

Research Article

Impacts of Light Rail Transit Tram on the Voltage and Unbalance of the Distribution System

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This paper presents the three-phase voltage and unbalance analysis for the distribution system with the loading of a light rail transit (LRT) tram. To investigate the dynamic responses of the system voltage and current, this paper adopts the Alternative Transients Program (ATP) software to model and simulate a multigrounded four-wire distribution system with an LRT loading. Two different definitions about unbalance are used to evaluate the problem. In this paper, the traction supply substation (TSS) with a single-phase transformer configuration is designed first for providing the electric power to the trams of LRT. However, it may result in the significant neutral line current and unbalance phenomenon to deteriorate the power quality of the distribution system. A Le-Blanc connection transformer in the TSS is therefore proposed to solve the problems.

1. Introduction

Many counties and cities in the world are keen on planning light rail transit (LRT) system to meet the growing demand of public transportation. The LRT takes the advantages of low cost, low noise, low pollution, mature technology, short construction period, and easy maintenance. In addition, it may utilize electrical power from distribution systems of power grid because of its lower power requirements than the traditional railway and mass rapid transit systems. In general, it is very suitable to use the LRT as the public transport of the metropolitan areas and a variety of urban transport connections [1–3]. The tram of LRT is a heavy and irregular load, and it carries many power electronic equipment; the power quality of the distribution system can inevitably be affected [4, 5]. For the distribution system with the LRT, it may cause voltage fluctuation, unbalance, and harmonic and other power quality issues. To ensure the power quality, utilities have published many limits on these issues.

The traction power substation (TSS) supplies the LRT with either alternating current (AC) or direct current (DC) electric power. Mostly, the AC power may cause three-phase unbalance problem, while the DC power supply will generate

a harmonic problem. In this paper, the AC supply systems are considered, and the three-phase unbalance problem is the main investigation issue. This study case is based on a typical Taiwan Power Company (Taipower) 11.4 kV distribution feeder with four-wire and multigrounded system [6]. And the ATP [7] software is applied to establish the selected distribution feeder and the different AC power supply structures of the LRT. After that, it is used to execute three different operating scenarios. The instantaneous three-phase voltage and current and neutral line current are therefore simulated to calculate unbalance. By the way, two different definitions, the negative sequence unbalance ratio and unbalance factors [8], are both adopted for evaluating the three-phase unbalance of the distribution system.

2. LRT Impacts on the Unbalance of the Distribution Systems

Three-phase voltages (V_A , V_B , and V_C) can be decomposed into three separate phase sequence (V_1), the negative phase sequence (V_2), and the zero-phase sequence (V_0) components, as shown in (1). It is well known that only the positive

phase sequence exists in the balanced system. Consider

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix}, \quad (1)$$

where $a = 120\angle 0^\circ$. Negative sequence unbalance in a three-phase system is defined as the ratio of the magnitude of the negative sequence component to the magnitude of the positive sequence component, while the zero sequence unbalance is defined as the magnitude of the zero sequence component to the magnitude of the positive sequence component, expressed as a percentage [8]. This definition can be applied for either voltage or current as shown in the following:

$$\begin{aligned} d_2 (\%) &= \frac{V_2}{V_1} \times 100\%, \\ d_0 (\%) &= \frac{V_0}{V_1} \times 100\%, \\ m_2 (\%) &= \frac{I_2}{I_1} \times 100\%, \\ m_0 (\%) &= \frac{I_0}{I_1} \times 100\%. \end{aligned} \quad (2)$$

In addition, three-phase voltage unbalance factor (VUF) and current unbalance factor (IUF) can also be defined as the ratio of the maximum deviation of a voltage or current from the average value to the average value, expressed in percentage, using phase-to-phase voltage or current as follows:

$$\begin{aligned} \text{VUF} (\%) &= \frac{\text{Max}(|V_{\text{avg}} - V_{AB}|, |V_{\text{avg}} - V_{BC}|, |V_{\text{avg}} - V_{CA}|)}{V_{\text{avg}}} \\ &\times 100\%, \\ \text{IUF} (\%) &= \frac{\text{Max}(|I_{\text{avg}} - I_{AB}|, |I_{\text{avg}} - I_{BC}|, |I_{\text{avg}} - I_{CA}|)}{I_{\text{avg}}} \\ &\times 100\%, \end{aligned} \quad (3)$$

where

$$V_{\text{avg}} = \frac{V_{AB} + V_{BC} + V_{CA}}{3}, \quad I_{\text{avg}} = \frac{I_{AB} + I_{BC} + I_{CA}}{3}. \quad (4)$$

The voltage and current unbalance ratio limitations are set with different provisions according to different types of load duration by different institutions. In general, the voltage service of negative sequence unbalance (d_2) is less than 3%. The current unbalance can be considerably higher, especially when single-phase loads are present [8]. For the rail systems in Taiwan, the value is limited to 1% and 1.2% for one day and 15 minute measurement period, respectively.

