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Application of ETAP™ eTraX™ software package for digital simulation of distribution network that feeds an AC traction power supply system

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Voltage unbalance in power systems feeding AC traction power systems is a worldwide known problem. One of the main aspects of this problem is the negative effect of voltage unbalance on motor loads causing operating problems and economic damage. It is necessary to perform unbalanced power flow studies and calculate voltage unbalance indexes to assess this negative effect of voltage unbalance and the develop of compensating measures during the design stage. Usually, calculations of the AC traction power supply system and the distribution network feeding it are carried out separately during the design of new lines of railways electrified by alternating current (AC) and reconstructing of existing ones. This approach is a source of deviations in the power flow studies because the lack of consideration of mutual influences between the traction power system and the distribution power system. In this paper, we compare a digital model in which the traction power supply system and the distribution network are modeled separately with a model that considers mutual influences between the traction and external power supply systems, including power flows through the traction network caused by the distribution network (transit currents). For digital modeling of these processes, authors used ETAP™ software with eTraX™ package. It allows to run unbalanced power flow studies when the generation and load are being changed over time, including train movement. During a separate simulation of the traction power system and distribution network, traction network was modelled using the equivalent sources connected to traction substation buses and the distribution network was modeled taking into account the fact that traction load was given from the simulation of the traction power system. The traction load was considered as lumped loads connected to the traction substation buses.At the same time, in both cases, the unbalanced power flow study was carried out by the phase domain method. Based on the results of two models comparison, it was concluded that the combined model containing a traction power supply system and distribution network, is more effective in terms of improving the accuracy of assessment voltage unbalance in accordance with current regulatory and technical documents on power quality.

1 Introduction

Voltage unbalance is the well-known worldwide important in power grids feeding AC traction power systems. AC traction power system trains are 1-phase loads with huge power consumption causing unbalanced power flows through traction substations. It causes voltage unbalance at all buses of the power system. According to Russian national standard [1] negative voltage unbalance factor (VUF2) should be lower than 2% during 95% of the period of measurement (one week) and lower than 4% at any moment of the same period. According to recent work [2] VUF2 value does not provide the full scope of information to analyze the negative influence of AC traction power system on the other loads in upstream power system including induction motors. It makes necessary to improve the methodology of AC traction power system modeling. In this paper authors compares the traditional way of AC traction power system modeling with equivalent sources with the way using the detailed model of the upstream power system. All results were given using made in ETAP™ software with eTraX™ based on Current Injection method described in [3]. In Russian papers this approach is described in [4]. The software package is certified under [5]. The idea of detailed consideration of

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the upstream power system in AC traction power system analysis is known and the examples of the models are described in [6,7]. Consideration of the detailed upstream power system provides the possibility to see power flows of non-traction power through AC traction power system. The traditional models with equivalent sources at each AC traction substation cannot provide these results. The main purpose of this paper is to show the benefits of the co-simulation of AC traction power and the upstream power system and the difference between these two approaches of AC traction power system modeling for design and operation.

2 AC traction power system modeling approaches

2.1 Traditional approach of AC traction system modelling

The design of AC traction power system has a long history of many decades. The implementation of AC traction was necessary to improve the capacity of railway lines to transfer more freight sand to increase the speed of passenger trains. According to limited capabilities of computational devices engineering companies used simplified models to size the equipment of traction substations and find the minimal value of the pantograph voltage. That approach was based on the idea that the power system could be replaced by equivalent sources. Each equivalent source is being represented as a voltage source and the impedance calculated from the fault current at the input bus of the traction substation. All voltage sources have the rated voltage and the same phase zero angle. That model (Fig. 1) makes the feeding of all substations independent without any power flows between substations at the side of the upstream power systems (grid).

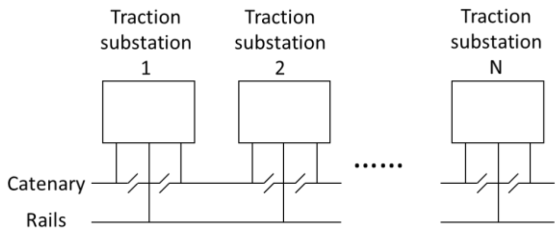

Fig.1. The traditional model of AC traction power system.

