

# VOLTAGE UNBALANCE PROBLEMS AND SOLUTIONS FOR ELECTRIFIED RAILWAY SYSTEMS

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**Abstract**—Voltage and current unbalance problems of power networks due to AC electrified railway systems are studied and their influences such as the voltage unbalance factor and the current negative sequence contribution factor injected to the network are calculated. Several methods can be used for reducing the power quality unbalance problems which have been proposed and the best of them is chosen by comparing the results of their unbalance and current negative sequence contribution factors.

**Index Terms**— Electrified railway, Power distribution system, Voltage unbalance, Current negative sequence.

## 1. Introduction

AC electrified railway systems are used widely around the world as a significant means of mass and public transportation. Such railway systems are usually fed by specialized traction substations which the main designs of them include the selection of a single phase 25 kV or two phase 2x25 kV systems which feed the train sets through the transformers and autotransformers in the traction substations, respectively. The schematic diagram of the power supply of AC electrified railways is shown in Fig. 1.

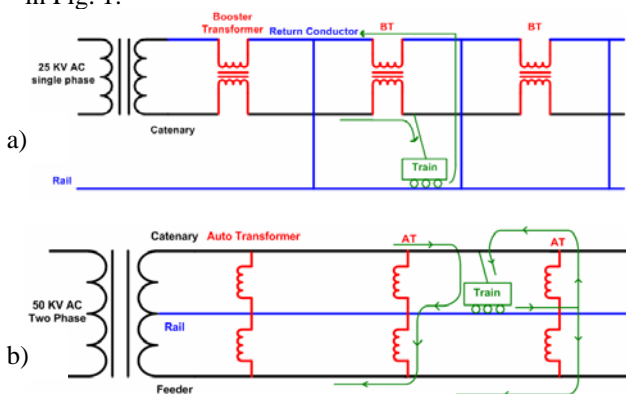


Fig. 1. Schematic of power distribution system feeding AC electrified railways utilizing:  
a) transformers, b) autotransformers

The moving characteristic of the train sets which either consumes or regenerates power on the track, causes the traction load to be considered mostly as unbalanced. This presents a huge unbalance impact to the utility as modern train sets are rated up to 20 MW while each supply zone can be up to 40–60 km. The specialized

traction substations are designed so that that when loads on the zones of a traction substations are the same and equal i.e. when  $I_1=I_2$  as shown in Fig. 2, the unbalance impact injected to the utility grid will be minimized except for the low-cost configuration case in which the zones are of the same phase. A typical load profile of a high-speed railway is also shown in Fig. 3.

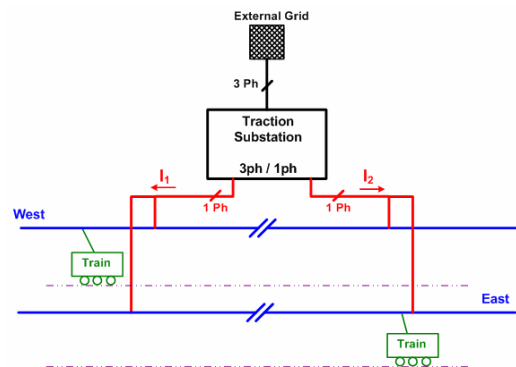


Fig. 2. AC traction substation feeding two sides of catenary in west and east directions

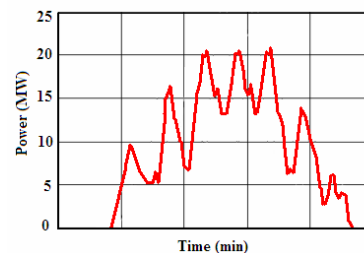


Fig. 3. Typical load profile of an AC electrified railway

In this paper, the voltage and current unbalance problems of the power network due to the AC electrified railways are studied and their impacts such as voltage unbalance and current negative sequence distribution factors are calculated. Several methods are proposed and studied for reducing the voltage unbalance problems of AC electrified railways and the unbalance factor and negative sequence contribution factor of such systems are calculated. By comparing the unbalance factors for the different solutions, the best method is chosen.

## 2. Unbalance factor

The maximum voltage unbalance factor should be calculated at the connection points of the main traction

substations to the utility network, which is dependant to the loading characteristics of the traction system. This calculation should be done for controlling and limiting the unbalance magnitude and duration.