3. Le-Blanc Connection Transformer

A single-phase power supply for LRT will give rise to the problem of three-phase unbalance. In general, this problem can be improved by using the static var compensators (SVC) or a special connection of transformers, such as the Le-Blanc transformer connection. The purpose of the Le-Blanc transformer connection is to convert a three-phase system into two single-phase systems with symmetrical primary current. Figure 1 shows the wiring diagram of the Le-Blanc transformer [9]. The secondary outputs of two single-phase voltages, V_m and V_t , have the characteristics of equal magnitude and 90 degrees phase shift. N_1 and N_2 are the number of winding turns at primary and secondary, respectively. Figure 2 gives the voltage vector diagram of the transformer.

The relations of the primary and secondary voltages of the Le-Blanc transformer can be written as

$$\begin{aligned} V_m &= \frac{1}{\sqrt{3}} \frac{N_2}{N_1} (V_B + V_C - 2V_A), \\ V_t &= \frac{N_2}{N_1} (V_B - V_C). \end{aligned} \quad (5)$$

The primary currents of the transformer are given by

$$\begin{aligned} I_A &= I_{AB} - I_{CA}, \\ I_B &= I_{BC} - I_{AB}, \\ I_C &= I_{CA} - I_{BC}. \end{aligned} \quad (6)$$

Also, the primary and secondary currents are dependent and can be expressed as

$$\begin{aligned} I_{CA} &= \frac{1}{\sqrt{3}} \frac{N_2}{N_1} I_m - \frac{1}{3} \frac{N_2}{N_1} I_t, \\ I_{BC} &= \frac{2}{3} \frac{N_2}{N_1} I_t, \\ I_{AB} &= -\frac{1}{\sqrt{3}} \frac{N_2}{N_1} I_m - \frac{1}{3} \frac{N_2}{N_1} I_t. \end{aligned} \quad (7)$$

Substituting (7) into (6) will result in

$$\begin{aligned} I_A &= -\frac{2}{\sqrt{3}} \frac{N_2}{N_1} I_m, \\ I_B &= \frac{1}{\sqrt{3}} \frac{N_2}{N_1} I_m + \frac{N_2}{N_1} I_t, \\ I_C &= \frac{1}{\sqrt{3}} \frac{N_2}{N_1} I_m - \frac{N_2}{N_1} I_t. \end{aligned} \quad (8)$$

Furthermore, the relation of voltages and currents at the secondary side can be expressed as

$$I_m = Y_m V_m, \quad I_t = Y_t V_t, \quad (9)$$

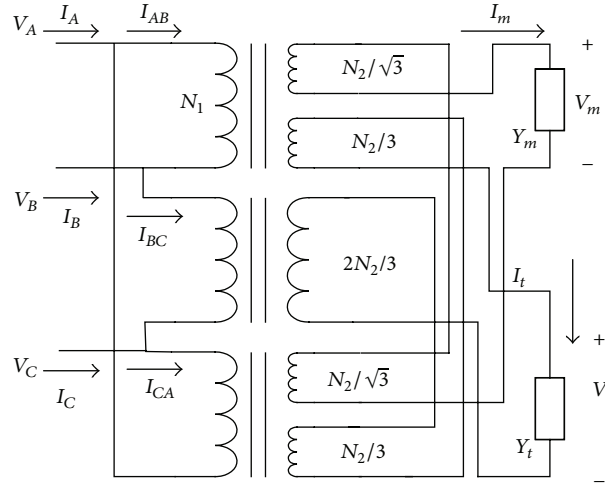


FIGURE 1: The Le-Blanc transformer connection diagram.

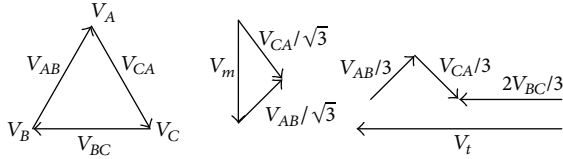


FIGURE 2: The Le-Blanc transformer voltage vector diagram.

where Y_m and Y_t are the admittances of the loading at secondary side. The primary line currents are thus obtained by substituting (9) into (8) as follows:

$$\begin{aligned} I_A &= -\frac{2}{\sqrt{3}} \frac{N_2}{N_1} Y_m V_m, \\ I_B &= \frac{1}{\sqrt{3}} \frac{N_2}{N_1} Y_m V_m + \frac{N_2}{N_1} Y_t V_t, \\ I_C &= \frac{1}{\sqrt{3}} \frac{N_2}{N_1} Y_m V_m - \frac{N_2}{N_1} Y_t V_t. \end{aligned} \quad (10)$$

It is found that the sum of the primary line currents must be zero, which keeps three-phase balanced, regardless of the load at the secondary side.

