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Estimation of Voltage Unbalance in Power Systems Supplying High Speed Railway

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Summary: **The electric high speed railway loads supplied by the three phase power system represent one of the main sources of voltage unbalance perturbation in the grid. The power system configuration and the load conditions influence the degree of this power quality perturbation. The present paper deals with the problems raised by the practical determination of the voltage unbalance factor in conformity with the European and IEEE standards. The procedure for identifying a vulnerability area in which the voltage unbalance presents values that exceed the standard limits is elaborated and comparison on the use of the two mentioned set of standards is performed. A case study referred to the 63 buses CIGRE network analyzed in the paper gives rise to interesting comments and discussion.**

Key words:
high speed railway,
voltage unbelence,
power quality

1. INTRODUCTION

The high speed railway systems, supplied by the high voltage power network represent an important source of voltage unbalance, leading to power quality problems that affect the proper operation of the equipments connected at the point of common coupling (PCC) or in other points of power system.

The supply of the traction loads is assured by dedicated substations operating at industrial frequency. The degree of voltage and current unbalances depends of the train motion, load condition and power system supply configuration [1].

Due to the unbalanced regime, perturbations appear at the electrical installations (machines, transformers, capacitor banks, static converters) at PCC and in the grid, too [2].

The induction motors, fed by an unbalanced system of voltages, present lower efficiency, overheats and increase the real power losses [3], so a significant loss of the life duration. Moreover, the influence of the voltage unbalance upon the operation conditions of the generators present in the power system is very important for limiting the overheating of the rotor windings [2]. Voltage unbalance may also cause the undesired tripping of relays, influences converters and PWM drives operation due to the amplitude or phase angle unbalance. The capacitor banks, connected to a power system with unbalanced voltages contribute itself to the aggravation of the unbalance. In fact, the phase with the smallest voltage amplitude, presents the smallest reactive power and then the smallest the power factor compensation.

In the paper, a study on the voltage unbalance propagation in the power system, due to the presence of the traction supply substations is developed. The examples of application are referred to the 63 buses CIGRE network that has been implemented in the ATP-EMTP environment.

2. CONNECTION SCHEMES OF THE TRACTION SUBSTATIONS

In Europe, the single phase 25 kV power system, operating at 50 Hz, supply the high speed railway. The traction loads are fed through dedicated substations, the configuration of the connection schemes being: single phase, V connection, Scott or Le Blanc transformers. Each connection scheme has different impact on the power system but also different investment, operation and maintenance costs. The configurations are shown in Figure 1, where S_L, S_{L1} and S_{L2} are the traction loads.

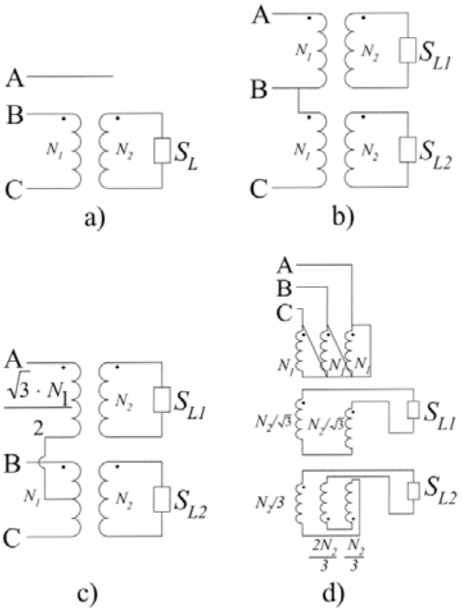

Fig. 1. Traction connection schemes: a) single-phase connection; b) V-connection; c) Scott connection; d) Le Blanc connection

The above illustrated connections have a different impact on the degree of voltage unbalance at the point of common coupling. In order to minimize the voltage unbalance distortion, the electric traction substations are connected to high voltage levels of the transmission network, with high values of the short circuit apparent power at the PCC. Due to economical reasons, solutions a) and b) of Figure 1 are the most commonly used ones for the traction substations, but from the point of view of the voltage unbalance reduction, in practice, the used configuration is the V connection.

3. THEORETICAL EVALUATION OF UNBALANCE FACTORS

The analysis of the problems regarding unbalance covers two aspects [2]:

- the influence upon the operation characteristics of the plants supplied by unbalanced voltages;
- the influence on the economical and technical indicators of the transmission and distribution network, as well as on the generator systems.