Most utilities around the world use the voltage unbalance factor as a simple measure to limit the unbalance injections at the connection points of the traction substations. Table 1 shows the formulae for calculating the voltage unbalance factor injected from the traction substations to the utility grid for some transformer configurations.

Table 1. Voltage Unbalance Factor injected from the traction system to the grid at the connection point

Transformer configuration	Voltage Unbalance Factor
Single Phase	$\varepsilon_v = \frac{S_L}{S_S}$
V-V Three Phase	$\varepsilon_v = \frac{S_{L2} + \alpha^2 S_{L1}}{S_S}$
Scott Leblanc	$\varepsilon_v = \frac{S_{L2} - S_{L1}}{S_S}$

Possible changes of network configuration, whether it is the changes within the traction supply system due to load transferring or the daily, weekly or seasonal changes in the utility grid, should be carefully considered in the voltage unbalance calculations.

### 3. Negative sequence factor

The electrical equivalent circuit of the traction power supply system is shown in the appendix. The traction loads seen from the utility side can be directly derived from traction currents through the transformer configuration used in the traction substations. The currents  $I_a$ ,  $I_b$  and  $I_c$  as the unbalanced feeding currents of the traction substation can be converted to three balanced currents of  $I_+$ ,  $I_-$  and  $I_0$  based on the theory of symmetrical component.

It should be noted that the generators in the closest power stations are facing the current negative sequences that is injected to the power network from the connection point of the main traction substations. The percentage contribution from each generator in the AC power network is fixed for any current negative sequence injected to the network. Therefore, assuming  $I_G^2$  as the current negative sequence flowing into that generator and  $I_{PCC}^2$  as the current negative sequence injected to the AC network, the ratio is fixed irrespective of the magnitude and phase angle of the current negative sequence source at main traction substation point. Therefore, the negative sequence current distribution factor (NCDF) for the connection point of each traction substation can be calculated by:

$$NCDF_G = \frac{I_G^2}{I_{PCC}^2} \quad (1)$$

To derive this ratio for each generator at the point of connection of a main traction substation, a line-to-line

fault can be simulated at that point of connection and then divide the current negative sequence of each generator to the current negative sequence injection at that point, where  $I_G^2$  is now the fault current negative sequence at the connection point and  $I_{PCC}^2$  is the fault current negative sequence from that generator.

The current negative sequence for some transformer configurations can be calculated through Table 2.

Table 2. Current Negative Sequence due to unbalance problems injected from the traction system to the grid at the connection point

Transformer configuration	Current Negative Sequence
Single Phase	$I^2 = \frac{-1}{S_{base}} \cdot \frac{S_S \cdot S_L}{2S_L + S_S}$
V-V Three Phase	$I^2 = \frac{-1}{S_{base}} \cdot \frac{S_S^2 (S_{L2} + \alpha^2 S_{L1})}{S_S^2 + 2S_S (S_{L1} + S_{L2}) + 3S_{L1} S_{L2}}$
Scott Leblanc	$I^2 = \frac{-1}{S_{base}} \cdot \frac{S_S^2 (S_{L2} - S_{L1})}{S_S^2 + 2S_S (S_{L1} + S_{L2}) + 4S_{L1} S_{L2}}$

However, as the grid network is seldom completely balanced, errors are inevitably produced due to the unbalanced problems in the network. For reducing such errors, the computations should be done once without considering the traction substations and the next time with the traction loads, therefore, the exact NCDF impact due to the traction load can be calculated.

### 4. Unbalance restricting solutions

In order to minimize the voltage distortion, traction loads are usually connected to an external grid of 100 kV or higher, however, this also makes them electrically very close to utility generators thereby raising concerns for excessive negative sequence injection into utility generators. In this paper, solutions of reducing such problems are studied.

The most applicable and effective solution is the repetitive choosing the feeding phases of the traction substations so that the whole network would be balanced if all the traction substations have the same load at the same time. This procedure is applied for the different transformer arrangements in the traction substations which have been described below.

#### 4.1. Single phase transformers

In this arrangement of the traction substations, a single phase transformer is used to feed the traction system which is fed through two phases. One of the two output phases is connected to the catenary feeding the trains along the track and the other is connected to the running rails as the negative return current path. The structure of such an electrification system is shown in Fig. 4.