2.2 Combined model of AC traction power system and the grid.

The necessity of co-simulation of AC traction power system and the grid could be shown using a simple example (Fig.2) made in ETAP.

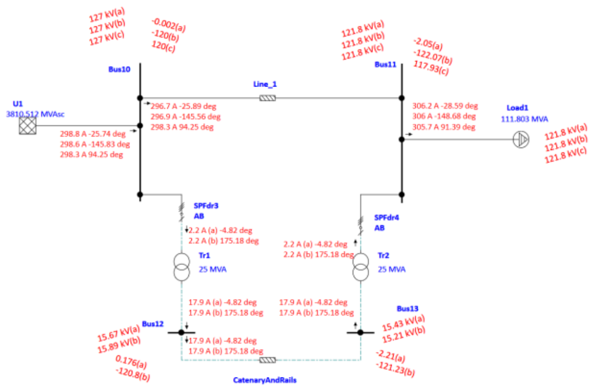

Fig.2. The simple model showing transit currents in the AC traction power system.

This effect is also known as transit currents. This example consist of:

- •U1 - Equivalent 220 kV power grid source with 10 kA 3-phase fault current and 12 kV 1-phase fault current. The operation voltage is 100%.
- •Line_1 - transmission line with 50 km length, R1=9 Ohm, X1 = 21 Ohm, Y1 = 0.000135 S, R0=16 Ohm, X0 = 70 Ohm, Y0 = 0.000067 S (lumped parameters)
- •Single-phase traction transformers 220/27.5 kV Tr1 and Tr2 with 25 MVA, Z=10%, X/R=20 connected to AB.
- •CatenaryAndRails – catenary and rails with 50 km length, R=11 Ohm, X=37 Ohm (lumped parameters).
- •Load1 – 100% constant power lumped load at the end of the line with 100 MW, 50 Mvar.

This simple example shows that even at no load conditions catenary is an additional transmission line for grid power. The current at 27.5 kV is 17.9 Amps. It is not quite big for the grid (2.2 Amps) but it is important in traction substations modeling. Of course this example does not show the real transit currents and voltage unbalance. It is described in the test case below.

3 Test case description

3.1 Railway, train parameters and train schedule data

The modeling of the traction power system starts from the railway and trains. The volume of freight transportation is being increased. The test case is related to high-load freight railways in Russia. The current typical configuration of a freight train in Russia is 7100 tons driven by 3S5K Yermak locomotive. It has the following rated parameters:

- •Rated traction motors power - 9840 kW
- •Maximum traction effort - 1017 kN
- •Maximum speed – 110 km/h

- Average speed – 49.9 km/h
- Mass – 288 tons.

The traction effort curve added to ETAP library for modeling is shown in Fig.3

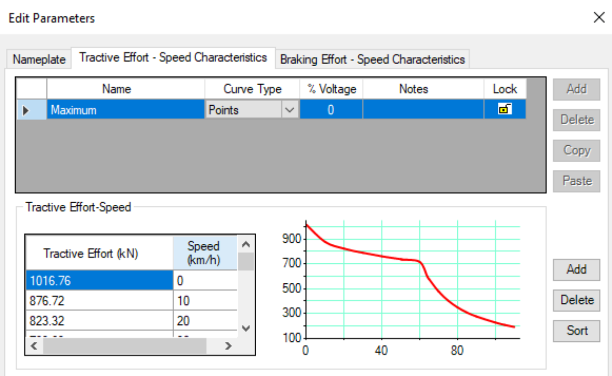

Fig.3. Traction effort curve of Yermak locomotive.

The railway modelled in this test case is two-way 150 km line with 3 stations (at the ends of the line and in the middle) with 5 substations (Fig.4). The elevation profile is assumed as flat.