4. Distribution System and LRT Modeling

Figure 3 shows the equivalent model of a multigrounded four-wire distribution system by the ATP software. The 69 kV high voltage side of the distribution substation is simplified as an ideal three-phase source with a short circuit capacity of 1000 MVA. The test feeder is fed by a 69 kV/11.4 kV, 25 MVA power transformer sited in the distribution substation. The primary feeders and laterals are all overhead construction and their parameters are listed in Table 1. In addition, there are 13 distribution transformers to serve the customers that are distributed along the test feeder. The active power and reactive power consumption of the customers in the feeder

TABLE 1: Line parameters.

Impedance	Conductor			
	Feeder		Lateral	
	Phase	Neutral	Phase	Neutral
Resistance (Ω/km)	0.131	0.209	0.945	0.945
Resistance (Ω/km)	0.364	0.382	0.355	0.355

are 4560 kW and 3420 kvar, respectively. Besides, a capacitor bank with a rating capacity of 2100 kvar is installed at the end terminal of the feeder. It is assumed that the test distribution system is operated under balanced condition. The grounding resistance of the neutral point of the substation power transformer and the grounding points along the neutral wire are assumed to be 1 ohm and 25 ohm, respectively.

The electrical power of the tram must be fed from the TSS. The site of the TSS is 300 m from the distribution substation along the feeder. Figure 4 shows the TSS with a single-phase transformer to supply the tram. In Figure 5, the transformer is replaced with the proposed Le-Blanc transformer connection, which converts a three-phase power into two single-phase powers to supply the tram. The AC power voltage is further step down by the transformer installed at the tram and is rectified into DC power then. Finally, it is converted into controllable voltage and frequency AC power to drive the induction motors with a total capacity of 720 kW for the tram.

5. Voltages and Unbalance Analysis

This section is to explore the influence of unbalance, voltage drop, and the neutral line current variation on the three-phase four-wire multi-grounding distribution feeder system with AC power supply to the tram.

5.1. Case 1: Original System. This case executes the relative analysis without considering the tram loading. First, the ATP software is applied to obtain the power system responses.

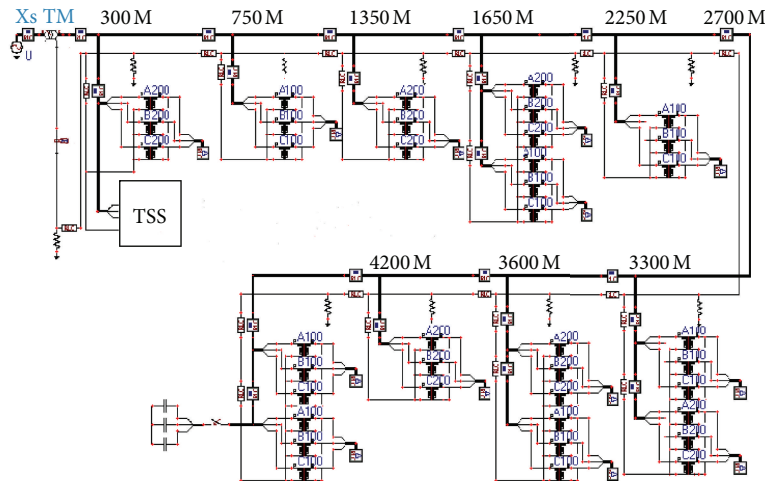


FIGURE 3: ATP modeling of the test distribution system.

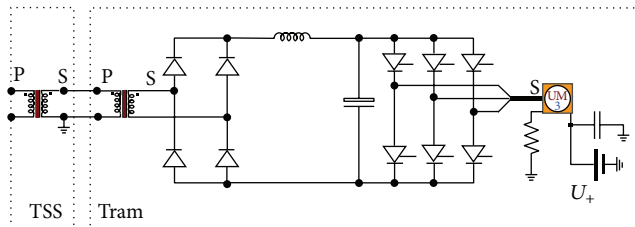


FIGURE 4: A TSS with the single-phase transformer connection.

