Modelling of Neutral to Earth Voltage (NTEV) using RLC Grounding System and Current Injection Method

Mohd Abdul Talib Mat Yusoh, Ahmad Farid Abidin, Zuhaila Mat Yasin

***Abstract*—Neutral to Earth Voltage (NTEV) rise on the commercial building can be categorized as one of the power quality (PQ) problems due to abnormal load, nonlinear load, poor grounding, and improper wiring. This paper presents the modelling of NTEV on the commercial building considering the magnitude and patterns of waveform using RLC circuit models and current injection method. The current injection and RLC circuit model are represented as a load distribution board and grounding electrode system on the commercial building respectively. Pearson correlation coefficient is utilized in order to validate the rate of accuracy on simulation model. According to the simulation, RLC grounding system produces the results which highly correlated as compare to the actual measurement.**

***Index Terms*—Neutral to Earth Voltage (NTEV), Power Quality, Neutral Current, Current injection, Pearson Correlation coefficient.**

I. Introduction

NEUTRAL TO EARTH VOLTAGE (NTEV) can be classified as one of the problems in power quality (PQ) on the commercial building[1]. The NTEV is the voltage between the neutral conductor and earth surface [2]. Generally, the NTEV magnitude is zero in a balanced system which means that the loads on phase A, phase B, and phase C are identical to others. However, in a real situation for a large scale Distribution System (DS), the unbalanced loading condition is a common phenomenon. It is difficult to produce a perfect load balance condition [3] due to the consumer behavior load, power electronic devices, poor wiring, and fault on the DS. The unbalanced load condition can lead to the NTEV rise. This situation could cause hazard for human, animal, and electrical equipment.

Under normal condition, the NTEV on the upstream (substation) and downstream (consumer load) will be less than several Volts. According to IEEE standard 1695, the nominal threshold voltage of NTEV level should be less than 10V [2].

There are many studies has been carried out to establish the reliable model for the NTEV. In reference [4], the study on the effect of harmonic distortion toward the NTEV by using bridge rectifier circuit has been conducted. However, the parameters of harmonic contents on the load is not stated clearly which lead an inaccurate NTEV result. Furthermore, the bridge circuit has limited in producing the multiple harmonic distortion which experience on the consumer load. Therefore, it is difficult to analyse the effect of the NTEV due to harmonic.

The NTEV analysis using single resistor grounding electrode which based on the imbalance load, power factor correction and variation length of grounding electrode has been conducted in [5]. However, this technique did not consider the effect of frequency variation on the grounding system. The analysis of NTEV by using three phase harmonic Current Injection Method (CIM) has been discussed in [6]–[9]. The systems are incorporated with the balanced load, nonlinear load, different resistance grounding, loss grounding electrode, and third harmonic load. However, the studies do not show in detail the operation of CIM circuit in order to produce the load which consisting the unbalanced and nonlinear load. Besides that, the validation and accuracy of CIM results is not thoroughly tested on the commercial building.

Theoretically, the NTEV profile is basically are identical with the neutral current (NC) on the DS. However, based on the actual measurement, the patterns are differ and seem not have related each other. Hence, the main contribution of this paper is to propose an accurate grounding system which show the relation between NTEV and neutral current. The model is developed based on RLC circuit and CIM circuit for the load of commercial building. From this model, it is expected that the troubleshooting of the neutral grounding problem can be easily traced.

This paper is organized as follows. In section 2, the design methodology is explained in which including circuit model with multiple load DB, CIM circuit model, lumped RLC grounding circuit and Pearson correlation coefficient. In section 3, the detail of the result such as CIM load DB waveform, validation result of DB load waveforms using Pearson correlation coefficient, Comparison NTEV and NC waveform based on magnitude and patterns has been

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reported. Finally, conclusions are presented in the last section.

II. DESIGN METHODOLOGY

Fig. 1 illustrates the overall methodology to develop the ground system which producing NTEV on commercial building. Firstly, the load data are collected from the commercial building by using fluke meter. Typically, the collected data could consist of the phase current, neutral current and NTEV. Then, based on the recoded data, the CIM and RLC circuit models are develop in order to produce the NTEV on the commercial building.

