of the electric field below the transmission line, the interval is divided from 1.4m in Figure 4, so the variation of electric field under the transmission line can be more intuitively seen. The variation of electric field intensity in the interval of 1.4m to 1.5m is particularly fast, while in the interval of 0 to 1.4m is very slow. Objectively to say, when the integral node is close to the wire, the measurement error caused by the sensor installation will increase. Therefore, the integral node should be selected as far away from the wire as possible to reduce the voltage measurement error and the installation difficulty of the sensor.

B. CALCULATION AND SELECTION OF INTEGRAL ALGORITHM NODE

According to the characteristics of numerical integration, the Gaussian quadrature formula of n nodes has the algebraic

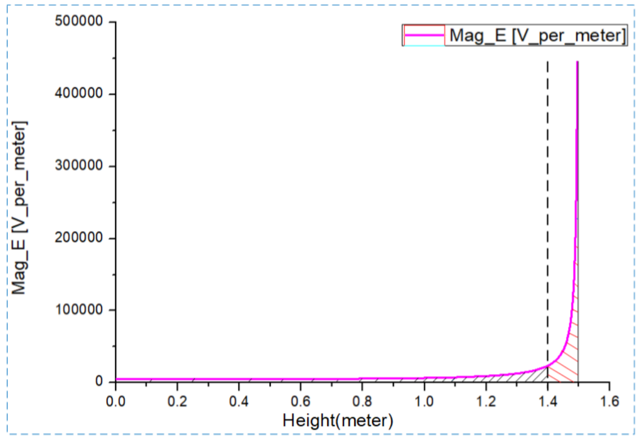

FIGURE 4. 20kV electric field distribution curve at height of 1.5m.

precision of 2n + 1, and the more integral nodes, the smaller the error. The integral measurement results of 1 ∼ 2 nodes will inevitably bring about a large algorithm error, the integration process of 3 and above nodes has a faster convergence. But the excessive number of integral nodes is not conducive to the installation of the measurement system when considering the practicability of the measurement method, and the calculation results of three integral measuring nodes can meet the voltage measurement standards, the algorithm error can be ignored. Therefore, this paper takes three integral nodes for solution. The algorithm described in the previous chapter is used to calculate the node position and integral weight. The calculation results of the Gaussian algorithm are shown in Table 1 below:

Results from Table 1 show that when the transmission line height is fixed, the coordinates and weights of the integral nodes are independent of the voltage level. And when the transmission line height is different, the integral node and the corresponding weight value are not the same under the same voltage level. The results show that the integral node and the corresponding weights obtained by the Gaussian integral algorithm are independent of the voltage level and are only related to the height of the transmission line.

The following is the integral nodes and the corresponding integral weights of the improved Gaussian integral algorithm, and the results are shown in Table 2 below.

Results from table 2 show that the properties of nodes and weights of the improved Gaussian Integral are the same as those of the original method. At the same height and voltage

TABLE 2. **Improved Gaussian algorithm integral node and weight calculation results.**

Integral Algorithm	Line Height(m)	Voltage Level(kV)	Fixed Node Coordinates z_i (m)	Residual Node Coordinates x_i (m)		Corresponding Integral Node Weight		
Improved Gaussian Integral	2.0	20	1.300	1.947	0.305	1.0192	0.2280	0.7495
			1.100	1.924	0.223	1.0707	0.3608	0.5703
			0.900	1.909	0.056	1.2249	0.4462	0.3191
	1.5	20	1.000	1.465	0.236	0.7840	0.1451	0.5774
			0.800	1.434	0.163	0.7866	0.3099	0.4223
			0.700	1.424	0.095	0.8467	0.3433	0.2999
		10	1.000	1.464	0.236	0.7865	0.1334	0.5791
			0.800	1.434	0.163	0.7865	0.2917	0.4167
			0.700	1.424	0.095	0.8478	0.3451	0.2998
		5	1.000	1.465	0.236	0.7851	0.1334	0.5776
			0.800	1.434	0.163	0.7860	0.2920	0.4159
			0.700	1.424	0.095	0.8455	0.3458	0.2996