For the original test feeder, the neutral line current is very close to zero as shown in Figure 6. It means that the original system is a balance system because all the load and lines are assumed to be three-phase balance. Figure 7 shows the three-phase voltage magnitude at different sites of the feeder. The secondary side of the substation has the highest phase voltage of 6543 V, which is about 0.994 pu. It is also observed that the lowest voltage of 6463 V occurred at the distance of 2700 m from the substation. It is acceptable for the utility because the voltage magnitudes at any feeder sites are higher 0.982 pu.

5.2. Case 2: TSS Using Single-Phase Transformer. In this case, the TSS supplies AC electric power to the tram through a singlephase transformer which is connected to the phase C of the utility grid as shown in Figure 4. First, the ATP software is executed to obtain the power system responses by assuming that one tram is running. Figure 8 shows the three-phase voltage magnitude. The secondary side of the substation has the highest phase voltages of 6536 V, 6543 V, and 6519 V for A, B, and C phases, respectively. Relatively, the lowest voltages appear at the distance of 2700 m from the substation, which are 6424 V, 6434 V, and 6433 V. It is acceptable for the utility because the voltage magnitudes at any feeder sites are higher than 0.976 pu. Figures 9 and 10 show the instantaneous three-phase voltage and current at the secondary side of the substation. It is observed that the current on phase C is larger than that on phases A and B due

to a contribution of 720 kW tram loading. Figure 11 shows the neutral current flow through the substation transformer.

By applying the unbalance definition previously, the voltage unbalances are calculated as $VUF = 0.65\%$, $d_2 = 0.47\%$ and $d_0 = 0.22\%$, while the current unbalances are obtained as $IUF = 27.3\%$, $m_2 = 15.7\%$, and $m_0 = 11.6\%$. Figures 12 and 13 show the voltage and current unbalances at the secondary side of the substation as the sites of the TSS change. When the TSS is located at 2250 m point, the voltage unbalances are calculated as $VUF = 0.52\%$, $d_2 = 0.27\%$, and $d_0 = 0.18\%$, and the current unbalances are obtained as $IUF = 23.7\%$, $m_2 = 13.6\%$, and $m_0 = 9.5\%$. Likewise, as the TSS is located at 4200 m point, the voltage unbalances are calculated as $VUF = 0.4\%$, $d_2 = 0.19\%$, and $d_0 = 0.13\%$, and the current unbalances are obtained as $IUF = 18.6\%$, $m_2 = 10.1\%$, and $m_0 = 7.2\%$. Figure 14 shows the neutral current flow through the substation transformer as the TSS is located at different points. The neutral currents are 132 A, 51.7 A, and 26 A as TSS is located at 300 m, 2250 m, and 4200 m points, respectively. Obviously, all the voltage and current unbalances and the neutral current vary as the TSS is located at different points. The further the TSS is located away from the secondary side of the substation, the smaller the values become.

5.3. Case 3: TSS Using the Le-Blanc Transformer. To reduce the unbalance problem resulting from the TSS with a single-phase transformer connection, the Le-Blanc transformer connection is adopted in the TSS as shown in Figure 5. Figure 15 shows the three-phase voltages at different buses along the feeder. At the secondary side of the substation, the three-phase voltages of V_A , V_B , and V_C are 6522 V, 6512 V, and 6521 V, respectively. These values decrease to 6435 V, 6425 V, and 6434 V at the distance around 2700 m from the substation. Figures 16 and 17 show the instantaneous three-phase voltages and currents at the secondary side of the substation. The neutral line current flows through the substation transformer, which is very small, as shown in

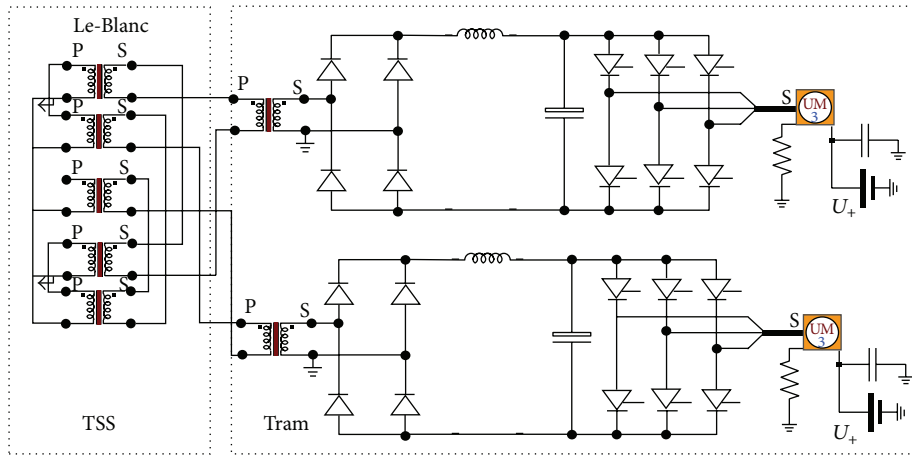


FIGURE 5: A TSS with the Le-Blanc transformer connection.

