Evaluation of New Kenten Substation Grounding System Based on IEEE 80-2013

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***Abstract—The* Grounding system in a substation is essential to human and equipment safety; therefore, the grounding system condition should always be under observation. Maintenance and evaluation should be regularly carried out in line with the possibility of disturbances in the system from lightning strikes. In this study, the New Kenten substation's grounding system was analyzed using analytical and numerical methods. The analytical calculation was based on IEEE Std. 80-2013 Guide for Safety in AC Substations Grounding. Then, the results were compared with simulation results using numerical software. From the study, it was obtained that the grounding system of the New Kenten substation has been maintained well to comply with the safety standard regulation.**

Keywords— substation, grounding system, touch-voltage, step-voltage

Abstrak—Sistem pentanahan pada gardu induk memiliki peranan penting bagi keselamatan manusia dan peralatan karena itu kondisi system pentanahan seharusnya selalu diobservasi. Pemeliharaan dan evaluasi seharusnya secara regular dilakukan sejalan dengan kemungkinan ganggunan-gangguan yang mungkin muncul pada sistem karena sabaran petir. Pada studi ini, sistem pentanahan pada Gardu Induk New Kenten dianalisis menggunakan metode analitik dan numerik. Kalkulasi analitik didasarkan kepada *IEEE Std. 80-2013 Guide for Safety in AC Substations Grounding*. Selanjutnya, hasil yang didapatkan dari kalkulasi menggunakan metode analitik dibandingkan dengan hasil simulasi menggunakan perangkat lunak yang menggunakan metode numerik. Dari hasil studi diperoleh bahwa sistem pentanahan Gardu Induk New Kenten telah dirawat dengan baik sehingga sesuai dengan standar keselamatan yang disyaratkan.

Katakunci— gardu induk, sistem pentanaha, tegangan sentuh, tegangan langkah

I. Introduction

As part of the electrical power delivery system, the substation is part of the load control, disruption recovery, data logging, and voltage control centre [1]. Therefore, the grounding system of a substation should comply with the standards and regulations for human, equipment, and environmental safety surrounding the substation area [2], [3]. Previously, the grounding system of the substation was only performed by vertically burying conductor rods into the ground surface. Over time, it was found that the vertical rod method was less effective in distributing fault currents to the ground. High fault currents resulted in rapid degradation of the conductor rod's performance. Hence, optimisation of the substation grounding system performance is required by adding horizontally interconnected rods to the ground surface, forming a mesh structure. This grounding system is a combination grid-rod grounding system [4].

The grounding system in a substation could evolve into a complex system. Since it is proposed to operate at very high currents and voltages due to short-circuit currents or lightning strikes. Although not an absolute requirement, the quality of the grounding system is assessed based on its grounding system resistance magnitude. The lower the resistance value of the grounding system, the better it is for overvoltage distribution [5], [6]. A study is needed to obtain an optimal grounding system design suitable for the possible fault currents occurrence in a substation. Although research on a substation grounding system design is usually conducted at the early stage of substation planning, an evaluation of the grounding system may be carried out as required. This design study can be conducted using both analytical and numerical calculation methods. Analytical calculations can be performed using the IEEE Std. 80-2013 Guide for Safety in AC Substations Grounding [7]. Meanwhile, numerical calculation methods can be executed using software.

There were several studies on the evaluation of the grounding system of the substation. Akhikpemelo [8] evaluated the grounding system substation using Finite Element Method (FEM). The results of the analysis showed that this substation meets the IEEE Std. 80-2013 standard after calculating the touch-voltage and step-voltage. A similar study for the design of the grounding system was conducted by Fitriani et al. [9] using ETAP software. Meanwhile, Yamina et al. [10] conducted a study on the sizing of the ground network of the 60/30 kV substation and the distribution of electrical energy of Si Mustapha. The simulation was carried out using CMYMGRD software.

II. RESEARCH METHODOLOGY

New Kenten Substation is in Tanah Mas, Talang Kelapa District, Banyuasin Regency, South Sumatra, with coordinates (-2.8836164678771095, 104.73899458650767). Figure 1 shows the New Kenten Substation. The grounding calculation of the substation was carried out based on IEEE Std. 80-2013: IEEE Guide for Safety in AC Substations Grounding. This standard uses two calculations: the grounding conductor cross-sectional area calculation, and the touch and step voltage that probably occurs at the substation.