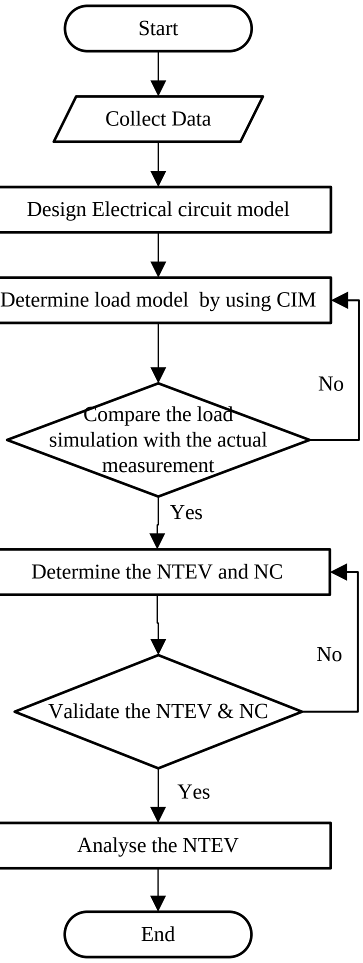

Fig. 1: Flowchart of NTEV analysis

A. *Low Voltage (LV) Electrical Circuit Network System*

The electrical circuit model as shown in Fig. 2 is abasic circuit on the DS which supply the voltage of 415V and frequency, 50Hz from substation to the consumer load. The impedance of cables from the transformer to the load has been determined based on standard IEC60502 [10].

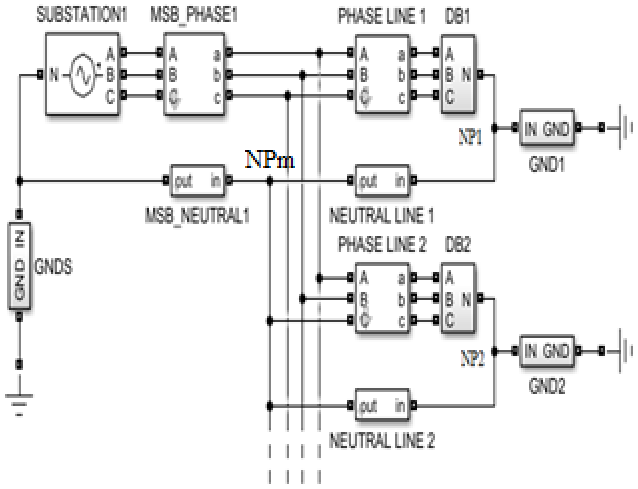

Fig. 2: Low voltage (LV) electrical circuit model with multiple DB load

Fig. 3 shows the neutral and ground current flow from the load DB1 to the substation. The NP1 point is simplified as the junction current flow from the DB1 load, (I_{NL1}) go throughout the substation via the line neutral conductor, (I_{N1}) and ground current, (I_{G1}).

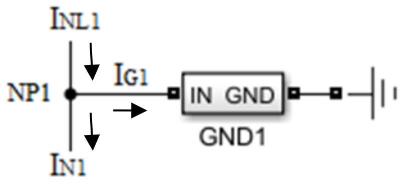

Fig. 3 Neutral and ground current flow

Based on the figure, the derivation equation to determine NTEV are as follows:

$$I_{NLn} = I_{Ln} + I_{Gn} \tag{1}$$

$$I_{Ltotal} = I_{L1} + I_{L2} + I_{Ln} \tag{2}$$

where

I_{NLn} =Neutral current from the DB load

I_{Ln} =Neutral current after point NP1

I_{Ltotal} = Total neutral current from each DB load

I_{Gn} = Ground current on the DB load

n = 1,2,3… represented number of the DB load

In (2) shows the total neutral current, I_{Ltotal} is also can be called as the neutral current on the MSB due to the flow of neutral current from each branch of DB will be combined at N_{Pm} point and produce the new neutral current. Besides that, (I_{GS}) is a total current return from the load of grounding system to the substation (3). Furthermore, the neutral current at the source of transformer can be determined as in (4) and the NTEV on the commercial building can be determined according the expression in (5).

