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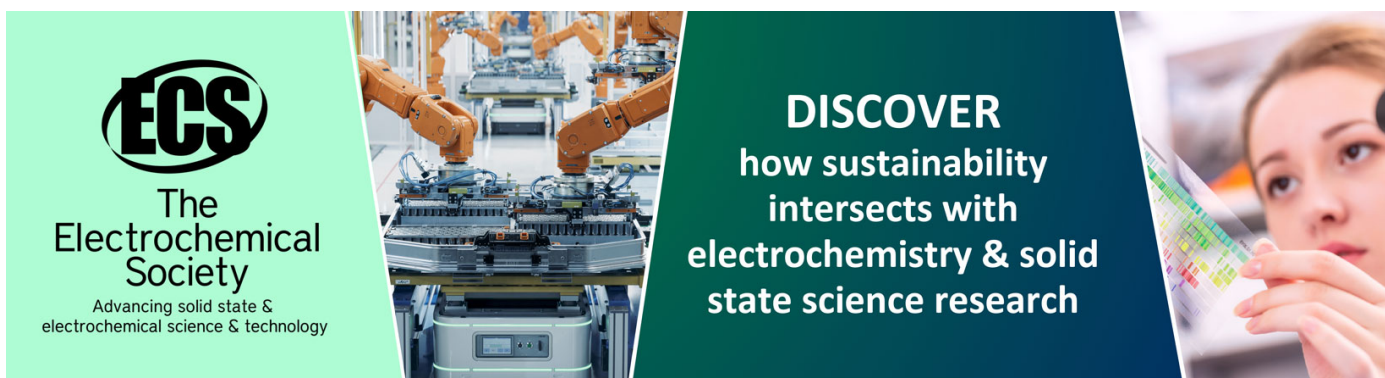
Analysis of the power quality impact in power supply system of Urban railway passenger transportation – the city of Ulaanbaatar

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Analysis of the power quality impact in power supply system of Urban railway passenger transportation – the city of Ulaanbaatar

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Abstract. The urgency and expediency of additional passenger transportation by urban railway as an extension of the transport infrastructure of megacities has been proved. The fact that the urban railway uses AC 2x25 kV, which is uses to out of the three phases of city's power supply system negatively impacts. Thus, it creates a significant asymmetry. In this paper, a comparative analysis on the negative sequence component of the voltage unbalance, which occurs in the nodes of connection of traction substations through both a three-phase transformer or a Scott transformer are been carried out. A mathematical method was created for determining the negative sequence voltage unbalance factor is based on the phase coordinates and symmetrical components methods. The results show that the Scott transformer provides a more symmetrical load distribution to the three-phase electric grid, when compared to the three-phase transformer and was verified using a simulated model in the Matlab program. Consequently, the use of a Scott transformer has better symmetrising abilities than a three-phase transformer, which gives it a significant advantage in the traction power systems.

1. Introduction

The growth of the world population leads to a significant increase in the urban population in most countries, including new the birth and growth of megacities. One of the problems arising in the development of megacities is the complication of passenger transportation, which requires new types of transport and significant additional material and financial costs. The most approachable solution regarding this task is the development of urban railways, including the connection with other passenger transport systems: subway, bus and air transportations. However, up until now, negative technical problems are not fully examined, such as quality of electric power that arise from the fact that modern electric trains operate on an AC 2×25 kV and use only two out of three phases. This entails an unbalance of voltages and currents in the feeding electric grids of megacities, as well as the higher harmonic components of the alternating current. In this paper, the results of a scientific study are presented specifically the asymmetric load flow caused by feeding electrified urban railway, in connection with the fact that the traction power supply system has a number of phases not multiples of three.

It is proved that among the traction transformer connections the Scott and Le Blanc transformers have the best symmetrising abilities, which ensure the voltage balance on the side of primary voltage, under condition equal currents in the feeding sections on the side of the secondary voltage.