Fig. 1. New Kenten Substation, (a) Top view, (b) Photo from the outside area, and (c) Photo from the inside area

The existing New Kenten Substation grounding system uses a combination of horizontal and vertical rods called a grid-rod system. The layout of the grounding system at New Kenten Substation is shown in Figure 2.

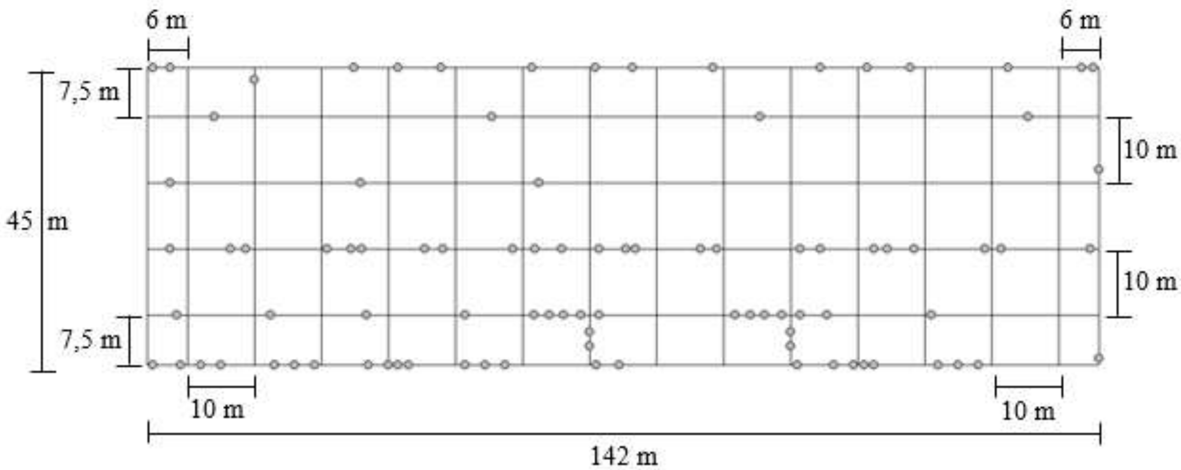

Fig. 2. Layout of grid-rod New Kenten Substation.

A. Grounding Conductor Cross-Sectional Area

The minimum cross-sectional area of the grounding conductor used as a grid is calculated using Equation (1).

$$A = \frac{I_f}{\sqrt{\left(\frac{TCAP\cdot 10^{-4}}{t_c \alpha_r \rho_r}\right) ln\left(\frac{K_o+T_m}{K_o+T_a}\right)}} \quad (1)$$

While the minimum conductor diameter is determined by utilizing Equation (2).

$$d = \sqrt{\frac{4\cdot A}{\pi}} \quad (2)$$

Where A is the conductor cross-sectional area (mm^2), I_f is the fault current to ground (kA), t_c is the fault duration (seconds), TCAP is the thermal conductivity capacity per unit volume [J/(cm^3.°C)], T_m is the maximum allowable temperature (°C), T_a is the ambient temperature (°C), α_r is the temperature coefficient of conductor resistivity at 20 °C (°C^{-1}), ρ_r is the resistivity of the grounding conductor at 20 °C (μΩ-cm), K_o is $1/\alpha_o$, and α_o is the temperature coefficient of conductor specific resistance at 0 °C.

B. Touch-voltage and Step-voltage in a Grounding Installation

A calculation process is required to obtain the touch-voltage and step-voltage that possibly appear in the substation area.

1) Soil Resistivity

Soil resistance measurement must be conducted to obtain the soil resistivity value. Soil resistance measurement can be performed using the four-point method (Wenner Method). Then, by utilising Equation (3), the soil resistivity value can be determined.

$$\rho_a = 2\pi a R \quad (3)$$

Where ρ_a is the average soil resistivity (Ωm), a is the distance between electrodes (m), and R is the measured resistance (Ω).