$$I_{GS} = I_{G1} + I_{G2} + I_{Gn} \tag{3}$$

$$I_{NS} = I_{Ntotal} + I_{GS} \quad (4)$$

$$\begin{aligned} NTEV_S &= I_{GS} Z_S \\ NTEV_1 &= I_{G1} Z_{G1} \\ NTEV_2 &= I_{G2} Z_{G2} \\ NTEV_n &= I_{Gn} Z_{Gn} \end{aligned} \quad (5)$$

Where:

$n = 1,2,3,...$

I_{GS} = Ground current at substation

I_{NS} = Neutral current to transformer

$NTEV_S$ = NTEV at the substation

$NTEV_1$ = NTEV at the load of DB1

$NTEV_2$ = NTEV at the load of DB2

$NTEV_n$ = NTEV at the load of other DB

B. CIM Circuit Model Concept

Normally, in real situation, the load DB consists of multiple harmonic distortions in which it is often disrupt the operation of the DS, electrical equipment, and others. The CIM circuit is designed in order to produce harmonic distortion due to its simplicity since it does not require the semiconductor components or nonlinear devices. Other advantages of the CIM circuit is a simple circuit (resistor and current source used) compare with semiconductor components due to more flexible, high reliability and more accurate. Regarding to design the stage of CIM circuit, the rule of circuit theory should be followed, in which the current source should be connected in parallel with the resistor. The number of current sources represented numbers of the harmonic order applied on the circuit.

Fig. 4 shows three stage of load DB on the building. Stage 1 (AN), stage 2 (BN) and stage 3 (CN) can be categoried as the load at phase a, phase b and phase c respectively. All the stages are having interconnecting on the neutral conductor (N). Each stage consists of four current sources which connected in parallel with the resistor. The first current source on each stage can classify as the fundamental value for the current. The others represent the third, ninth and fifteenth current harmonic. Furthermore, the other harmonic content is not considering due to not effect on the waveform of neutral current, however if consider the waveform on the phase of loads building are more identical with actual measurement.

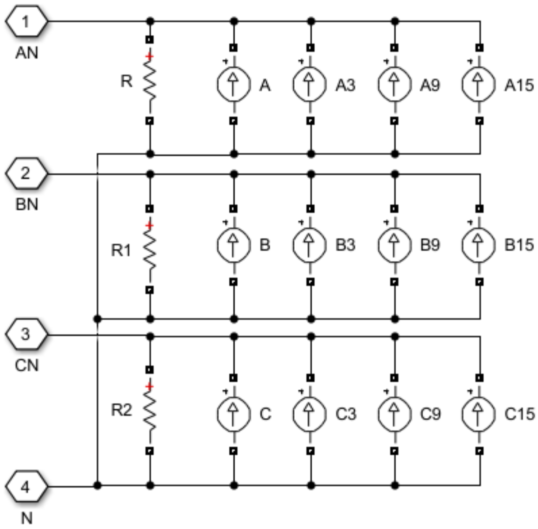

Fig. 4 Three stage CIM as the three phase DB load

Equation (7) and (6) show the simple equivalent CIM circuit.

$$\begin{aligned} I_{AN}\angle\theta_{AN} &= I_{h1}\angle\theta_{h1} + I_{h3}\angle\theta_{h3} + I_{h9}\angle\theta_{h9} + I_{h15}\angle\theta_{h15} \\ I_{BN}\angle\theta_{BN} &= I_{h1}\angle\theta_{h1} + I_{h3}\angle\theta_{h3} + I_{h9}\angle\theta_{h9} + I_{h15}\angle\theta_{h15} \\ I_{CN}\angle\theta_{CN} &= I_{h1}\angle\theta_{h1} + I_{h3}\angle\theta_{h3} + I_{h9}\angle\theta_{h9} + I_{h15}\angle\theta_{h15} \end{aligned} \quad (6)$$

$$I_{NL}\angle\theta_{NL} = I_{AN}\angle\theta_{AN} + I_{BN}\angle\theta_{BN} + I_{CN}\angle\theta_{CN} \quad (7)$$

The load current, I_{AN}, I_{BN} and I_{CN} as in (6) can be determined by adding the fundamental, third, ninth and fifteenth current source. Then, the neutral current, I_{NL} is adding all the phase of load current, I_{AN}, I_{BN}, and I_{CN} due to the phase current connected at the neutral point, N (7).