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In this case, the most simple and practical way to balance the voltage is to tight train schedule.

2. Urgency and brief historical overview

Ulaanbaatar – the capital of Mongolia, is located in the broad valley of the Tuul River, at the foot of the Bogd-Uul mountain, at an altitude of 1300–1350 m. The city's area is 4704.4 km², at the moment the city's population is 1.405.000 people, and it is separated into the independent, administrative, political, commercial, cultural and scientific center of Mongolia and is also an important financial center of Asia. It is a megacity and a major transport hub. The city is served by the international airport of Genghis Khan and two airfields, and this year it is promised to put into operation a new international airport. The central railway station of the Ulaanbaatar is the center of regional and international railway service [1].

Officially, the capital of Mongolia is almost 400 years old, but Ulaanbaatar – looks like a very young city since the master plan for Ulaanbaatar development was only developed in 1975. Then the specialists predicted that the capital's population will not exceed 400 thousand people, and no more than 10 thousand cars will participate in the traffic.

Now Ulaanbaatar is on the 451st place in the list of the largest cities in the world. Forecasts were not justified: according to official data of the Traffic Police Department of Mongolia, in 2017 more than 458 thousand cars were registered in the capital. Every day more than 200 thousand cars leave on the roads of Ulaanbaatar. Since almost all governmental and state organizations are located in the center of Ulaanbaatar, there is morning and evening hours of traffic peaks, the morning peak continues from 7:30 to 9:00 and the evening peak from 17:00 to 21:00 hours. Therefore, one of the headaches of city residents is traffic jams.

To date, one of the most urgency problems for the world's largest cities is traffic jams. Measures are offered in different ways. Some cities increase the number of paid parking lots and automobile interchanges, somewhere they offer drivers to travel by public transport for free. To reduce traffic jam, the city administration has taken several measures. One of them is restriction of movement of vehicles. Since 2014 in Ulaanbaatar cars can move around the city on weekdays taking turn, depending on the data indicated on the state plates. And try to solve this problem there are several ways.

The development of modern megacities also requires the development of the transport system, along with buses, trolleybuses and the subway, in recent years the delivery of passengers has become much simpler in some cities and is getting cheaper by using the urban railway or as we call by municipal train. The essence of railway transport is that it passes located above ground, does not require large expenditures. In many cities, these lines already exist, they just need to be merged and run in circle.

Table 1. Prospects for a new urban railway in the city of Ulaanbaatar

№	Station	Additional benefits
1	Tolgoit	1. Train time en route: from Tolgoit to Amgalan – 45–47 minutes, travel time by public transport is not less than 90 minutes
2	Tavan shar	
3	Bars-2	2. Number of passengers carried: 350–400 people / one train
4	Ulaanbaatar railway station	
5	Dund gol	3. Periodicity of cruising: on the route to each side during the day – 3 trains
6	Narantuul	
7	Janjin club	4. Speed of the passenger train: up to 100 km/h
8	Amgalan	

In 2014, according to the joint project of the Ulaanbaatar City Hall and the Russian-Mongolian Joint Stock Company "Ulaanbaatar Railway", on the 65th anniversary of its founding, it was decided

to create a new public transport network based on the existing railway infrastructure in the city [2]. At the moment there is only one line, the first stage of construction has been built four new intermediate stations with low platforms, two terminal stations have been reconstructed – the Tolgoit station and Amgalan station, and the central station – Ulaanbaatar.

Unfortunately, this method of transporting passengers was not fully realized in because of the costly system of transportation of people, the rare frequency of trains and the uncomfortable waiting conditions. One of the main reasons for the collapse of the project is that the movement of the trains was carried out on diesel locomotives, operating on expensive diesel fuel.

3. Choice of traction power system for electrified urban railways

In the near future, the Ulaanbaatar Railway JSC plans to electrify the central railway line, to create a transport corridor between Europe and Asia, through Mongolia. This will open the possibility for Ulaanbaatar megacity to electrify the internal urban railway, which will reduce the traffic load in the city by 30 %.