2) Additional Layer Material

An additional layer must be attached to enhance the soil surface resistivity in the grounding system installation area. An often-utilised supplementary attachment is gravel. The thickness of this gravel layer ranges from 0.08 m to 0.15 m to achieve a layer resistance of 5.0 kΩ.

Due to the limited thickness of the gravel surface layer material, an effective calculation of the grounding resistance requires derating. The derating factor can be obtained using Equation (4).

$$C_s = 1 - \frac{0{,}09\left(1-\frac{\rho}{\rho_s}\right)}{2h_s+0{,}09} \quad (4)$$

Where C_s represents the derating factor, ρ denotes soil resistivity (Ωm), ρ_s signifies material resistivity (Ωm), and h_s stands for layer thickness (m).

3) Substation Grounding Resistivity

The conductor of the GI grounding system installed horizontally in a grid pattern with a specific depth can be used to calculate the grounding resistance value using Equation (5).

$$R_g = \rho \left[\frac{1}{L_T} + \frac{1}{\sqrt{20\cdot A}}\left(1 + \frac{1}{1+h\sqrt{\frac{20}{A}}}\right)\right] \quad (5)$$

Where R_g is the grounding resistance (Ω), ρ is the soil resistivity (Ωm), L_T is the total length of the buried conductor (m), A is the grounding area (m^2), and h is the depth of the grid conductor burial (m).

4) Maximum Current

Furthermore, the maximum electrical current flowing through the grid is obtained based on the magnitude of the fault current to the ground multiplied by the Decrement factor value, as in Equation (6).

$$I_G = I_g \cdot D_f \quad (6)$$

Where, I_G is the maximum current (A), I_g is the fault current to ground (A), and D_f is the Decrement factor. The D_f is obtained using Equation (7).

$$D_f = \sqrt{1 + \frac{T_a}{t_f}\left(1 - e^{-\frac{2t_f}{T_a}}\right)} \quad (7)$$

Where, D_f is the Decrement factor (s), T_a is the dc offset time constant (s), t_f is the disturbance duration (s), X/R is the system reactance-to-resistance ratio and f is the frequency (Hz). To obtain T_a, Equation (8) can be utilized.

$$T_a = \frac{X}{R} \cdot \frac{1}{2\pi f} \quad (8)$$

5) Touch-voltage and Step-voltage

Touch-voltage is the voltage between an energised object touched by another object directly connected to the ground. The voltage for a human weight of 50 kg and 70 kg is seen in Equations (9) and (10).

$$E_{touch\ 50} = (1000 + 1{,}5\ C_s\rho_s)\ \frac{0{,}116}{\sqrt{t_s}} \quad (9)$$

$$E_{touch\ 70} = (1000 + 1{,}5\ C_s\rho_s)\ \frac{0{,}157}{\sqrt{t_s}} \quad (10)$$

Step-voltage is the voltage difference on the ground surface between two human feet spaced one step or 1.0 m apart when standing on the ground being traversed by fault current to the ground without touching any equipment. The voltage calculations for human weights of 50 kg and 70 kg are shown in Equations (11) and (12).

$$E_{Step\ 50} = (1000 + 6\ C_s\rho_s)\frac{0{,}116}{\sqrt{t_s}} \quad (11)$$

$$E_{Step\ 70} = (1000 + 6\ C_s\rho_s)\frac{0{,}157}{\sqrt{t_s}} \quad (12)$$

Where $E_{touch\ 50}$ is the touch voltage for a 50 kg human body weight (V), $E_{touch\ 70}$ is the touch voltage for a 70 kg human body weight (V), $E_{step\ 50}$ is the step voltage for a 50 kg human body weight (V), $E_{step\ 70}$ is the step voltage for a 70 kg human body weight (V), C_s is the surface layer material reduction factor, ρ_s is the surface resistivity (Ωm), and t_s is the fault duration (s).

6) Ground Potential Rise (GPR)

The Grounding Potential Rise (GPR) can be determined from the value of I_G and R_g. The magnitude of GPR can be calculated using Equation (13):

$$GPR = I_G \cdot R_g \quad (13)$$

Where I_G is the maximum grid current (kA), and R_g is the grounding resistance (Ω).

If the value of GPR < E_{touch}, then the grounding system meets safety standards; however, if the value of GPR > $E_{touch,}$ further evaluation proceeds to the next step.