All the parameters as shown TABLE I need to considered during to design the CIM circuits because there are useful in produce the identical waveform with the measurement data. Furthermore, the parameters are significant important to the NTEV in which can cause high current on the neutral conductor.

TABLE I
PARAMETERS OF HARMONIC DISTORTION IN CIM CIRCUIT

Item	Phase A		Phase B		Phase C	
H	Magnitude	Angle	Magnitude	Angle	Magnitude	Angle
1	121.54	144.17	84.22	24.56	94.67	-70.85
3	8.82	-140.03	8.24	-41.45	9.63	-90.36
9	9.61	169.63	2.20	-157.76	2.43	-30.95
15	3.30	154.34	0.88	154.98	2.06	-48.16

The parameters of harmonic distortion on the DB loads as shown in TABLE I can be determined by using Fourier series as in (8).

$$f(t) = a_0 + \sum_{n=1}^{\infty} (a_n \cos n\omega_0 t + b_n \sin n\omega_0 t)$$
$$a_0 = \frac{1}{T}\int_0^T f(t)\,dt$$
$$a_n = \frac{2}{T}\int_0^T f(t)\cos n\omega_0 t\,dt \qquad (8)$$
$$b_n = \frac{2}{T}\int_0^T f(t)\sin n\omega_0 t\,dt$$

The parameters are important and useful for the CIM circuit in order to generate the identical waveforms with the actual measurement on the load building and produce an accurate result of phase load and neutral current. Furthermore, the shape of neutral current can influence the shape of NTEV due to the connection of grounding system connected on the neutral point, NP1.

C. Frequency Dependent Effect f or the Grounding system

Usually for the static analysis, the low frequency grounding is applied in which to consider as a single resistance grounding. However, in this case, the lumped RLC circuit as shown in Fig. 5 represented high frequency grounding used on the system due to the frequency variation [11], [12]. Moreover, the physical and chemical contents in the soil also plays vital rules on the reaction values of resistance, inductance and capacitance in lumped RLC[13], [14].

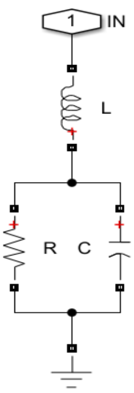

Fig. 5: Lumped RLC circuit

Based on the lumped RLC circuit model, the impedance will change based on frequency as follows[13]:

$$Z_G = j\omega L + \frac{R + \frac{1}{j\omega C}}{\frac{R}{j\omega C}} \qquad (9)$$
$$Z_{GS} = Z_{G1} = Z_{G2} = Z_{Gn}$$

$$Z_G = \frac{R}{1+[\omega.R.C]^2} + j\omega\left\{\frac{L - R^2C + (\omega.R.C)^2 L}{1+[\omega.R.C]^2}\right\} \qquad (10)$$

Where $n = 1,2,3,...$

According to the equation (10), the grounding system can be influenced by the frequency variation due to the $\omega = 2\pi f$. If frequency is zero, the impedance will become as Z=R and it can be classified as low frequency.

$$Z_G = X + jY \qquad (11)$$

$$X = \frac{R}{1+[\omega.R.C]^2}$$
$$\mathrm{Y} = \omega\left\{\frac{L - R^2C + (\omega.R.C)^2 L}{1+[\omega.R.C]^2}\right\} \qquad (12)$$

$$Z_G = r\angle\delta$$
$$r = \sqrt{X^2 + Y^2} \qquad (13)$$
$$\delta = \tan^{-1}\left(\frac{Y}{X}\right)$$

Where;

X = Real number of Z_G

Y = Imaginary number of Z_G

r = Magnitude of Z_G

δ = Phase angle of Z_G

According in (12) and (13), the NTEV can be expressed as follows:

$$NTEV\angle\theta = I\angle\alpha \times Z_G\angle\delta = IZ_G\angle(\alpha + \delta) \qquad (14)$$

θ = Phase angle of NTEV

α = Phase angle of current

From (14), if the frequency on the grounding system is zero, the impedance (Z) is equal to R, and its' phase angle is equal to zero with same magnitude. Therefore, the waveform of NTEV is identical with ground. In most cases, the shape of NTEV waveform will differs from the neutral current due to changes of frequency in the grounding system. For example, if the frequency regularly changes, then, the magnitude and phase angle of impedance will also change.