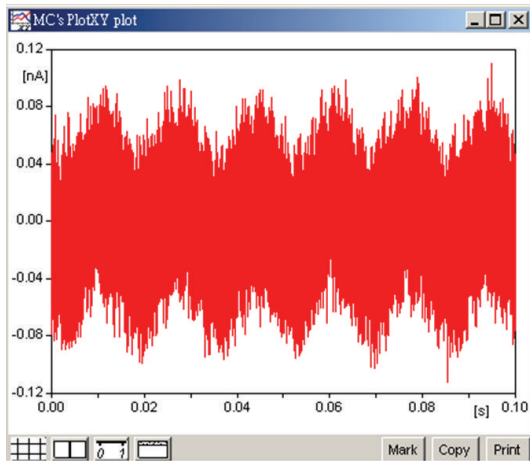


FIGURE 6: Instantaneous neutral line current at substation terminal for Case 1.

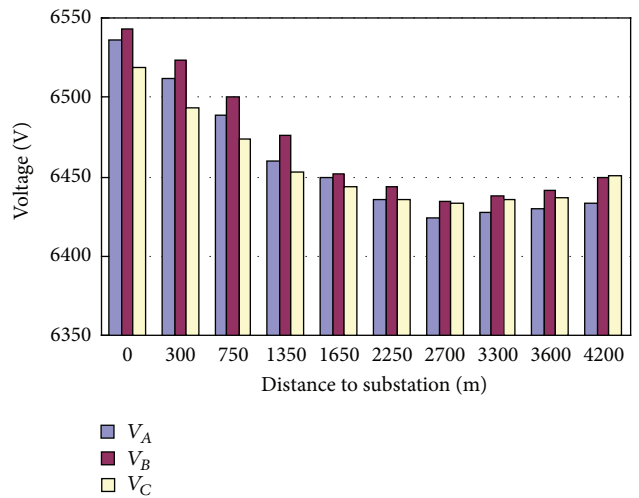


FIGURE 8: Three-phase voltage magnitudes at different feeder sites for Case 2.

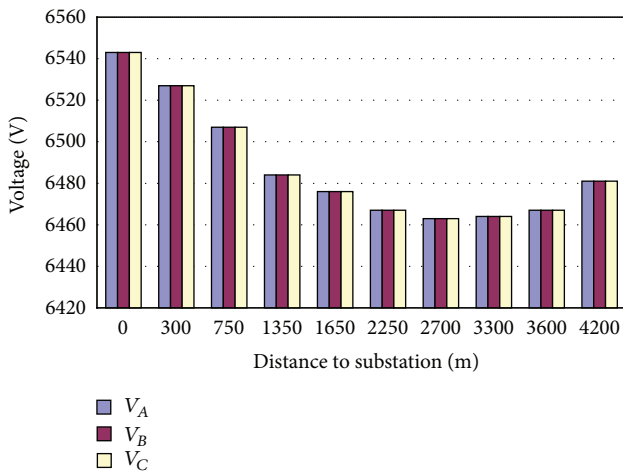


FIGURE 7: Three-phase voltage magnitudes at different feeder sites for Case 1.

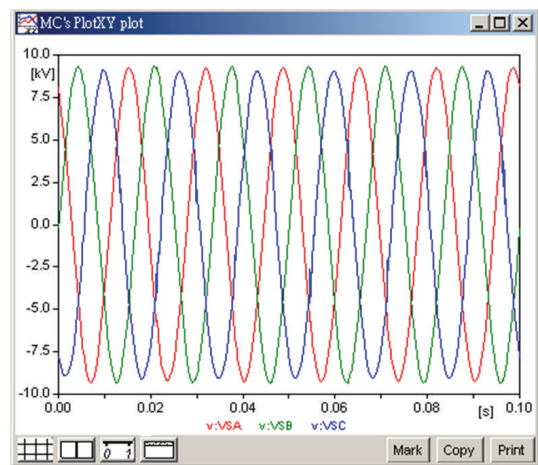


FIGURE 9: Instantaneous three-phase voltages at substation terminal for Case 2.