7) Ground Grid Voltage and Maximum Step Voltage

The design is deemed safe if the touch-voltage and step-voltage that may occur are smaller than the allowable touch-voltage and step-voltage. The magnitude of the maximum grounding grid voltage is calculated using Equation (13).

$$E_m = \frac{\rho \cdot I_G \cdot K_m \cdot K_i}{L_M} \quad (13)$$

And the maximum step-voltage can be calculated using Equation (14):

$$E_s = \frac{\rho \cdot I_G \cdot K_s \cdot K_i}{L_s} \quad (14)$$

Where, K_m is the geometric factor, K_i is the corrective factor, L_M is the effective embedded length (m), L_s is the effective conductor length embedded (m), and K_s is the geometric factor.

III. Result and Discussion

A. Identification Data Result

Fig. 2 was converted to a 3D model in ETAP 12.6.0. as shown in Figure 3. The New Kenten Substation utilises grounding rods of 3.0 m in length and 16.0 mm in diameter. In total, 93 pieces of grounding rods were installed at the substation. The visualisation of the grounding rod is shown in Fig. 4.

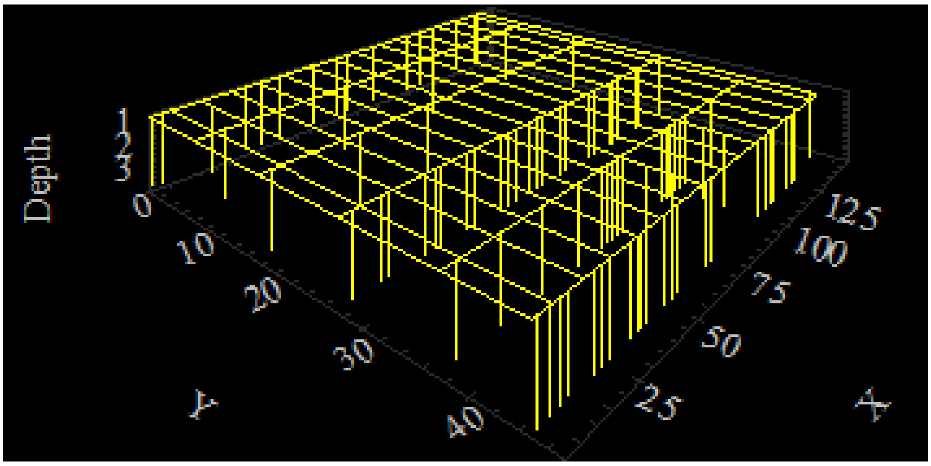

Fig. 3. Three-dimensional view of New Kenten Substation.

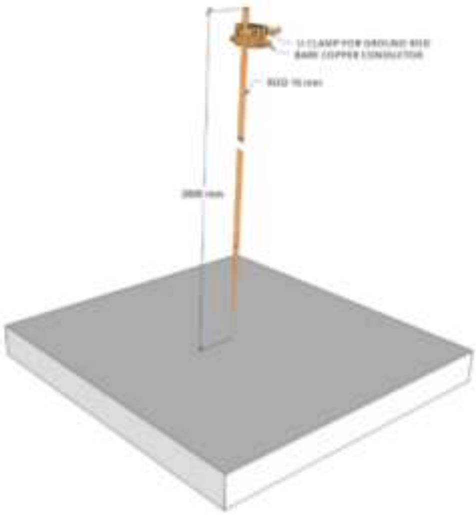

Fig. 4. Vertical Rod

Based on the requirements of IEEE Std. 80-2013, the grid configuration on the substation ground grid that complies with the standard must have the following conditions: 1) 6.25 m^2 ≤ A ≤10,000 m^2 where A is the area of grounding; 2) The number of parallel conductors on one side is less than 40 ($n \leq 40$); 3) 0.25 m ≤ h ≤ 2.5 m where h is the depth of conductor embedding; 4) 2.5 m < D < 22.5 m where D is the distance between parallel conductors. Based on the requirements of IEEE Std. 80-2013, the conditions of the New Kenten Substation will be described in Table 1. It shows that the grid condition at the New Kenten Substation has complied with the IEEE Std. 80-2013.