The frequency on the grounding system that contribute to the shape of NTEV is also known as the harmonic frequency. The harmonic frequency appears at the neutral current and consequently its' generate the shape of NTEV which differ from neutral current. Fig. 6 shows the comparison of variation the harmonic frequency on the voltage and current. From the figure, it is clearly observed that the third, fifth and ninth harmonic frequency injected through lumped RLC generate a different shape of NTEV as compare to neutral current.

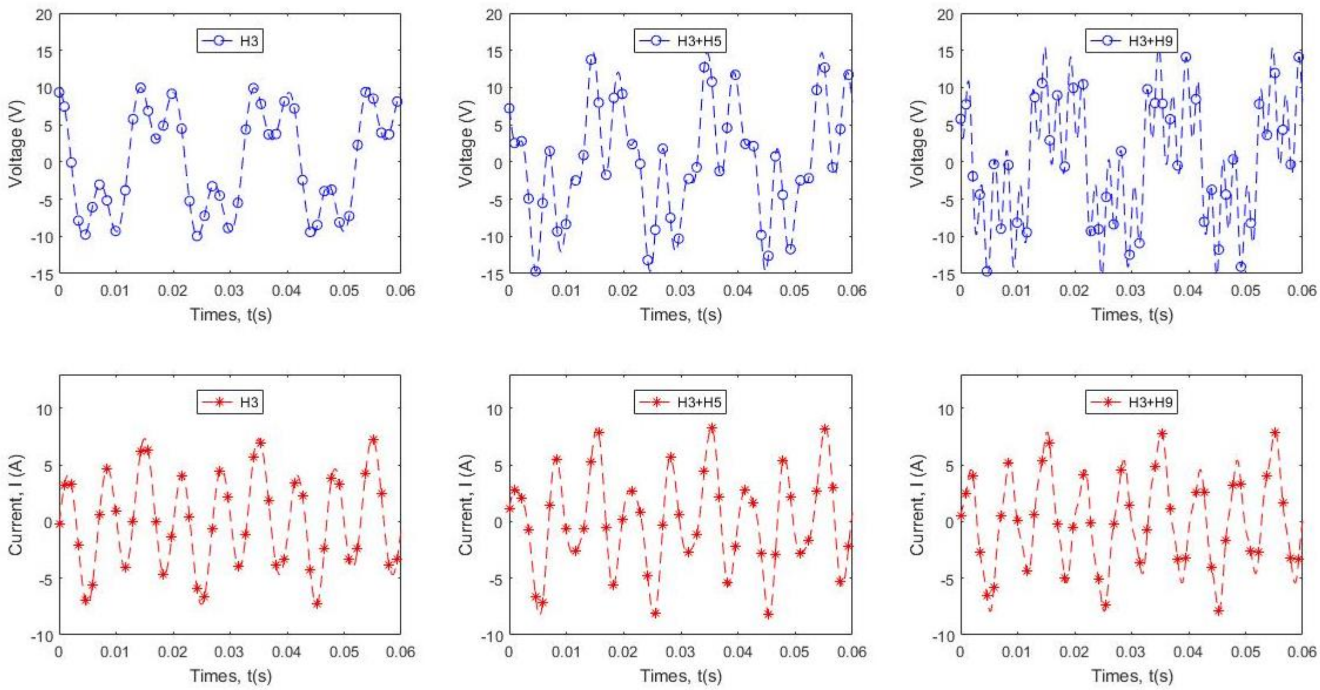

Fig. 6: The harmonic frequency effect on the voltage and neutral

D. *Pearson Correlation Coefficient Technique*

All the validation will be done through the comparison of the actual reference signal with the simulation signal model. Pearson correlation coefficient is selected to indicates the relationship between two variables caused reliability and popular [16].