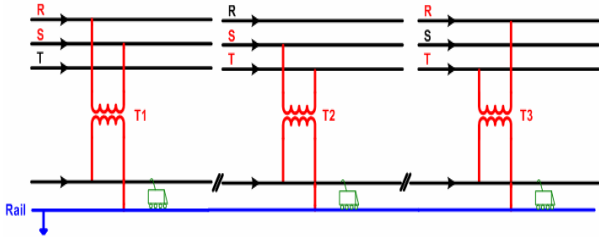


Fig. 4. Traction electrification system with single phase transformer arrangement

Using the symmetric component calculations, the voltage unbalance factor is calculated as reminded in the appendix as:

$$V_+ = 0.0577 \angle 120^\circ, V_- = 0.972 \angle -30^\circ$$

$$\Rightarrow \varepsilon_v = \frac{V_-}{V_+} = 5.9\% \quad (5)$$

Studying the different loading schedules for the traction system for this arrangements prove that if the three in after traction substations have almost the same loading, the voltage unbalance can reduce greatly and it might be even zero, but in the worst case, the maximum voltage unbalance of the AC network reaches 12.8%.

#### 4.2. Two single phase transformers

The principle of this arrangement is dividing the single-phase load between all the three phases resulting in decreasing the voltage unbalance of the AC network. Therefore, two single phase transformers are used as seen in Fig. 5 which each feeds half of the whole power demand. Studying and calculating the voltage unbalance factors for this transformer arrangement proves a maximum of 6.5% unbalance which is almost half of utilizing a single transformer like the previous and zero, in the case of equal loading of all the transformers.

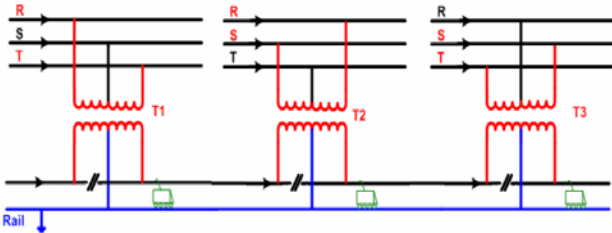


Fig. 5. Traction electrification system with two single-phase transformer arrangement

#### 4.3. Start-Delta transformer

In such a structure, a three-phase transformer is utilized in the traction substations with the primary winding as Star and the secondary as Delta. The feeding phases of the primary winding are changed respectively so that the whole power network seems balanced. The schematic structure of such an arrangement is shown in Fig. 6. The maximum voltage unbalance factor of this configuration is about 8.6% but can be reduced to zero in the case of equal loading of all of the transformers.

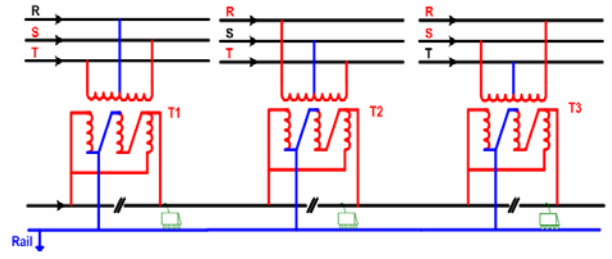


Fig. 6. Traction electrification system with three-phase Star-Delta transformer arrangement

#### 4.4. Star-Start transformer

In this configuration, a three-phase transformer is utilized in the traction substation with a Start-Start winding but the winding of the secondary side is irregular, i.e. the winding on one of the phases on the secondary has twice as many turns as the windings of other phases on that side. This causes a reduction in the other unbalance as the highest voltage unbalance factor is equal to 11%. The structure of this configuration is shown in Fig. 7.

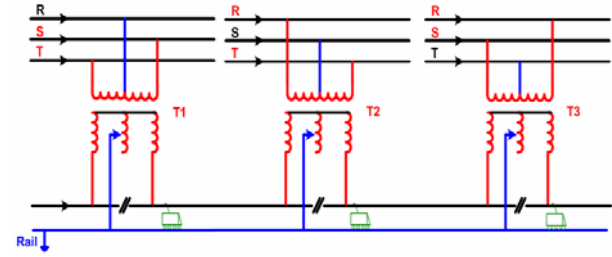


Fig. 7. Traction electrification system with three-phase Star-Start transformer arrangement

#### 4.5. Scott transformer

Utilizing Scott transformers is one of the most popular ways of reducing the unbalance problems in traction substations which can transfer the load side balanced two-phase system to the balanced three-phase AC network. The schematic structure of such an arrangement is shown in Fig. 8. The maximum voltage unbalance factor of this configuration is about 10.24% but can be reduced to zero in the case of equal loading of all of the transformers.