TABLE I. New Kenten Substation Condition

Parameter	Requirements	Substation Condition	Complied
Area	6.25 m^2 ≤ A ≤10,000 m^2	6,390 m^2	Yes
The number of parallel conductors on one side	$n \leq 40$	16 conductors x-axis, 6 conductors y-axis	Yes
Conductor depth	0.25 m ≤ h ≤ 2.5 m	0.8 m	Yes
Distance between parallel conductor	2.5 m < D < 22.5 m	6.0 m, 7.5 m and 10.0 m	Yes

B. *Analytical Calculation*

The calculation was based on the IEEE Std. 80-2013 standard. Two calculation processes should be carried out: the grounding conductor cross-sectional area and the touch and step voltage on the substation.

1) Grounding Conductor Cross-Sectional Area

The type of conductor used in the design of the grounding system at the New Kenten Substation, both as grounding grid and grounding rod, was copper (commercial hard drawn). According to IEEE Std. 80-2013, the specifications of the commercial hard-drawn copper conductor are shown in Table 2.

TABLE II. COPPER COMMERCIAL HARD DRAWN SPECIFICATION

Parameter	Value
Material Conductivity (%)	97
The temperature coefficient of the conductor resistivity at 20 ºC, α_r [1/ ºC]	0.00381
K_o ($1/\alpha_o$) at 0 ºC	242
Melting temperature, T_m [ºC]	1,084
Conductor Resistivity at 20 ºC, ρr [μΩ-cm]	1.78
TCAP [J/(cm^3. ºC)]	3.42

To calculate the minimum cross-sectional area of the conductor, the formula in Equation (1) was utilised. In this calculation, the ambient temperature (T_a) is 40 ºC.

$$A = \frac{I_f}{\sqrt{\left(\frac{TCAP \cdot 10^{-4}}{t_c \alpha_r \rho_r}\right) ln\left(\frac{K_o + T_m}{K_o + T_a}\right)}}$$

$$A = \frac{40}{\sqrt{\left(\frac{3{,}42 \cdot 10^{-4}}{1 \cdot 0{,}00381 \cdot 1.78}\right) ln\left(\frac{242 + 1.084}{242 + 40}\right)}}$$

$$A = 143.16\, mm^2$$

After the calculation, the minimum cross-sectional area to withstand a fault current of 40 kA was 143.16 mm^2. Subsequently, the next step was to calculate the minimum size of the conductor diameter. It should be calculated using the equation.

$$d = \sqrt{\frac{4 \cdot A}{\pi}}$$

$$d = \sqrt{\frac{4 \cdot 141.19}{3.14}}$$

$$d = 13.504\, mm$$

The minimum diameter required to withstand fault currents at the New Kenten Substation is 13.504 mm. Both calculations indicated that the minimum surface area of the conductor and the conductor diameter complied with the safety standards according to IEEE Std. 80-2013. The conductor type at the New Kenten Substation is Bare Copper Conductor (BCC) with Copper Commercial Hard Drawn conductors based on SPLN 41-5. The BCC conductor has a cross-sectional area of 150 mm^2 and a diameter of 15.75 mm. These values are above the minimum requirements. Table 3 shows the comparison between the calculation and the installed grounding conductor and rods.

TABLE III. COMPARISON OF MINIMUM VALUES AND VALUES AT SUBSTATIONS

Parameter	Minimum Value	Value in Substation
Cross-Sectional Area	143.16 mm^2	150.00 mm^2
Diameter	13.504 mm	15.75 mm

It can be seen that the area cross-sectional size and diameter of the grid at the New Kenten have complied with the safety standards according to IEEE Std 80-2013 because the minimum value is less than the value at the substation ($A_{min} < A_{GI}$ dan $d_{min} < d_{GI}$).