Based on the development of railway electrification in the world and in neighboring countries, Russia and China, are taking into account the increase in the transport of cargo, both domestic and transit for the electrification of the Mongolian railway, it is appropriate to choose the traction system of 2x25 kV, 50 Hz of alternating current [3].

Small changes in phase voltages can lead to more asymmetries in the phase currents. This causes heat and loss and makes the grid less stable. In order to remain within the permissible limits specified by the standard and the electric utility, the consumer is obliged to search for optimal solutions for ensuring the quality of electric energy.

In real conditions, traction substations tend to be located at large railway substations. At the same time, according to profile conditions, inequality of distances between substations, and changes in cargo traffic, even the average loads of the substations are different. When considering the effect of the asymmetrical load of a three-phase system on the operation of electrical power system and consumers, it will be noted that the voltage unbalance is determined to a large extent by the voltage drop in the wires of the transmission line [4–6]. The latter depends on the load and location of the traction substations. It is not difficult to come to the conclusion that, as if the substations were not connected to a three-phase line, it is not possible to obtain identical voltage losses in all phases, since asymmetrical loads are located at different distances from power supplies. The load of traction substations continuously varies over a wide range and almost never the loads of individual substations are equal to each other. Thus, in practice, the problems of current and voltage asymmetry are solved only on the basis of concrete conditions [7].

The most common types of transformers used in Russia are three-phase and single-phase transformers. Lately in Europe transformer Scott and Le Blanc is being commonly used, which transforms the three-phase system into a two-phase 25 kV. There are also two systems of not widely spread so-called V/V system and also a Y/ Δ system. As will be shown below, they don't fulfill the symmetry requirement on the primary side.

The main advantage of the Scott transformer is the fact that when the currents in two feeding sections of the secondary winding of the transformer (25 kV) are equal, the voltage on the upper side becomes practically balanced. Figure 1 shows the phasor diagrams of the voltage and current of the Scott transformer [8, 9].

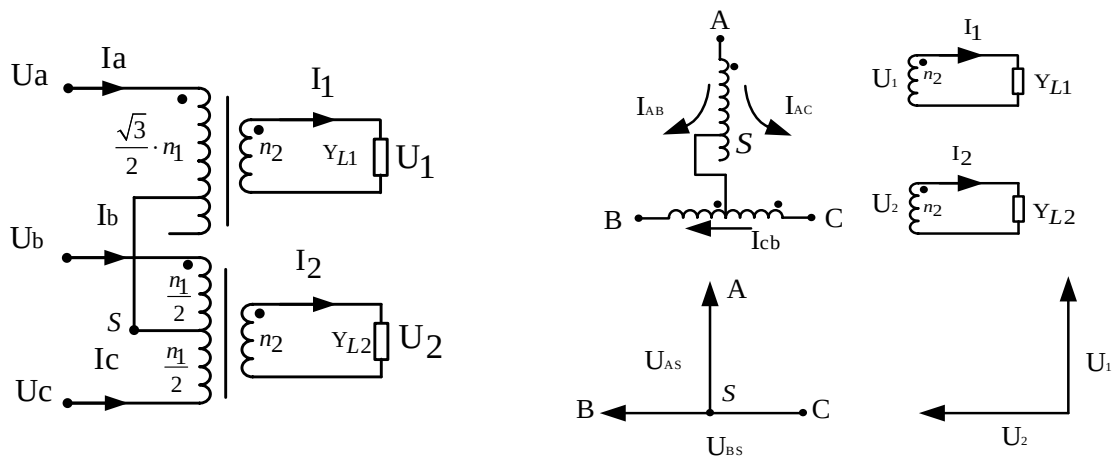


Figure 1. Scott connection transformer and its phasor diagram

4. Calculation of the voltage unbalance factor in the power grid

In order to compare the ability to ensure symmetry of the transformer connections, we use the symmetrical component method. The C.L Fortesque recommended this method in 1918. He states in his paper, the most striking thing about the results of his mathematical investigation of induction motors under unbalanced conditions was their symmetry. The result of his inquiry is the method of symmetrical components, the essential means for analyzing unbalanced conditions in power systems.