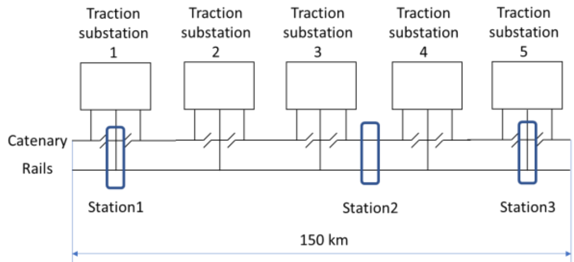

Fig.4. Railway and substations.

The modelled train schedule is 10 min headway and 5 min dwell time (Fig.5).

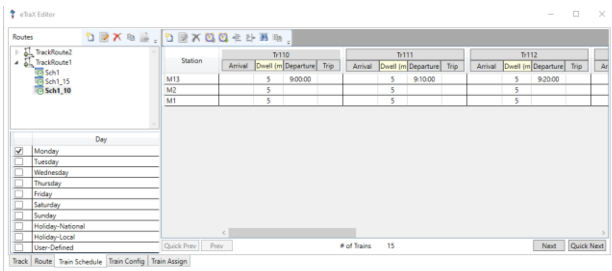

Fig.5. Train schedule.

The modelled configuration of the train is:

- 1 3S5K Yermak locomotive (288 tons);
- 84 freight cars (85 tons and 7140 tons in total).

Fig.6 shows this configuration.

Order	Quantity	Type	Manufacturer	Model	Weight	% Loaded	Length	Library
1	1	Locomotive	АС Грузовой	3ЭС5К Ермак	288	100	52.5	...
2	84	Passenger	Passenger	Груз.рол_новый	85	100	14	...

Fig.6. Train configuration.

The limit of acceleration was assumed as 0.5 m/s^2. The limit of deceleration was assumed as 1 m/s^2.

The model of the moving train is based on solving of differential equations using numerical integration. The results are:

- Traction effort, kN
- Acceleration, m/s^2
- Speed, km/h

It provides the mechanical power of the train and it is being recalculated to the active and reactive power. These values are being substituted to the location of the train as the constant power load. The model of the constant power load is a good assumption for traction power system analysis because the purpose of the driver and locomotive automation systems is to keep the speed fixed the specific location. Thus we get the necessity to keep the mechanical power as the fixed value regardless of the pantograph voltage level.

3.2 Substations and grid data

All 5 substations has 2 3-phase 3-winding transformers with the following parameters:

- 40 MVA rated power
- Rated voltages of windings 230 kV (primary) 27.5 kV(secondary) and 10 kV (tertiary)
- Z_{PS}=17.5 %, Z_{PT}=9.97 %, Z_{ST}=6.68 %
- X/R = 19

Each traction substation also has 3 MVA non-traction load (signaling systems and other loads).

In the normal conditions only one transformer at each substation feeds the catenary.

The modelled grid is 11 bus 220 kV grid with 2 slack bus sources.

Impedance data is presented in Table 1. Load and generation data is presented in Table 2. Fig.7 shows the graphical view of the grid with traction substations. All impedances of lines are considered as lumped values. Bus SS2 also contains shunt reactor with 60 Mvar rating. All traction substation buses (TSS1-TSS5) does not have specified load power because its load is the result of moving trains analysis.

#	Branch ID	Start bus ID	End bus ID	R, Ohm	X, Ohm	Y, µS
1	Z_SS2-3	SS2	3	3.7	16.6	100
2	Z_SS2-4	SS2	4	4.3	19	100
3	Z_SS2-TSS3	SS2	TSS3	1.8	8	50
4	Z_SS2-TSS4	SS2	TSS4	6.5	29	180
5	Z_SS3-2	SS3	2	9.5	40	250
6	Z_TSS2-SS3	TSS2	SS3	4.5	20	120
7	Z_TSS3-SS1	TSS3	SS1	10	48	280
8	Z_TSS4-TSS5	TSS4	TSS5	6	27	160
9	Z_TSS5-1	TSS5	1	10.3	46.1	280