2) Touch-voltage and Step-voltage in the Substation

There were several data and stages to calculate the touch-voltage and step-voltage: (a) Soil Resistance – Based on the conducted calculation, the value of *R* was 0.122 Ω. Thus, the value of *ρ* with an electrode spacing (*a*) of 5.0 meters was 3.83 Ωm; (b) Additional Layer Material – An additional layer of gravel with a depth h_s of 0.15 m and a resistivity ρ_s of 5,000 Ωm was used. The derating factor (C_s) was 0.769; (c) Substation Grounding Resistance – L_T (total length of the grid conductor and rod conductor) had a value of 1.851 m. Thus, the value of R_g was 0.023 Ω; (d) Maximum Current – The maximum grid current (I_G) with a value of D_f 1.016, frequency 50 Hz, and $X/_R = 10$ was 40.64 kA; (e) Permissible Touch Voltage and Step Voltage – A reference weight of 70 kg was utilised, as adults frequently inhabit the Substation area under this assumption. If a disturbance occurs for 1 second, then $E_{touch\ 70}$ was 1,062.98 V and $E_{Step\ 70}$ is 13,780.91 V; (f) *Ground Potential Rise* (GPR) – From the obtained values of I_G and R_g, the magnitude of GPR was 936.431 V; (g) Grounding System Design – From the calculation results with a value of K_m of 0.7664, a value of K_i of 1.98, and a value of L_M of 2,011.305, the calculated mesh voltage or touch voltage was 118.03 V. And for the calculation of step voltage with a computed value of K_s of 0.26 and L_s of 1,416.15, it yielded a result of 56.89 V.

Therefore, based on the analytical calculation results for the New Kenten Substation, the following calculation results were obtained, as shown in Table 4.

TABLE IV ANALYTICAL CALCULATION RESULT OF NEW KENTEN SUBSTATION

Parameter	Allowed voltage (V)	Calculation voltage (V)
Touch voltage	1,062.98	118.03
Step voltage	3,780.91	56.89

C. Software Simulation

Table 5 shows the input of various values into ETAP 12.6.0 software and subsequent simulation; the obtained values include Grounding Resistance (R_g), Maximum Fault Current (I_G), Ground Potential Rise (GPR), Allowable Touch Voltage ($E_{touch70}$), Allowable Step Voltage (E_{step70}), Actual Touch Voltage (E_m), and Actual Step Voltage (E_s).

TABLE V. PARAMETER FOR THE SIMULATION USING ETAP 12.6.0.

Parameter	Symbol	Value
Length (m)	L_x	142
Width (m)	L_y	45
Grid conductor depth (m)	h	0.8
Grid cross-sectional area (mm^2)	$A_{conductor}$	150
Grounding rod length (m)	L_r	3
Grounding rod diameter (mm)	d_{rod}	16
Standard human weight (kg)	*Weight*	70
Ambient temperature (°C)	T_a	40
Fault duration (s)	t_c	1
Fault current (A)	I_g	40
Ground resistivity (Ωm)	ρ	3.83
Surface material resistivity (Ωm)	ρ_s	5,000
Surface material thickness (m)	h_s	0.15
Reactive and resistive impedance comparison	X/R	10

From the ETAP 12.6.0 simulation, a 3D Touch-voltage distribution was obtained, as shown in Figure 5. The 3D graph was obtained by analysing 9172 points. With similar points, the Step -voltage was simulated; the result is shown in Figure 6.