level, the coordinate of the integral node moves down with the decreasing of fixed node, but in actual process, the lowest point cannot be less than 0. Because of the distribution mechanism of electric field below the transmission line, the change of electric field intensity is particularly fast when approaching the wire, so the change of electric field intensity caused by the small change of the highest integral node is very large, and this small change of the note has a great influence on the accuracy of voltage measurement. Therefore, the fixed nodes can be reasonably divided to make the remaining nodes better. Comparing TABLE 1 and 2, it can be shown that transmission lines with the same voltage level in the same height, given a node coordinates of 0.7 m, the highest node position obtained from the improved Gaussian Integral is lower than that from the original. So integral node coordinates of 1.424m, 0.700m and 0.095m are selected for test analysis when adopting the improved Gaussian algorithm in this paper.

To sum up, the improved Gaussian Integral method can seek for other nodes with better performance under the condition of a given integral node, so as to reduce the system measurement error and further improve the measurement accuracy of the Gaussian integral method.

V. EXPERIMENTAL VERIFICATION

A. EXPERIMENTAL PLATFORM CONSTRUCTION

In order to verify the accuracy and advantages of the transmission line voltage measurement method with improved Gaussian Integral proposed in this paper, the simulation and calculation results in the previous chapter are used for experimental analysis. Figure 5 shows the experimental diagram of three-phase transmission line voltage measurement platform, so as to measure the transmission line voltage results of Gaussian integral method and improved Gaussian integral method under actual working conditions.

The physical diagram of three-phase transmission line voltage measurement experimental platform constructed is shown in Figure 6 below. On the experimental platform, and the three-phase voltage regulator and the step-up transformer work together to generate a three-phase power

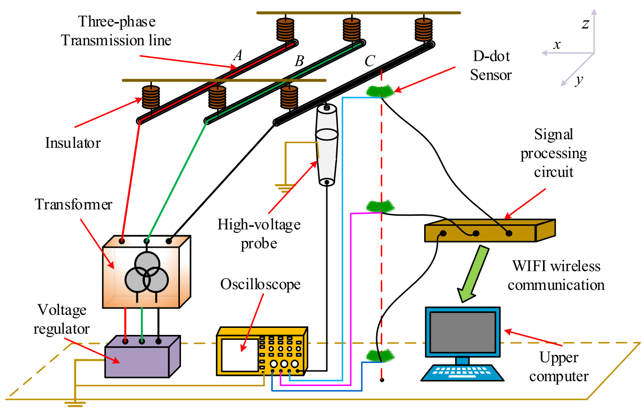

FIGURE 5. **Schematic diagram of three-phase transmission line voltage measurement test platform.**

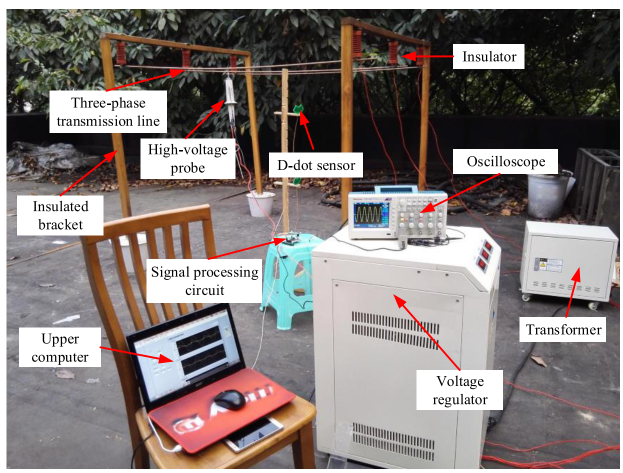

FIGURE 6. **Physical diagram of three-phase transmission line voltage measurement text platform.**

frequency voltage with controllable amplitude, at the same time use the D-dot sensor voltage measurement system and Tektronix P6015A high-voltage probe with attenuation ratio of 1000:1 to measure transmission line power

TABLE 3. Gaussian integration results from three voltage levels.