The relation between primary and secondary voltages and currents of the transformer are shown in the following equations

$$I_1 = Y_{L1} U_1 = \frac{2}{\sqrt{3}} \beta \cdot (U_A - \frac{1}{2} U_B - \frac{1}{2} U_C) \cdot Y_{L1}, \quad (1)$$

$$I_2 = Y_{L2} U_2 = \beta \cdot (U_B - U_C) \cdot Y_{L2}, \quad (2)$$

where:

Y_{L1} and Y_{L2} are traction loads in the two feeding section

β – factor of transformation, defined by the formula $\beta = \frac{n_2}{n_1}$.

After some transformations, we get the currents in the phases of the primary side, depending on the unbalance of currents on the secondary side of the Scott transformer

$$I_A = \frac{4}{3} \beta^2 \cdot Y_{L1} U_A - \frac{2}{3} \beta^2 \cdot Y_{L1} U_B - \frac{2}{3} \beta^2 \cdot Y_{L1} U_C$$

$$I_B = -\frac{2}{3} \beta^2 \cdot Y_{L1} U_A + (\frac{1}{3} \beta^2 \cdot Y_{L1} + \beta^2 \cdot Y_{L2}) U_B + (\frac{1}{3} \beta^2 \cdot Y_{L1} + \beta^2 \cdot Y_{L2}) U_C$$

$$I_C = -\beta^2 \cdot Y_{L1} U_A + (\frac{1}{3} \beta^2 \cdot Y_{L1} + \beta^2 \cdot Y_{L2}) U_B + (\frac{1}{3} \beta^2 \cdot Y_{L1} + \beta^2 \cdot Y_{L2}) U_C$$

Given $\beta^2 \cdot Y_{L1} = Y_1$ and $\beta^2 \cdot Y_{L2} = Y_2$ the relation between the U_{ABC} and the I_{ABC} is defined as

$$\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} = \begin{bmatrix} \frac{4}{3}Y_1 & -\frac{2}{3}Y_1 & -\frac{2}{3}Y_1 \\ -\frac{2}{3}Y_1 & \frac{1}{3}Y_1 + Y_2 & \frac{1}{3}Y_1 - Y_2 \\ -\frac{2}{3}Y_1 & \frac{1}{3}Y_1 - Y_2 & \frac{1}{3}Y_1 + Y_2 \end{bmatrix} \cdot \begin{bmatrix} U_A \\ U_B \\ U_C \end{bmatrix} \quad (3)$$

Transforming (3) into symmetrical components, the relation between U_{120} and I_{120} can be obtained as follows

$$\begin{bmatrix} I_1 \\ I_2 \\ I_0 \end{bmatrix} = \begin{bmatrix} Y_1 + Y_2 & Y_1 - Y_2 & 0 \\ Y_1 - Y_2 & Y_1 + Y_2 & 0 \\ 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} U_1 \\ U_2 \\ U_0 \end{bmatrix} \quad (4)$$

The three-phase equivalent circuit represents the traction load on the secondary side of the transformer and can be referred to the primary side. The circuit is directly connected to the power grid.

It can be used, drawing up the circuit of the positive, negative and zero sequences and an equivalent circuit, to obtain a simplified formula for the quickly evaluation of voltage unbalance. If we assume that the power grid is balanced then it can be replaced by the Thevenin's equivalent circuit.

$$\begin{bmatrix} E_A \\ E_B \\ E_C \end{bmatrix} + \begin{bmatrix} E_n \\ E_n \\ E_n \end{bmatrix} = \begin{bmatrix} Z_P & Z_M & Z_M \\ Z_M & Z_P & Z_M \\ Z_M & Z_M & Z_P \end{bmatrix} \cdot \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} + \begin{bmatrix} U_A \\ U_B \\ U_C \end{bmatrix} \quad (5)$$

where Z_P – phase impedance;

Z_M – mutual impedance;

U_A, U_B, U_C – phase voltages at the point of common coupling.