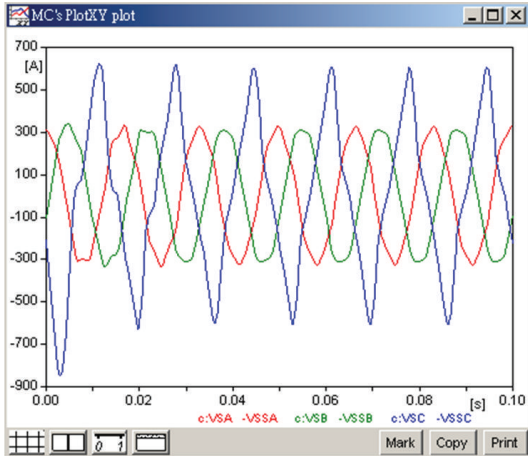


FIGURE 10: Instantaneous three-phase currents at substation terminal for Case 2.

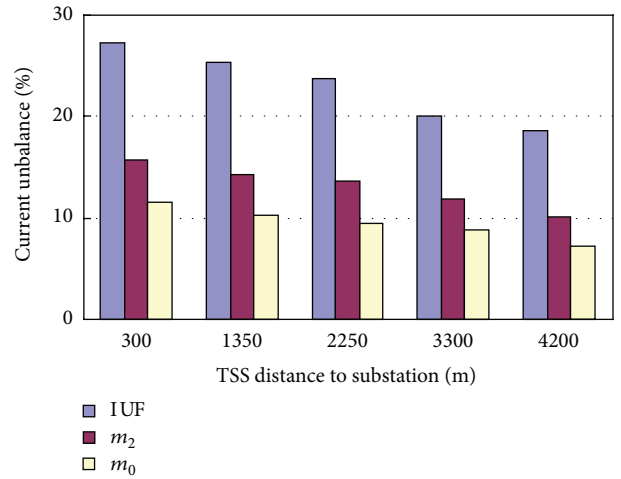


FIGURE 13: Current unbalance at substation terminal with different TSS sites for Case 2.

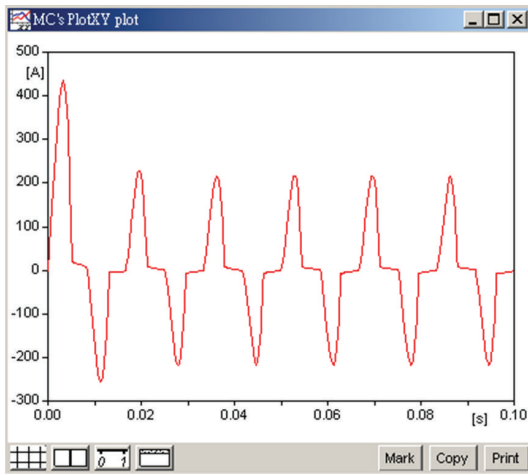


FIGURE 11: Instantaneous neutral line current at substation terminal for Case 2.

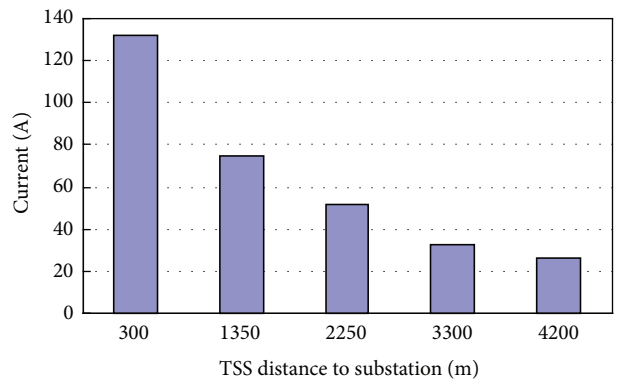


FIGURE 14: Neutral current at substation terminal with different TSS sites for Case 2.

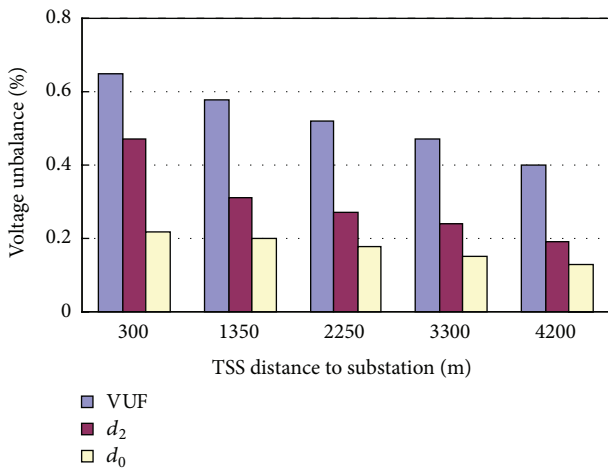


FIGURE 12: Voltage unbalance at substation terminal with different TSS sites for Case 2.