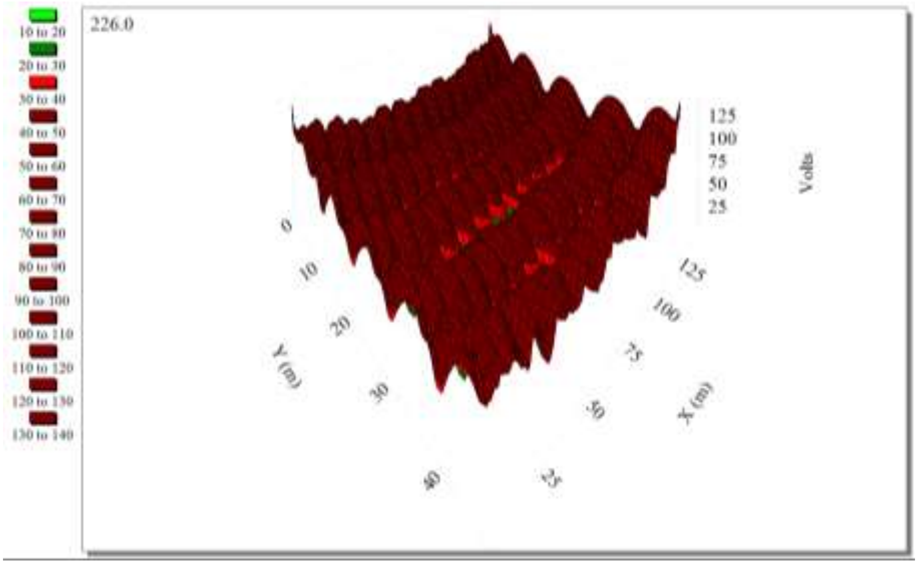

Fig. 5 Touch-voltage simulation

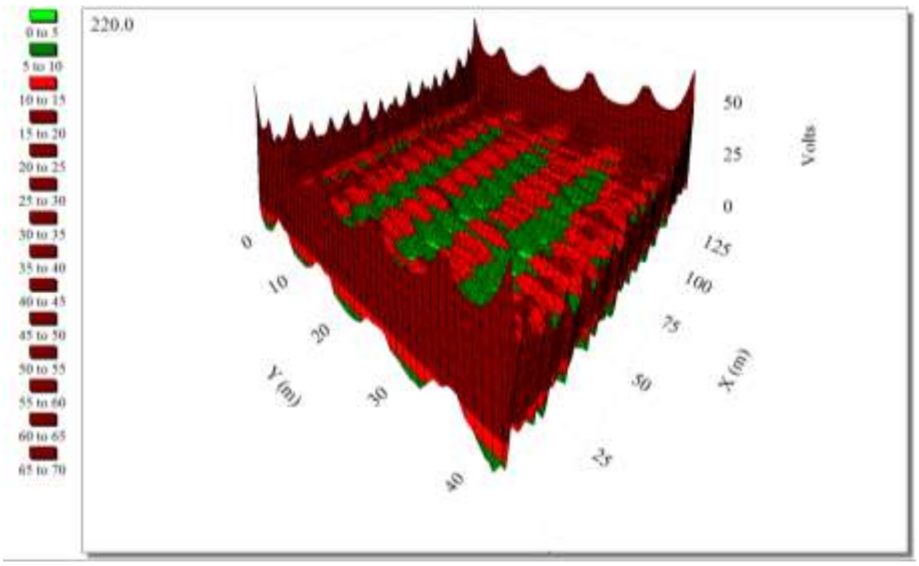

Fig. 6 Step-voltage simulation

Analytical calculations and simulation results are compared as presented in Table 6. There are several differences between analytical and numerical results due to the differentiation of input data at the initial conditions. However, both analytical and numerical calculations show that the grounding system of New Kenten Substation has complied with the safety level.

TABLE VI COMPARISON BETWEEN ANALYTIC AND NUMERICAL CALCULATION

Parameter	**Symbol**	**Analytical Calculation**	**Numerical Calculation**	**Absolute Difference Value**
Grounding Resistance (Ω)	R_g	0.023	0.02	0.003
Maximum Current (A)	I_G	40,640	40,632	8
Ground Potential Rise (V)	*GPR*	936.431	814.5	121.931
Allowable Touch-voltage (V)	$E_{touch\ 70}$	1,062.98	1,063	0.02
Allowable Step-voltage (V)	$E_{step\ 70}$	3,780.91	3,780.9	0.01
Calculation Result of Touch-voltage (V)	E_m	118.03	139.4	21.37
Calculation Result of Step-voltage (V)	E_s	56.89	141.8	84.91

IV. CONCLUSION

A quantitative method was used to examine the condition of the New Kenten Substation grounding system using analytical and numerical calculations. Both calculation results show that the grounding system complies with the safety standard despite several differences in calculation results.

ACKNOWLEDGEMENT

Authors thank to Universitas Sriwijaya for providing the funding Anggaran DIPA Badan Layanan Umum SP DIPA -023.17.2.677515/2022, 13 December 2021; SK Rektor Nomor 0004/UN9/SK.LP2M.PM/2022, 15 June 2022; with the contract No. 0029.14/UN9/SB3.LP2M.PM/2022, 11 July 2022, to carry out this community service (Pengabdian kepada Masyarakat).

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