Effective Value of Line Voltage (kV)	Integral Node Coordinates(m)	Field Intensity at Integration Node(m)	Integral Node Weight	Numerical Integral Voltage(kV)	Value of High-Voltage Probe (kV)	Relative Error
	1.440	9555.18	0.2602			
5	0.854	1424.53	0.7717	4.167	4.19	-0.55%
	0.189	1239.24	0.4693			
	1.440	19135.36	0.2602			
10	0.854	2868.50	0.7672	8.339	8.37	-0.37%
	0.189	2466.57	0.4698			
	1.440	37707.23	0.2600			
20	0.854	5704.11	0.7699	16.53	16.61	-0.48%
	0.189	4973.99	0.4684			

frequency voltage. After correction, the high-voltage probe measurement result is set as actual conductor voltage U_s, and the result by the integral algorithm as U. Therefore, the integral algorithm can be used to solve the relative error of line voltage ε. The calculation formula is as follows:

$$\varepsilon = \frac{(U - U_s)}{U_s} \times 100\% \tag{11}$$

As can be seen from Figure 6, the sensor is attached on the wooden bracket, since the sensor is in the form of a thin layer PCB, its own volume parameter can be neglected, so it can be accurately positioned under the transmission line. This kind of sensor layout will not bring an obvious electric field distortion, and ensure the accuracy of the sensor measurement. The transmission line uses a copper wire with a diameter of 1cm, and the distance between the center of the wire and the ground is 1.5m, and the phase span is 0.6m. In this paper, the integrated node coordinates calculated by the Gaussian algorithm of 1.440m, 0.854m, 0.189m, and the integrated node coordinates calculated by the improved Gaussian algorithm of 1.424m, 0.700m and 0.095m respectively are compared and analyzed.

During the experiment, the oscilloscope collects the output of the high-voltage probe and three sensors at the same time to verify the measurement effect of the sensor. The output of the high-voltage probe is taken as the actual standard voltage value, and its display effect is shown in Figure 7 below.

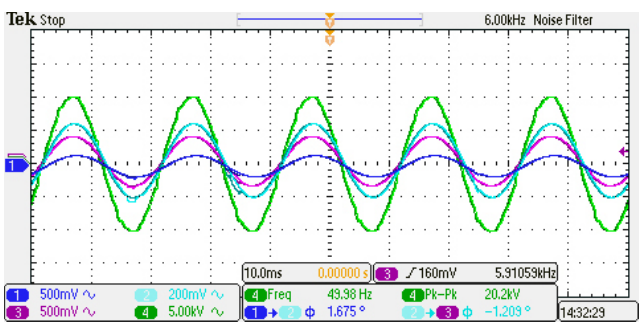

FIGURE 7. Contrast waveform of D-dot sensor output and high voltage probe output.

As is shown in Figure 6 above, the D-dot electric field sensors are placed at the integral nodes directly below the

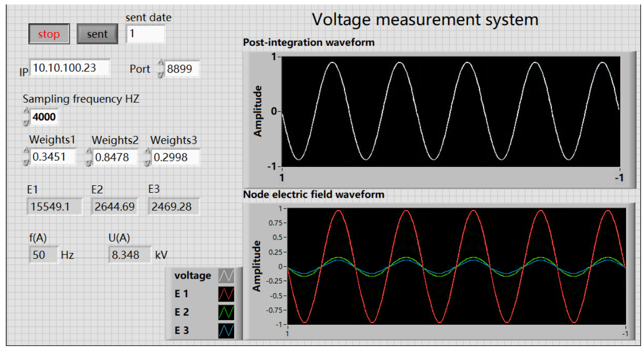

FIGURE 8. Front panel of voltage measurement system.

wire to collect electric field information, the information is then processed and changed into discrete electric field signal by the hardware circuit, with the signal being sent to the PC of the LabVIEW software through WIFI wireless transmission module, and to be displayed by the front panel after processing and computing. Here, taking the test result of 10kV as an example, and as shown in Figure 8, the result is displayed in the front panel.