In the first case, the utility must ensure to the customer the agreement of the voltage unbalance indices within the standardized limits. The customer is interested to monitor the supplying voltage for obtaining the information regarding unbalance and the agreement with the stipulated limits.

In the second case, the customer must ensure the correspondence of the produced disturbances within the allocated limits, established by the utility, as condition for power quality assessment to others customers in the electrical network. The utility is interested to survey the electrical quantities of the customer and to verify the limits.

In order to determine the unbalance impact of the loads on the utility grid, the unbalance voltage factor is used, defined as [4]:

$$u_u[\%] = \frac{|\underline{V}_2|}{|\underline{V}_1|} \cdot 100 \tag{1}$$

where u_u is the unbalance factor, $|\underline{V}_2|$ is the magnitude of the negative-sequence voltage and $|\underline{V}_1|$ is the magnitude of the positive-sequence voltage.

In case of simultaneous appearance in the power systems of unbalances and harmonics, this factor is defined to the fundamental frequency:

$$u_{u1}[\%] = \frac{|\underline{V}_2^1|}{|\underline{V}_1^1|} \cdot 100 \tag{2}$$

where $|\underline{V}_2^1|$ is the voltage negative sequence component, $|\underline{V}_1^1|$ is the voltage positive sequence component, corresponding to the fundamental frequency (50 Hz).

In some cases, especially for the power converters, the information regarding the phase shift ψ_u between negative and positive sequence voltages is very important.

In these conditions, the determination of the complex voltage unbalance factor $\overrightarrow{u_u}$, can ensure useful data for analysing the unbalance perturbations injected in the supplying power system. The complex voltage unbalance factor is:

$$\overrightarrow{u_u} = u_u \cdot e^{j \cdot \psi_u} \tag{3}$$

The exact method for determining the voltage unbalance factor, after measuring the rms values of the line voltages, is:

$$u_u[\%] = \sqrt{\frac{\left(1 - \sqrt{3 - 6 \cdot \beta}\right)}{\left(1 + \sqrt{3 - 6 \cdot \beta}\right)}} \cdot 100 \tag{4}$$

with:

$$\beta = \frac{\left(V_{AB}^4 + V_{BC}^4 + V_{CA}^4\right)}{\left(V_{AB}^2 + V_{BC}^2 + V_{CA}^2\right)^2} \tag{5}$$

where V_{AB}, V_{BC} and V_{CA} are the rms line-to-line voltages.

The phase shift ψ_u is:

$$\psi_u = tan^{-1}\left(\frac{\sqrt{3 \cdot \left(V_{AB}^2 - V_{CA}^2\right)}}{V_{AB}^2 + V_{BC}^2 + V_{CB}^2}\right) \tag{6}$$

The values of the voltage unbalance factor depend on the voltage level to which the load is connected. In many countries of the European Union the compatibility level on LV is $u_u \le 2\%$. The planning limits on MV and HV are $u_u \le 2\%$ for MV and $u_u \le 1\%$ for HV. In standard adopted in United Kingdom, the above $u_u \le 2\%$ is taken for HV, too [3, 5].

In France, for the case of high speed trains, new values have been proposed for HV network: respectively $u_u \le 1\%$ for periods higher or equal than 15 min and $u_u \le 1.5\%$ for periods less than 15 min.

The exact expressions (4), (5), (6) for computing the voltage unbalance factor are difficult to use in practice. An acceptable compromise brings to approximate analytic expressions of the voltage unbalance factor derived to the series development of (4).

The first order form of the expression (4) that leads to a scalar value of the voltage unbalance factor and to a zero phase shift ψ_u is applied in USA. The voltage unbalance factor is defined as the maximum phase voltage deviation from the average value of the three phase voltages, reported to this average value. In this case, for the three phase voltages it is computed an average value V_{avg} and the deviations δ_A, δ_B and δ_C [6]:

$$V_{avg} = \frac{V_A + V_B + V_C}{3}$$

$$\delta_A = \frac{V_A - V_{avg}}{V_{avg}}$$

$$\delta_B = \frac{V_B - V_{avg}}{V_{avg}}$$

$$\delta_C = \frac{V_C - V_{avg}}{V_{avg}} \tag{7}$$

The voltage unbalance is evaluated as follows:

$$\delta_u = max\left(\left|\delta_k\right|\right) \ , \ k = A,B,C \tag{8}$$

The prediction of the voltage unbalance due to single-phase traction loads connected between two of the three-phase lines, at PCC, is [3]:

$$u_u[\%] \cong \frac{S_L}{S_{cc}} \cdot 100 \tag{9}$$

where S_L is the traction load power and S_{cc} is the three-phase short circuit level at PCC.