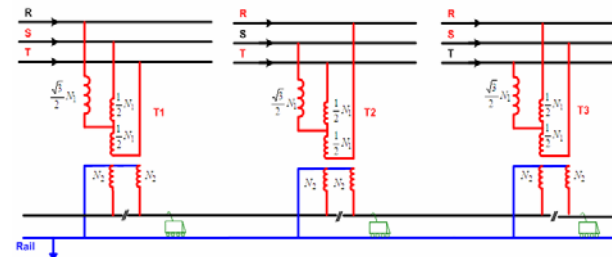


Fig. 8. Traction electrification system with Scott transformer arrangement

#### 4.6. Leblanc transformer

Another transformer configuration for reducing the unbalance problems is utilizing Leblanc transformers in

traction substations which can transfer the load side balanced two-phase system to the balanced three-phase AC network. But due to the designing characteristics of Leblanc transformers in comparison with the Scott, Leblanc transformer configuration can be said to be the most utilized system in the world. The schematic structure of such an arrangement is shown in Fig. 9. The maximum voltage unbalance factor of this configuration is about 6.69% but can be reduced to zero in the case of equal loading of all of the transformers.

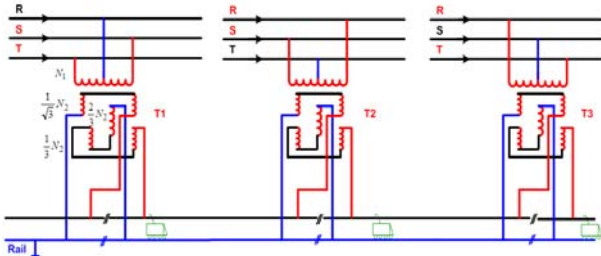


Fig. 9. Traction electrification system with Leblanc transformer arrangement

### 5. Tabriz - Jolfa AC electric railway case study

Tabriz - Jolfa AC electrified railway is the main means of mass transportation connecting the 146 kilometers distance between Jolfa, as the most important importing and exporting city in the north-west boundary to Tabriz, as the most populated and industrial city in the north-west of Iran. The railway was constructed in 1979 by the Russian and is being utilized till now. The electrical power distribution system feeding the railway is a single phase 25 kV system which is fed through three 132/25 kV main traction substations in the beginning, middle and the end of the route. The no-load voltage of the system is 27.5 kV. One switching substation utilizing booster transformers are located between each main traction substation, as was shown in Fig. 1a. The single line diagram of the power distribution system feeding the traction system is shown in Fig. 10.

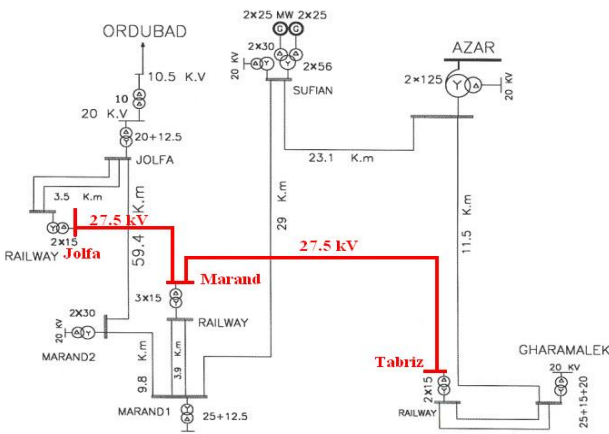


Fig. 10. Single line diagram of the power distribution system feeding the traction system

Two parallel transformers are used in the main traction substations, each with the rating of 15 MW. The transformers are fed from two-phase and a single

phase output which energizes the catenary system. The single line diagram of the traction substations is also shown in Fig. 11.