Table 1. Branch data

#	Bus ID	Type	Vmag, % of 220 kV (rated)	Vang, deg.	P, MW	Q, Mvar
1	1	Slack	103.39	-0.25	-	-
2	SS1	Load	-	-	4.3	2
3	3	Load	-	-	11	7
4	4	Load	-	-	10	6
5	SS2	Load	-	-	40	-40
6	TSS1	Load	-	-	Result of analysis	Result of analysis
7	TSS2	Load	-	-	Result of analysis	Result of analysis
8	TSS3	Load	-	-	Result of analysis	Result of analysis
9	TSS4	Load	-	-	Result of analysis	Result of analysis
10	TSS5	Load	-	-	Result of analysis	Result of analysis
11	2	Slack	102.55	-7.93	-	-

Table 2. Bus load and generation data

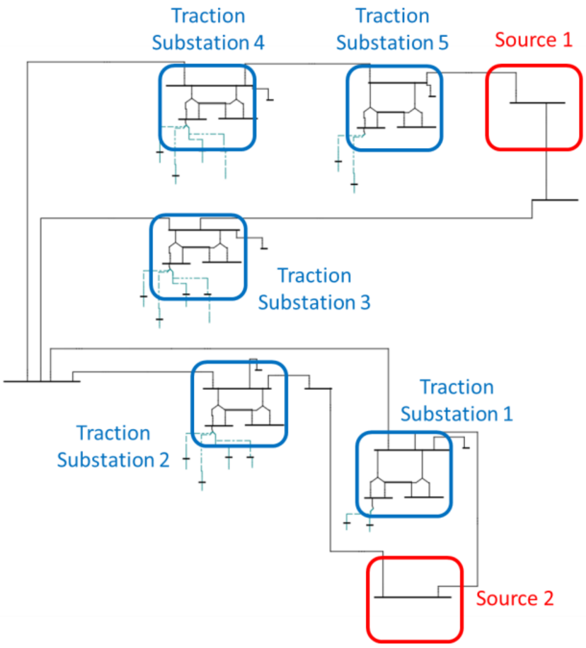

Fig.7. Visual representation of the modeled system

3.3 Equivalent sources modelling

The standard way to calculate equivalent source parameters is to calculate 3-phase and 1-phase faults at the selected bus. It has been done using StarZ module of ETAP. Its main advantage is consideration of prefault power flow. All currents calculated at traction substations buses are shown in Table 3.

#	Bus ID	3-phase fault current, kA	3-phase fault X/R	1-phase fault current, kA	1-phase fault X/R
1	TSS1	4.657	14.78	4.595	14.22
2	TSS2	4.828	14.93	4.522	13.84
3	TSS3	5.131	12.8	4.773	11.93
4	TSS4	3.995	8.98	3.838	8.77
5	TSS5	4.03	7.133	3.942	7.07

Table 23. Equivalent sources data

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4 Results analysis and comparison

4.1 Train output results

The result of moving train shows the following curves of Mw and Mvar for one train (Fig.8,9). The simulated time is 3 h 30 mins. Axis X shows time in seconds.

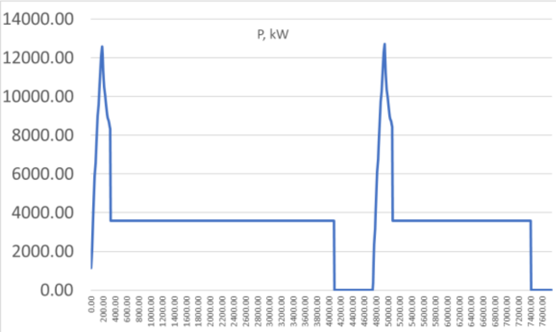

Fig.8. Train active power consumption

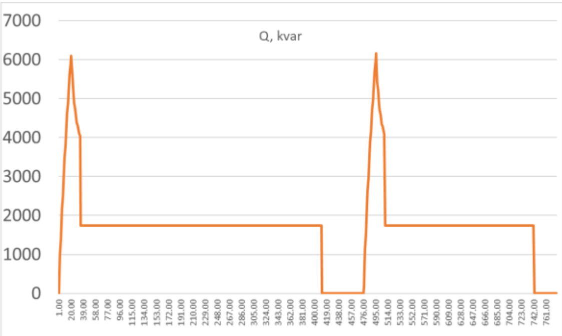

Fig.9. Train reactive power consumption.