Pearson correlation coefficient is a measure of linear dependence between two variables (actual value vector and estimated value vector). Normally two variable x and y as the covariance (different value x and y change together) of the two variable divided by the product of their standard deviation (act as a normalization factor) and it can be equivalently defined [17]:

$$r_{xy} = \frac{\sum(x_i - \bar{x})\sum(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2}\sqrt{\sum(y_i - \bar{y})^2}} \tag{15}$$

Pearson correlation coefficient indicates the degree of the relationship between two variables x and y. The sign of coefficient correlation is positive if the variables are directly related and negative if inversely related. The range coefficient, r_{xy} value is between -1 until 1. If r_{xy}=0, the variables x and y are uncorrelated. The perfect correlation, if the variable r_{xy} closer to 1 or negative 1. The specific relationship is shown in the following table [18], [19].

TABLE II
CORRELATION COEFFICIENT AND CORRELATION DEGREE

Correlation Coefficient	**Correlation Degree**
R_{xy}=1	Completely related
R_{xy}=0	Completely unrelated
R_{xy}=-1	Completely opposite
0.00~±0.30	Extremely weak correlation
±0.30~±0.50	Low correlation
±0.50~±0.80	Moderate correlation
±0.80~±1.00	Highly positively correlated or negatively correlated

III. RESULTS

This section describes the CIM circuit analyses, Pearson correlation coefficient and the comparison of waveforms based on the magnitude and patterns.

A. *CIM Circuit Analyses for The DB Load*

Based on the data in TABLE I, the DB load waveforms as shown in Fig. 7-Fig. 9 are similar with the actual measurement. However, according to the Fig. 8 and Fig. 9, there are slightly different in magnitude of the waveforms due to a several of harmonic distortion on the load DB which is not consider in CIM circuit model. This CIM model only concentrates on the triplen harmonic since others harmonic are not significant in this study.

As a conclusion, the DB load on the commercial building can be determined by using CIM circuit. Then, the load of waveforms can be more accurate and precise, if more harmonic distortions are attached to the CIM circuit models.