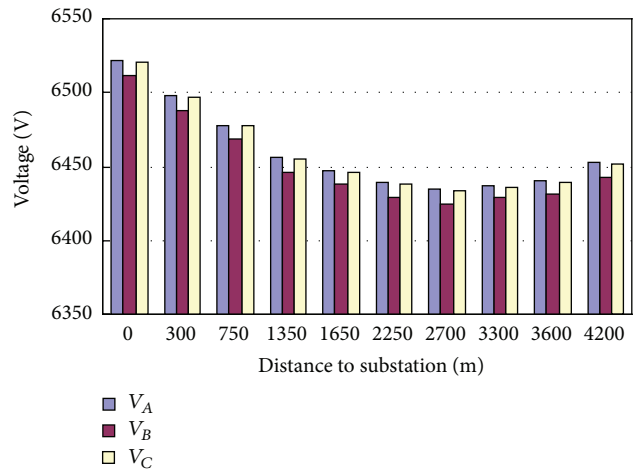


FIGURE 15: Three-phase voltage magnitudes at different feeder sites for Case 3.

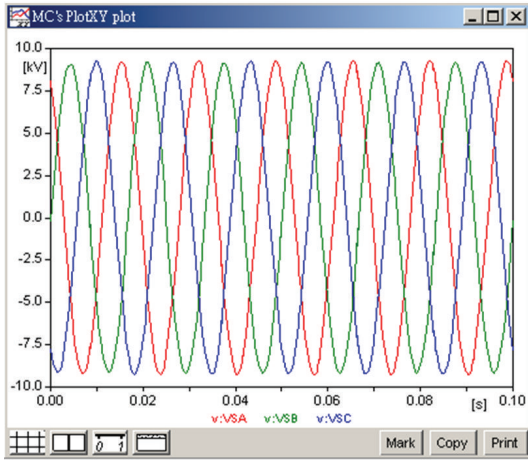


FIGURE 16: Instantaneous three-phase voltages at substation terminal for Case 3.

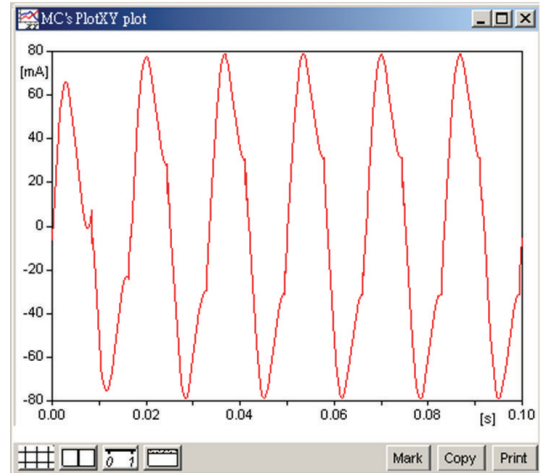


FIGURE 18: Instantaneous neutral line current at substation terminal for Case 3.

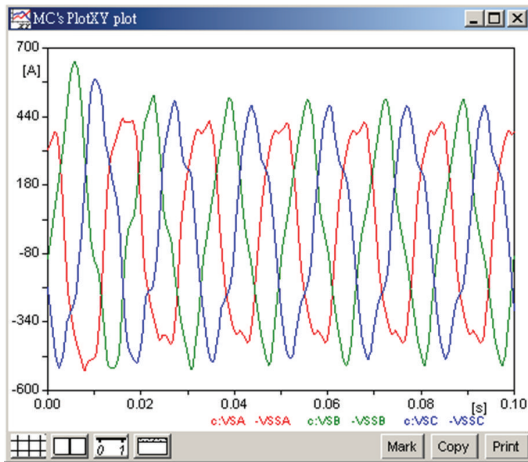


FIGURE 17: Instantaneous three-phase currents at substation terminal for Case 3.

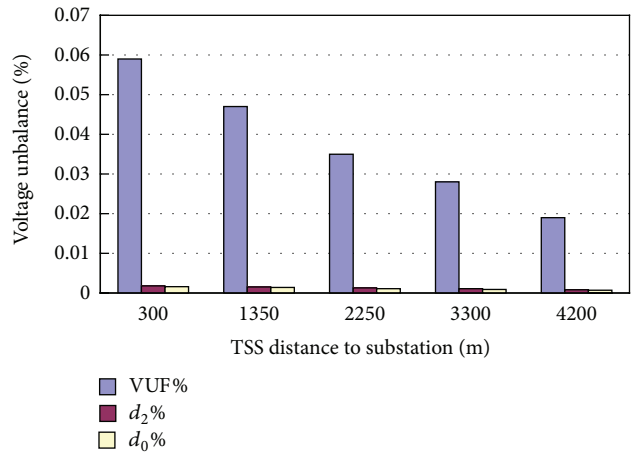


FIGURE 19: Voltage unbalance at substation terminal with different TSS sites for Case 3.