Thanks to the symmetric transformation

$$\begin{bmatrix} E_S \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} Z_S & 0 & 0 \\ 0 & Z_S & 0 \\ 0 & 0 & Z_0 + 3Z_n \end{bmatrix} \cdot \begin{bmatrix} I_1 \\ I_2 \\ I_0 \end{bmatrix} + \begin{bmatrix} U_1 \\ U_2 \\ U_0 \end{bmatrix}, \quad (6)$$

where $Z_1 = Z_2 = Z_S = Z_P - Z_m$ the impedance of the forward and reverse sequences, $Z_0 = Z_P + 2Z_m$ is the zero sequence impedance.

An equivalent circuit of symmetrical components will be compiled by combining equation (6) with equation (3). The results will be used to obtain a formula for evaluation the voltage unbalance at the point of common coupling.

Table 1 shows the evaluation formulas used to calculate the maximum voltage unbalance factor for some types of transformer connections. The advantage of the evaluation formulas is that it provides a quick and easy way to calculate the maximum voltage unbalance factor at the point of common coupling.

In this case, the ratio of the negative and the positive sequence voltages can be approximately defined as the ratio of the load on the secondary side in the two-phase system, the three-phase short-circuit capacity $S_{SC(3p)}$ in the three-phase system [10]. This three-phase short-circuit capacity is an important parameter when designing a power system. For better voltage regulation, the short-circuit capacity must be high enough.

The formulas obtained for the comparison of transformer connections used in traction substations are based on two assumptions. At first, the feeding system is considered to be a three-phase

symmetrical system. Second, the equivalent impedance of the traction load (contact network, electric locomotive, rail) is much larger than the impedance of the network (source, transmission line).

Table 2. The formulas of voltage unbalance factor for various traction power supply

Transformer connection	Voltage unbalance factor, %
Single phase	$k_{2U} = \frac{S_{1p}}{S_{SC(3p)}} \cdot 100$
Scott Le Blanc Woodbridge	$k_{2U} = 1 - 2k \left \frac{S_{1p}}{S_{SC(3p)}} \right \cdot 100$
V/V Y/Δ Δ/Δ	$k_{2U} = \sqrt{3k^2 - 3k + 1} \left \frac{S_{1p}}{S_{SC(3p)}} \right \cdot 100$

In the formulas there is a multiplier besides the power ratio, which determines the difference of the transformers connection and divides all the transformer connections into three categories. The coefficient k is within the limits $0 \leq k \leq 1$. A comparison of the voltage unbalance factor for various types of transformer is shown in Figure 2.

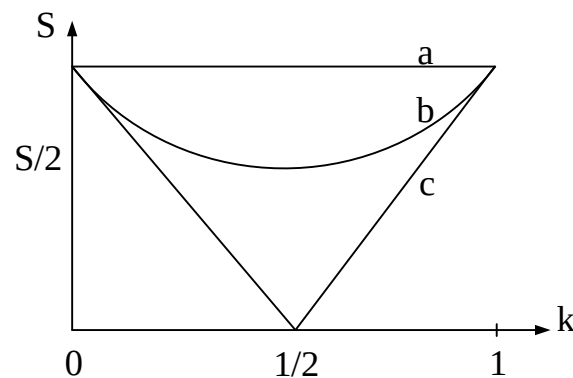


Figure 2. The comparison diagram of voltage unbalance factor of the transformer connections, a – single phase transformer, b – three phase transformer, c – Scott transformer

There is an urgent problem of installing and improving the device for load currents balance in the feeding sections of the Scott transformer. Thus, the usual problem of voltage balancing in a three-phase system is transferred from the grid 110–220 kV to the grid 25 kV. In this case, the balancing problem itself is also simplified, since it is necessary to balance not three phases but two. Other transformer connections of traction power supply have greater asymmetry on the primary side compared to the Scott and Le Blanc connection. This method is simpler and requires less financial costs, since it can partly be realized by the correct train schedule. For example, on the railways in Japan and South Korea, they strictly adhere to the schedule and thus solve the problem of unbalance in high-voltage grids.