Considering the traction connection schemes and the railway loads S_L, S_{L1} and S_{L2}, shown in Figure 1, the expression (9) can be applied for calculating of the voltage unbalance in any substation configuration represented in Figure 1 [7].

$$\begin{aligned} u_u[\%] &\cong \frac{S_L}{S_{cc}} \cdot 100 \quad \text{single phase transformer} \\ u_u[\%] &\cong \left|\frac{S_{L2} + \underline{a}^2 \cdot S_{L1}}{S_{cc}}\right| \cdot 100 \quad \text{V transformer} \\ u_u[\%] &\cong \left|\frac{S_{L2} - S_{L1}}{S_{cc}}\right| \cdot 100 \quad \text{Scott/Le Blanc trasformer} \end{aligned} \tag{10}$$

where $a = exp(2 \cdot \pi \cdot j/3) = -0{,}5 + j \cdot \sqrt{3}/2$.

The propagation of the unbalance due to a single line-to-line load in a radial system (see Fig. 2) is calculated with (11) and (12) depending on the location of the observation points *A* and *B* [3]:

$$u_u(B) = \frac{S_L}{S_{cc}(B)} \tag{11}$$

$$u_u(A) = \frac{S_L}{S_{cc}(A)} \tag{12}$$

where S_L is the load power and $S_{cc}(A)$ and $S_{cc}(B)$ are the short circuit powers at the observation points *A* and *B*.

The voltage unbalance in *A* can be computed basing on the voltage unbalance in *B* as:

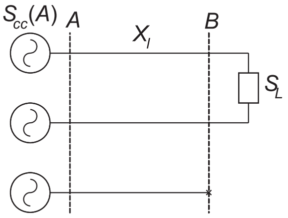

Fig. 2. Single line-to-line load in a radial system

$$u_u(A) = u_u(B) \cdot \left(1 - \frac{X_l}{V^2} \cdot S_{cc}(B)\right) \tag{13}$$

where X_l is the reactance of the line between *A* and *B* and *V* is the line-to-line voltage.

In the case of looped systems the voltage unbalance propagation can not be estimated with the same algorithm due to the influence of the voltage level, length of the transmission lines, generators reactance, balanced loads present in the network etc. In this case, power flow studies can lead to the estimation of the voltage unbalance propagation in the buses of the power system.

4. EXAMPLES OF APPLICATION

The impact of voltage unbalance, due to single phase high speed railway loads, on the power system becomes very important during the peak demands of the traction loads or when the short circuit power at the bus of the power system decreases. The voltage unbalance propagation in the power system has to be evaluated for determining the areas of vulnerability in which the negative effects are produced to rotation machines (induction motors, generators) and on equipments including power electronic devices.

In order to study the voltage unbalance propagation in a power system, the test network CIGRE with 63 buses is considered [8, 9]. This is a test network also used for many investigation purposes and for the present study it was implemented on ATP-EMTP environment [10]. The layout of the studied network is reported in Figure 3, while all the related data are listed in [9].

The test network presents buses at two high voltage levels, 220 kV and 150 kV respectively, where the high speed railway substations can be connected. The transmission lines are considered transposed, having symmetric-sequence parameters.

The high speed railways are time varying loads, but for the studied cases the peak demands are considered, for the purpose of establishing the critical cases.

The traction substations and its loads have been transformed in equivalent line-to-line loads, with single phase connection or V connection, which are the most used practical solutions.

The presence of multiple traction substations in the power system determines interactions between the bus voltages and generates the propagation of the voltage unbalance.