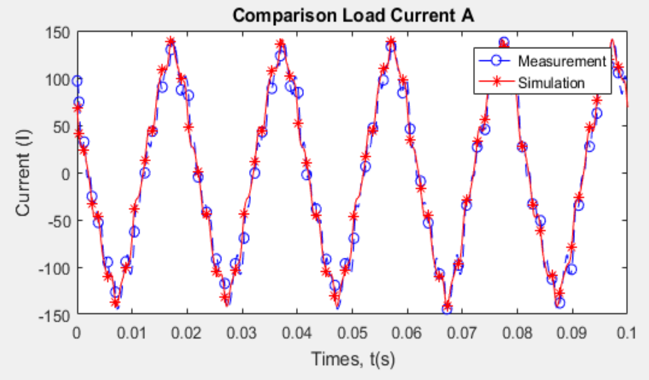

Fig. 7: Comparison DB load current at phase A with actual measurement

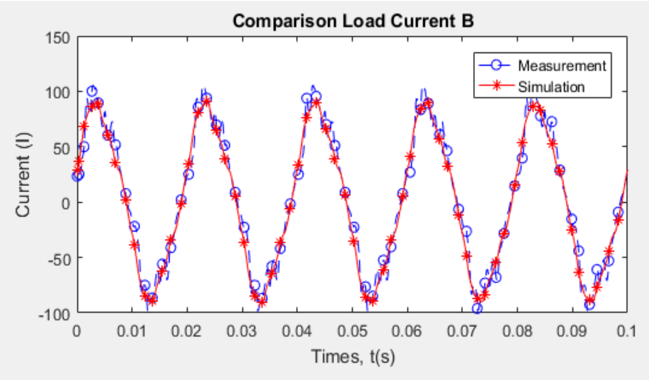

Fig. 8: Comparison DB load current at phase B with actual measurement

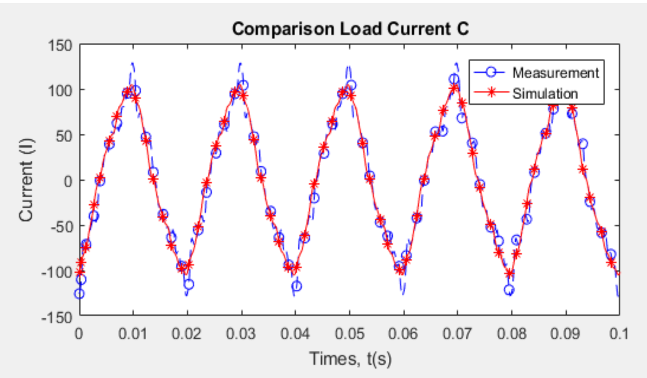

Fig. 9: Comparison DB load current at phase C with actual measurement

B. *Pearson Correlation Coefficient for CIM circuit model*

In order to validate the accuracy of the model, the Pearson correlation coefficient technique is used to compare the simulation and actual measurement data. Fig. 10, Fig. 11, and Fig. 12 show the Pearson correlation coefficient results are 0.98917, 0.9855, and 0.98309 respectively. All the results obtained are near to unity, therefore, it can be concluded that the simulation waveforms are highly identical with the actual measurement.