5. Symmetrisation of the load flows based on the equalization of currents in the feeding sections

As an example, was calculated the voltage unbalance factor in the node of the city's electric grid, where connected the Tolgoit traction substation, with capacity $40 + j15$ MVA, from which feed on 8 urban railway stations of the Ulaanbaatar.

The results of calculation current and voltage unbalance factor, when the current inequality in the traction feeding sections, are given in the table 3. With an inequality of the currents up to 10 %, the current unbalance on the primary side remains at the maximum permissible values. The divergence of

the currents in phase instead of 90 degree, creates unbalance in the supply grid also at the level within limit values.

Table 3. Results of the calculation of voltage unbalance factor of three phase and Scott transformer

Parameters of the grid	Three phase transformer				Scott transformer			
	0	10 %	20 %	30 %	0	10 %	20 %	30 %
S_{L1} , MVA	21.3	23.4	25.6	27.7	21.3	23.4	25.6	27.7
S_{L2} , MVA	21.3	19.2	17.1	14.9	21.3	19.2	17.1	14.9
I_A , A	85.6	89.4	93.4	97.5	112.1	100.9	89.6	78.4
I_B , A	32.3	32.8	34.3	36.5	112.1	118.1	124.8	132.1
I_C , A	85.6	82.1	78.7	75.7	112.1	118.1	124.8	132.1
φ_A	170.3	173.0	175.5	177.8	69.4	69.4	69.4	69.4
φ_B	69.4	59.0	50.3	41.9	-50.5	-45.8	-41.6	-37.8
φ_C	-31.4	-28.0	-25.3	-21.8	-170.5	-175.2	-179.5	176.7
I_1	64.7	64.7	64.7	64.7	112.1	112.1	112.1	112.1
I_2	32.3	32.8	34.3	36.5	0	11.2	22.4	33.6
k_{2I} , %	50.00	50.74	52.91	56.34	0	10.0	20.0	30.0
k_{2U} , %	2.34	2.40	2.61	2.96	0	0.49	0.99	1.46

6. Conclusion

It is shown that with the development of the transport infrastructure of megacities, the technical and economic problems of optimizing passenger flows due to above ground urban railway transport. However, due to the fact that the 2×25 kV traction supply system has a different physical basis, the use of two phases instead of three, it introduces unbalance into three-phase city electric grid of the megacity. This reduces the quality of electrical energy and increases losses in electric consumers for household and industrial purposes.

The researches carried out by the authors on the example of the Ulaanbaatar megacity and results show that the Scott and Le Blanc transformers have an advantage in reducing the asymmetry compared to the three-phase transformers. It is very important to ensure the equality of currents in the feeding sections of the balancing transformers, since there is no asymmetry in the electric grids. When an inequality of currents from 10 % to 30 %, the voltage unbalance factor in the 220 kV grid is for the three-phase transformer from 2.34 % to 2.96 %, which exceeds the permissible limit 2 %, while at the same time for the Scott transformer from 0.49 % to 1.46 %, which satisfies the allowable level of 2 %.

The resulting coupling equations for input and output variables for transformer connections utilized in traction substations make it possible to determine k_{2U} , when given the traction load on the secondary side of a transformer (25 kV). Also, using the method determining contributes of voltage unbalance from each elements of electric grid [11], we determined the negative sequence voltage unbalance factor at the point of evaluation. The results of the calculation were adequate with the simulation results, which confirm the correctness of the proposed method [12].

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