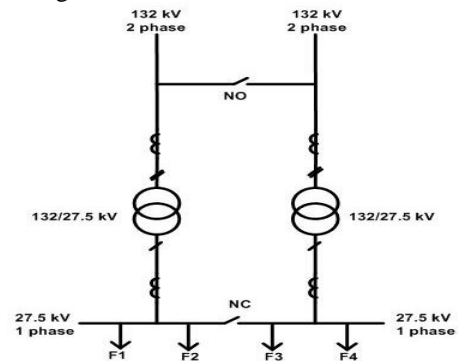


Fig. 11. Single line diagram of the main 132/25 kV traction substations

The results of calculating the voltage unbalance factor for Tabriz-Jolfa Electrified railway with concerning the transformer configurations of section 4 for the different loading schedules of the transformers (Table 3) are shown respectively in Table 4.

Table 3. Loading Schedule of the Transformers in the Traction Substation

Transformer configuration in Section 4	Loading Schedule					
	TS 1		TS 2		TS 3	
	W	E	W	E	W	E
1	✓					
2	✓	✓				
3		✓		✓		
4	✓	✓		✓		
5	✓	✓	✓	✓		
6		✓		✓	✓	

Table 4. Voltage Unbalance Factor Calculated for Tabriz-Jolfa Electrified Railway With different Transformer Configurations and the Loading Schedule of Table 3

Transformer configuration in Section 4	Loading Schedule					
	1	2	3	4	5	6
4.1	5.9	12.1	6.04	10.9	12.8	0
4.2	5.9	6.3	6.39	6.39	2.64	6.5
4.3	4.9	4.97	8.6	0	4.9	4.94
4.4	5.7	3.9	1.97	11	4.04	9.9
4.5	5.7	0	5.68	5.68	0	10.2
4.6	3.3	0	3.32	0	0	6.69

### 7. Conclusion

In this paper, the unbalanced power quality problems of the AC electrified railway systems including the voltage unbalance factor and the current negative sequence distribution factor injected to the AC network were studied. Different applicable solutions are utilized for reducing these problems which have been proposed and

studied. Comparing the unbalanced factor and current negative sequence contribution factor for each of the solutions, the best way of limiting the unbalance power quality problems of the AC network is chosen.

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### Appendix

For a balanced power network, the three phases of the current and voltage waveforms have equal magnitudes with an exact phase difference of 120 degrees. Connecting a single-phase or an unbalanced three-phase load to the network, the current and voltage waveforms would be unbalanced. The voltage unbalanced factor of a single phase load with the power rating of  $S_n$  and the short circuit rating of  $S_{cc}$  is equal to:

$$\% \varepsilon_v = \frac{S_n}{S_S} \quad (2)$$

For example, the unbalanced voltage factor of an AC electrified railway system considered as an unbalanced single-phase load, with the power rating of 10 MVA and the short circuit rating of 1000 MVA, is about 1%.

Voltage unbalance is due to the voltage negative sequence which can be calculated by dividing the negative sequence of voltage to its positive sequence as shown by 2.

$$\% \varepsilon_v = \frac{V_-}{V_+} \quad (3)$$

The currents  $I_a$ ,  $I_b$  and  $I_c$  as the unbalanced feeding currents of the traction substation can be converted to three balanced currents of  $I_+$ ,  $I_-$  and  $I_0$  based on the theory of symmetrical component analysis with their equivalent balanced  $Z_+$ ,  $Z_-$  and  $Z_0$  as the positive, negative and zero sequence impedance of the Thevenin equivalent and  $E_+$  as the open-circuit voltage at the input, respectively as determined by 3 and shown in Fig. 5.

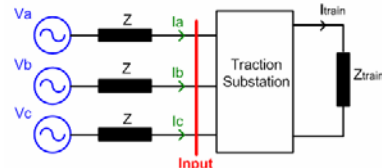


Fig. 12. Electrical circuit equivalent of the power network feeding the traction system

$$\begin{bmatrix} I_+ \\ I_- \\ I_0 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}, \quad a = 1e^{j120^\circ} \quad (4)$$

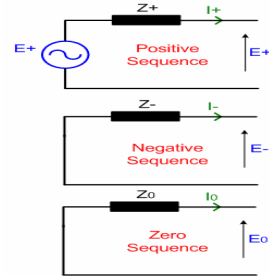


Fig. 13. Sequence network of the grid utility feeding the traction substation