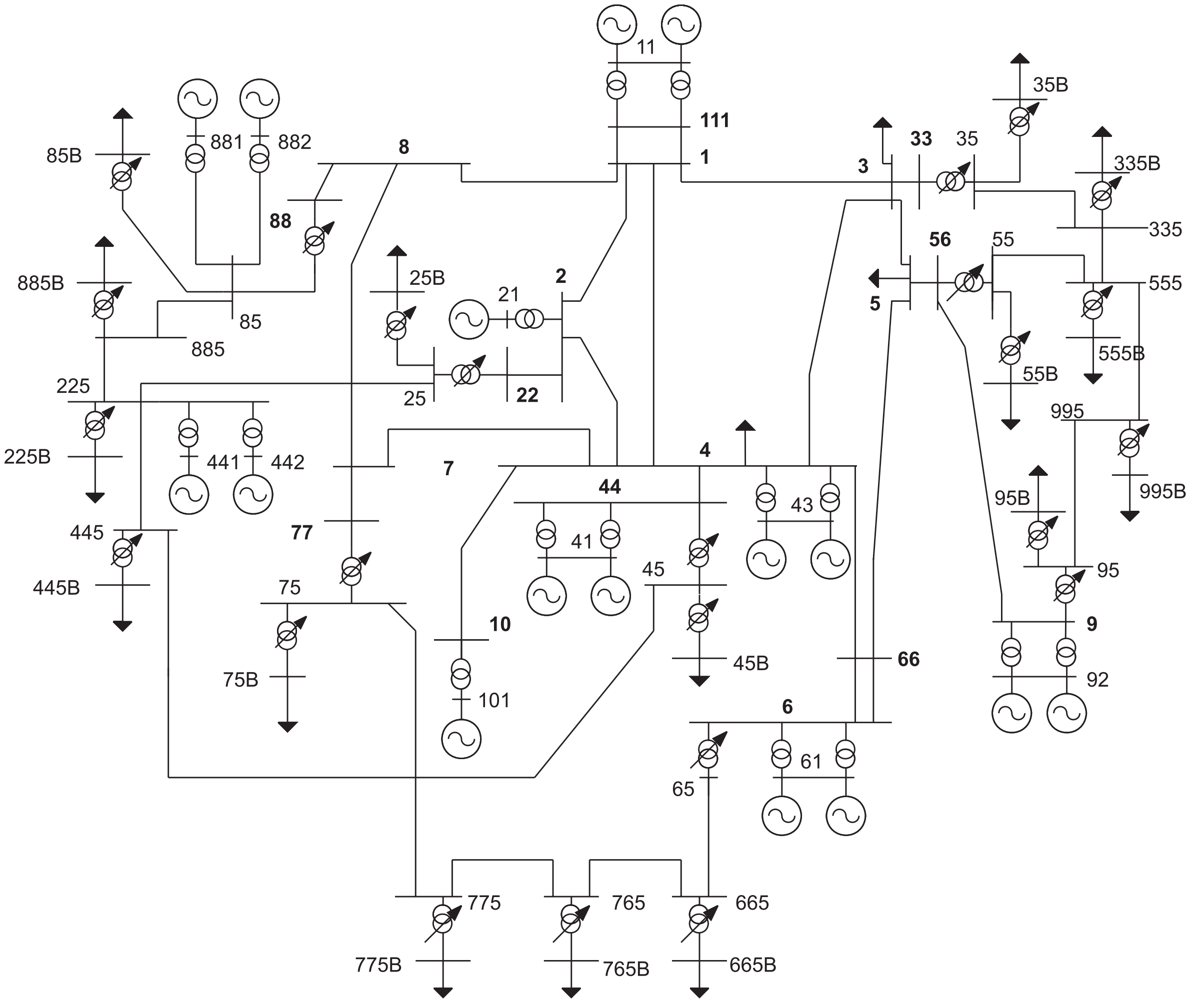

Fig. 3. Layout of the power system taken as reference for the example [9]

The propagation's study of the voltage unbalance on the analyzed network is conducted in the following cases:

A1) 48 MVA traction concentrated load, connected line-to-line between phases B and C, at the bus 33 (220 kV voltage level);

A2) 48 MVA traction concentrated load, connected line-to-line between phases B and C, at the bus 555 (150 kV voltage level);

B1) substations with single phase connection of the loads (24 MVA), at bus 335, bus 555, bus 995 and bus 95 (all of them at 150 kV level);

B2) substations with V connection loads (24 MVA), at bus 335 (between phases A–B and B–C), bus 555 (between phases B–C and C–A), bus 995 (between phases C–A and A–B) and bus 95 (between phases A–B and B–C).

For each one of the above reported cases, a vulnerability area, in which the unbalance voltage index (1) and (8) reach values greater than 1% (threshold established by the current standards), is calculated.

A1) Concentrated traction load connected between phases B and C at bus 33

The results of the simulation performed are reported in Table 1, where the voltage unbalance factor is computed with (1) and (8).