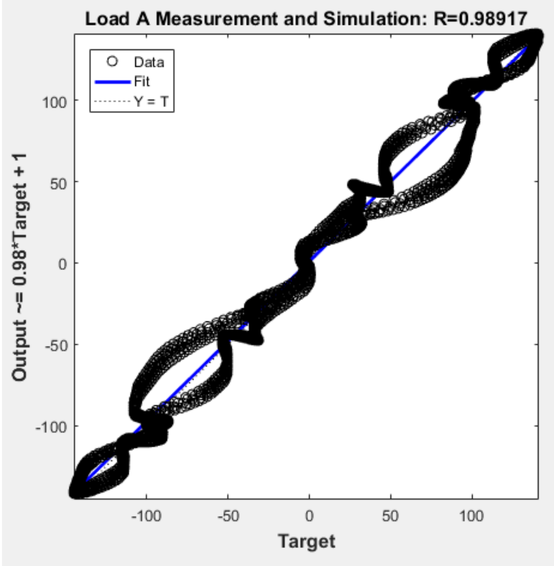

Fig. 10: Identify an accuracy of CIM model on phase A by using linear regression

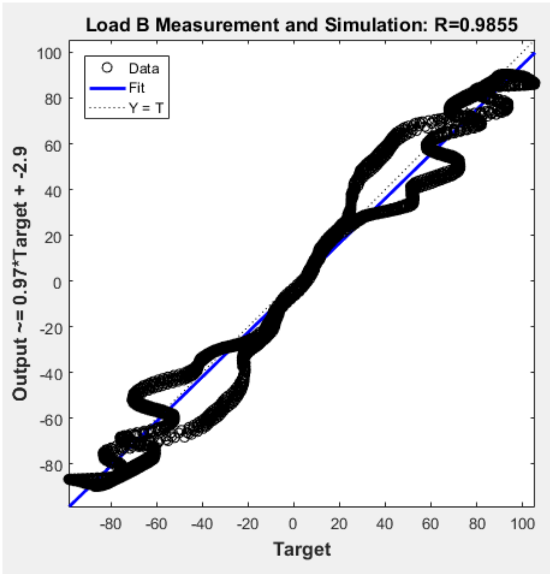

Fig. 11 Identify an accuracy: of CIM model on phase B by using linear regression

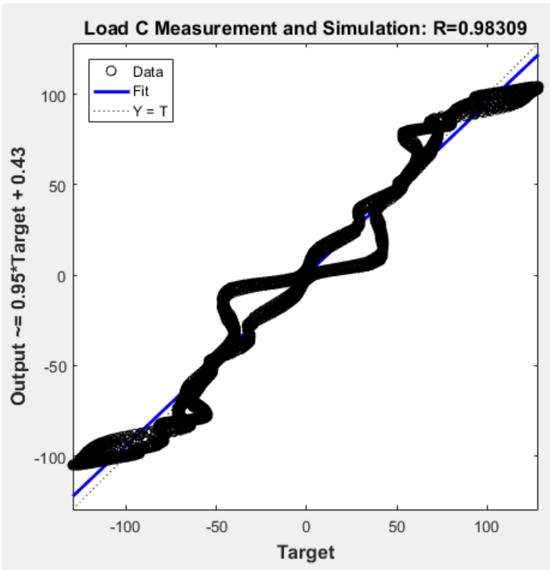

Fig. 12: Identify an accuracy of CIM model on phase C by using linear regression

C. Comparison the NTEV and NC waveforms Based On Magnitude and Patterns

Fig. 13 and Fig. 14 present a comparison between measurement of NTEV and NC results based on the magnitude and pattern respectively. From, Fig. 13 it can be observed that the simulation results are almost similar with the actual measurement data. However, there are slightly different in the NTEV magnitude.

Similar observation can be seen in Fig. 14 where the pattern of NC measurement and simulation are quite similar even though the magnitude are different.

Then, the shape of waveform between NTEV and NC are totally different in each other due to the effect of the lumped RLC grounding. Normally the lumped RLC grounding is including the effect of frequency variation.

Furthermore, by using Pearson method, the values of correlation coefficient for NTEV and NC are 0.85276 and 0.88566 respectively. According to the Pearson method, the results are accurate due to the correlation coefficient value is close to the perfect value, 1.

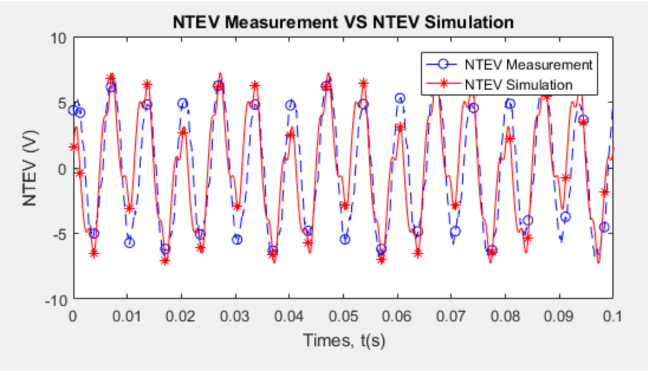

Fig. 13: Comparison of NTEV result based on magnitude and pattern

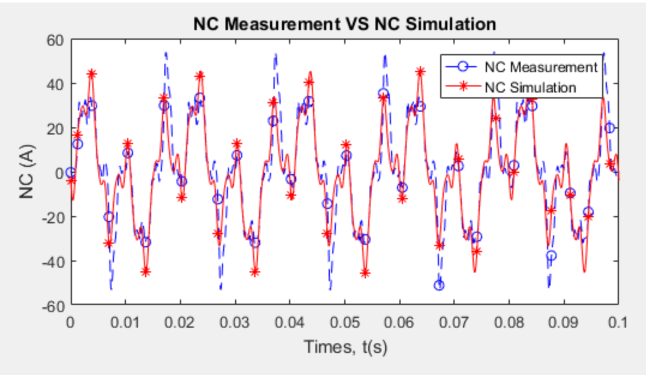

Fig. 14:Comparison of NC result based on magnitude and pattern

IV. CONCLUSION

This paper is presented the RLC grounding and CIM circuit models which can be utilised to analyse the NTEV on the commercial building. As the conclusion, the methods are proven to be reliable and accurate due to the simulation results are highly correlated and the NTEV waveform is almost similar with the actual measurement. The current injection model can be used in order to identify the load building which contains multiple harmonic distortions even the waveform in the non-sinusoidal condition. For the magnitude and patterns of the NTEV, the RLC grounding model is utilised in order to consider as the frequency variation and soil characteristic on the DS which can identical the actual waveforms.

For the further studied a comparison models of grounding system on the building can be explored to analyse the NTEV due to the different mode of frequency grounding. That is important to identify the accuracy model due to avoid miscalculating and misassumption on the NTEV analyses.

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