B. EXPERIMENTAL RESULTS AND ANALYSIS

As the maximum pressure value of the experiment platform and the largest range of high-voltage probe are 20kV, here three kinds of voltage level 5kV, 10kV and 20kV are tested using the experimental platform respectively, and the corresponding field intensity E_x of integral node is measured by D-dot sensor. The numerical integral voltage U can be acquired by weighted summation of the electric field intensity at the integral node through LabVIEW software and the actual relative error ε can be obtained from Formula (11). The recorded data and the relative errors solved are shown in Table 3 below:

By changing the position of the sensor and placing it at 1.424m, 0.700m and 0.095m respectively, the corresponding electric field intensity E_x is obtained. Similarly, the integral result of the improved Gaussian integral method is measured as shown in Table 4 below:

The following conclusions can be drawn from the experimental results and Table 3 and 4:

TABLE 4. Improved Gaussian integration results from three voltage levels.

Effective Value of Line Voltage (kV)	Integral Node Coordinates(m)	Field Intensity at Integration Node (m)	Integral Node Weight	Numerical Integral Voltage(kV)	Value of High-Voltage Probe (kV)	Relative Error
5	1.424	7749.78	0.3458	4.173	4.19	-0.41%
	0.700	1326.27	0.8455			
	0.095	1240.00	0.2996			
10	1.424	15549.1	0.3451	8.348	8.37	-0.26%
	0.700	2644.69	0.8478			
	0.095	2469.28	0.2998			
20	1.424	30952.8	0.3433	16.59	16.61	-0.12%
	0.700	5301.64	0.8467			
	0.095	4904.38	0.2999			

1) It can be seen from the oscilloscope waveform output that the phase difference between D-dot sensor output waveform and that of the high-voltage probe is less than 2°, and both are standard power frequency sinusoidal waveform.

2) The electric field and voltage waveforms obtained by the LabVIEW software are all standard power-frequency sinusoidal waveforms with small distortion, which well reflects the actual operating conditions of transmission wires.

3) According to the comparison results between Table 3 and 4, the absolute value of the wire voltage value's relative error calculated by the improved Gaussian integral method is smaller than that by the original method under same voltage level, which fully shows that better integral node can make the voltage measurement accuracy higher.

4) It can be seen from Table 4 that the transmission line voltage can be measured by the measurement system with improved Gaussian integral, and the error absolute value is less than 0.45%, indicating high measurement accuracy.

VI. CONCLUSION

By comparing the application of Gaussian Integral in voltage measurement system and considering the existing problems, this paper proposes to improve the Gaussian Integral algorithm and introduces it into the D-dot sensor voltage measurement system. Through theoretical research, simulation analysis and test, it is concluded that the improved Gaussian Integral for transmission line voltage measurement can achieve accurate measurement of transmission line voltage, as well as optimize Gaussian Integral nodes and improve measurement accuracy. Meanwhile, the solution process is simple and the voltage measurement error is within 0.45%. The research work in this paper provides a new idea on the integral algorithm selection and the integral node optimization for transmission line voltage measurement, which provides an important scientific basis for the practical application of voltage measurement in the power system.

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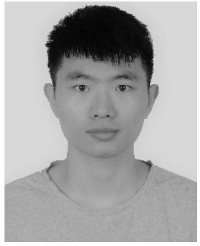

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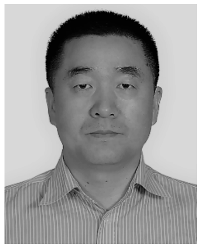

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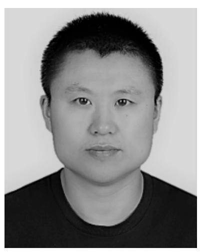

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