Table 1 shows that the voltage unbalance factor δ_u defined by (8) leads to errors with respect to u_u, depending on the values of the phase shift. The values of the voltage unbalance factor, listed in Table 1, show that the disturbance is propagating over the bus 335 (the length of the line between bus 3 and bus 335 is 30 km), and also up to the bus 555 has a great value.

In Figure 4 the vulnerability area is reported on the network schematic diagram and the region interested by an unbalance index greater than 1% in bordered by the blue line.

A special consideration has to be given to the values of the voltage unbalance factor at the buses 1 and 4, because are generator buses, and there is the possibility that negative currents flow into the generator machines [11].

A2) Concentrated traction load connected between phases B and C at bus 555

The results of the simulation conducted are reported in Table 2, where the voltage unbalance factors are computed with (1) and (8).

The values listed in Table 2 show that the voltage unbalance is propagating up to bus 335 (for a length of 30 km between bus 555 and 335) and up to bus 995 (for a length of 50 km).

The vulnerability area is defined in this case by the green line on the network schematic diagram of Figure 4.

B1) Single phase connected loads (24 MVA) at bus 335, bus 555, bus 995 and bus 95

The results of the simulation conducted are reported in Table 3, where the voltage unbalance factors are computed with (1) and (8).

In this case, at bus 995 a very high value of the voltage unbalance is observed. This is because the power system is very weak in this point. Also, the values of the voltage unbalance at the buses where the traction loads are connected are very high, exceeding even the 1.5% limit accepted by the standards for the case of high speed trains, for a period less than 15 min [12].

The vulnerability area in this case is bounded by the red line on the network schematic diagram of Figure 4.

B2) V connected loads (24 MVA) connected at bus 335 (between phases A – B and B – C), bus 555 (between phases B – C and C – A), bus 995 (between phases C – A and A – B) and bus 95 (between phases A – B and B – C)

The results of the simulation are reported in Table 4, where the voltage unbalance factors are computed with (1) and (8).

Table 1. Voltage unbalance propagation Case A1

Bus number	Voltage unbalance factor [%]	
	u_u	δ_u
bus 33	1.28	1.26
bus 35	1.27	1.25
bus 3	1.2	1.17
bus 335	1.14	1.08
bus 555	0.84	0.82
bus 56	0.58	0.57
bus 5	0.57	0.56
bus 1	0.42	0.42
bus 4	0.16	0.17