Figure 18. In this case, the voltage unbalances are calculated as $VUF = 0.059\%$, $d_2 = 0.0018\%$, and $d_0 = 0.0016\%$, and the current unbalances are obtained as $IUF = 0.06\%$, $m_2 = 0.0105\%$, and $m_0 = 0.0127\%$ at the secondary side of the substation.

Figures 19 and 20 depict the voltage and current unbalance as the TSS is in different locations away from the secondary side of the substation. The voltage unbalances are calculated as $VUF = 0.035\%$, $d_2 = 0.0013\%$, and $d_0 = 0.001\%$ when the TSS is located at a distance of 2250 m from the secondary side of the substation, and the current unbalances are obtained as $IUF = 0.0043\%$, $m_2 = 0.0092\%$, and $m_0 = 0.01\%$. The voltage unbalances are calculated as $VUF = 0.019\%$, $d_2 = 0.0008\%$, and $d_0 = 0.0007\%$ as the TSS is installed at the 4200 m point away from the secondary side of the substation, and the current unbalances are determined as $IUF = 0.0027\%$, $m_2 = 0.0074\%$, and $m_0 = 0.007\%$. Figure 21 illustrates the neutral line currents for different locations of the TSS. The neutral line currents are 73.5 mA, 26.4 mA,

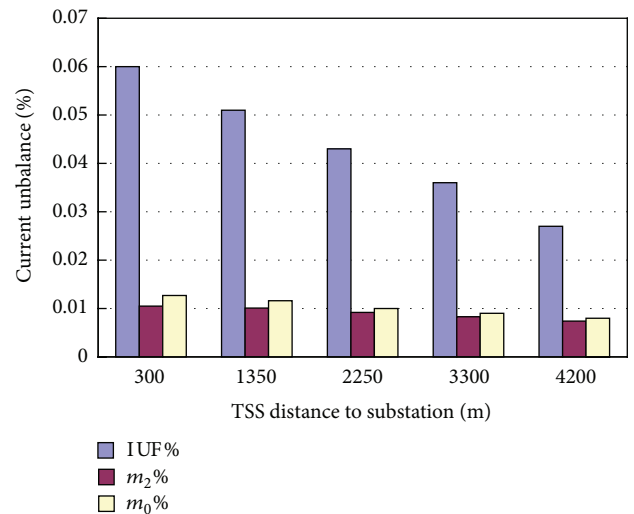


FIGURE 20: Current unbalance at substation terminal with different TSS sites for Case 3.

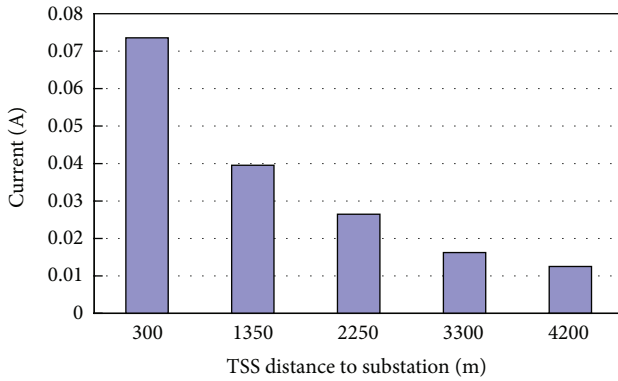


FIGURE 21: Neutral current at substation terminal with different TSS sites for Case 3.

and 12.5 mA when the TSS is located at 300 m, 2250 m, and 4200 m points, respectively.

6. Conclusions

For the original test system, it is a three-phase balance system. However, the neutral line current flowing through the substation transformer is increased to 132 A when the TSS of the LRT adopts a single-phase transformer to supply the tram. In addition, the negative voltage and current sequence unbalances at the secondary side of the substation are obtained as 0.47% and 15.7%, respectively. To improve the poor power quality phenomenon, the TSS with the proposed Le-Blanc connection transformer is then used. It is found that the neutral line current flowing through the transformer and the negative voltage sequence unbalance decreases to the values of 0.074 A and 0.002%, respectively. It is concluded that the proposed TSS design has a significant effect on three-phase unbalances reduction for the distribution system with an LRT loading.

Acknowledgment

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