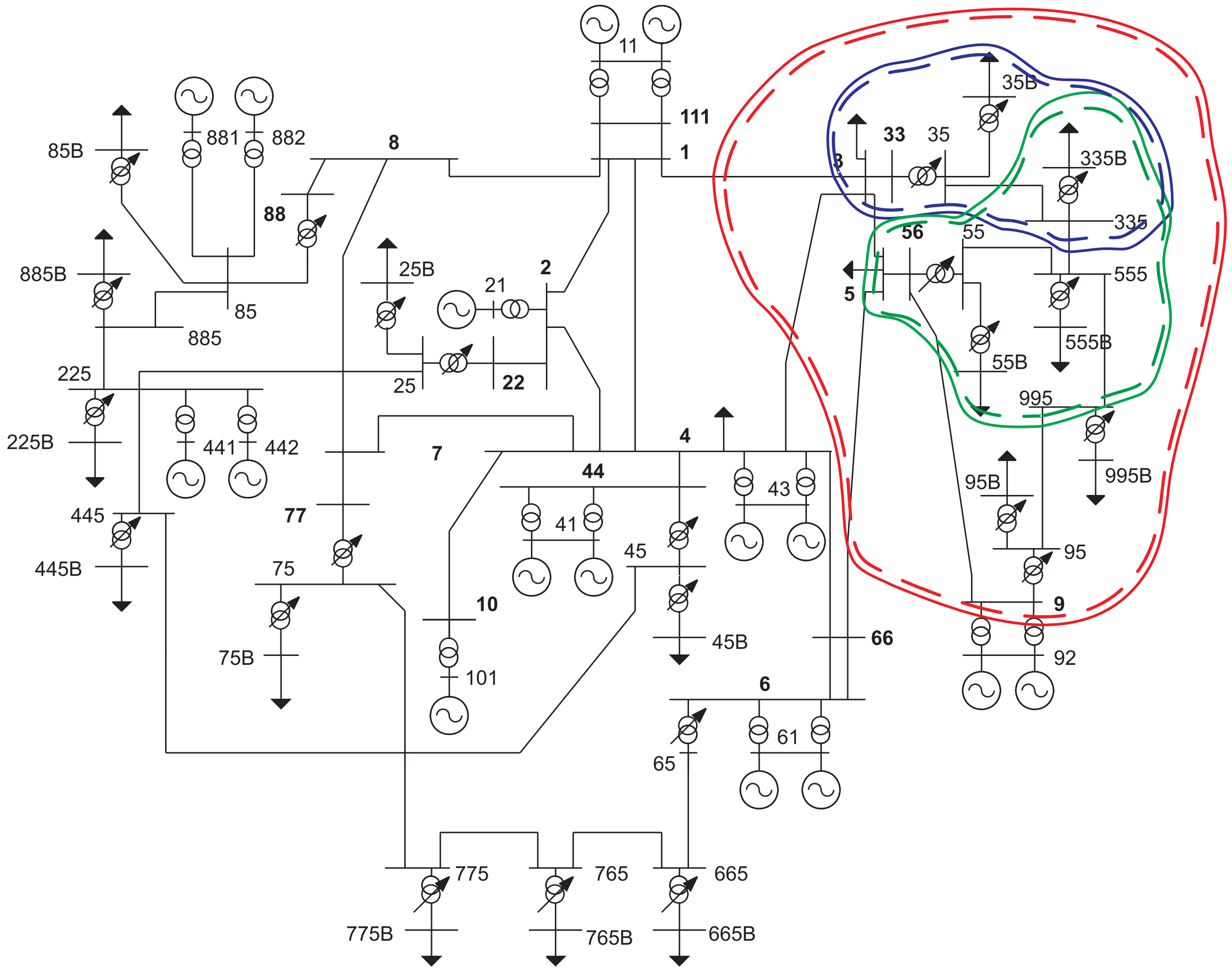

Fig. 4. Vulnerability areas in the test network (case A1: – blue line; case A2 – green line; case B1 – red line)

Table 2. Voltage unbalance propagation Case A2

Bus number	Voltage unbalance factor [%]	
	u_u	δ_u
bus 555	1.72	1.708
bus 335	1.18	1.172
bus 995	1.05	1.048
bus 5	1.02	1.014
bus 35	0.83	0.823
bus 3	0.78	0.776
bus 95	0.41	0.404
bus 66	0.28	0.277

Table 3. Voltage unbalance propagation Case B1

Bus number	Voltage unbalance factor [%]	
	u_u	δ_u
bus 995	4.25	3.91
bus 555	2.05	2.01
bus 335	1.8	1.776
bus 5	1.42	1.388
bus 35	1.26	1.237
bus 95	1.23	1.199
bus 9	1.22	1.155
bus 3	1.18	1.165
bus 1	0.43	0.424
bus 66	0.4	0.382
bus 4	0.22	0.207

With reference to the previous case, the V connection limits the propagation of voltage unbalance and the standard limits are respected.

5. CONCLUSIONS

In this paper the study of voltage unbalance propagation for various configuration and sizes of high speed railway loads is performed. The unbalance perturbation of the high speed railway depends on the peak demands of the traction loads and on the short circuit power of the grid.

Table 4. Voltage unbalance propagation Case B2

Bus number	Voltage unbalance factor [%]	
	u_u	δ_u
bus 995	1.38	1.348
bus 335	0.3	0.286
bus 95	0.26	0.236
bus 9	0.24	0.229
bus 555	0.23	0.216
bus 35	0.21	0.195
bus 3	0.19	0.1825
bus 5	0.17	0.165
bus 1	0.07	0.0658
bus 66	0.05	0.049
bus 4	0.03	0.0309

A vulnerability area, in which the voltage unbalance propagation overpasses the required standard limits is also determined. This is very useful in planning and operation activity of the network.

The application of the vulnerability area studies to a test case, represented by the CIGRE 63 busses standard network [9], brings to the following conclusions:

- the use of voltage unbalance factor, computed with (8) can be useful in a first estimation stage. More detailed voltage unbalance evaluation requires the use of the relation (1);
- traction substations connected to the highest value of the supply voltage give rise to smallest vulnerability regions (see cases A_1 and A_2 in the examples);
- traction substations with V connection scheme (case B_2) present at each bus lowest values of voltage unbalance factors, and then reduced propagation area, with reference to the single phase parallel connection solution (case B_1);

The conclusion is that the V connection of the traction substations and its loads should be applied. It should be noted that also in the V connection case there are buses where voltage unbalance exceeds the limits. This is due to the possible weakness of the power system.

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