It shows that the considered train configuration is a high load for the power system. The assumption of the flat elevation profile provides a possibility to compare the energy required to accelerate the train from 0 to 80 km/h and the power need to maintain the speed without additional resistances considering:

- Track elevation
- Track bend radius

In the real case with elevation profile and bend radius of track Mw and Mvar curves of trains will be more complicated and will have more impacts related to acceleration after changing of slope.

Results at Fig.8 and Fig.9 are independent from the upstream grid because it is constant power model but the voltage at the pantograph. But if we compare the current of any train we get the difference shown on Fig. 10. The current in the model with equivalent sources is higher because of the lower source voltage.

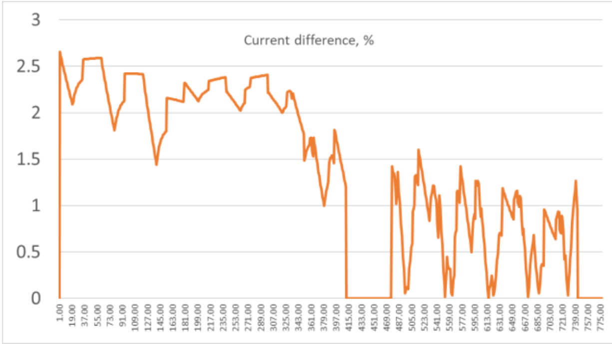

Fig.10. The relative difference between the locomotive current in the equivalent source model and the model with the detailed grid.

4.1 Power system response on traction load

The design and operation of traction power system require assessment of transformers power rating and power quality factors. The kVA function as the sum of power of 3 phases for the 4th substation is shown on Fig.11. This result has been calculated in the model with the detailed grid.

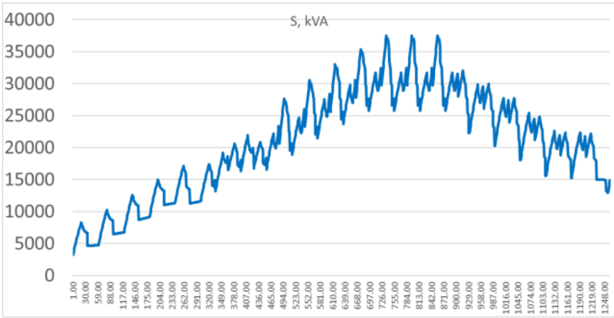

Fig.11. 3-phase kVA versus time for the 3rd substation calculated in the model with the detailed grid.

The calculation in the case with equivalent sources at each traction substation. The Fig. 12 shows the relative difference between P, Q and S calculated in the model with the detailed grid and the model with equivalent sources for the same substation.

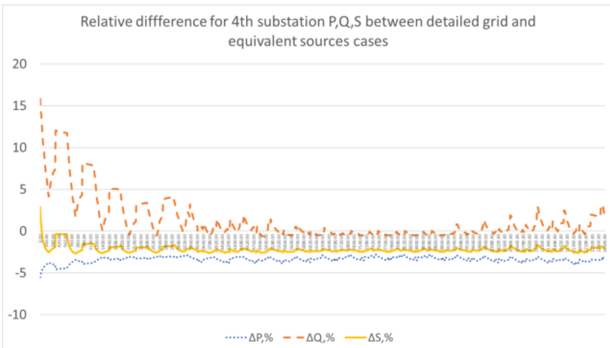

Fig.12. Relative difference between P, Q, S calculated in the model with the detailed grid and model with the equivalent sources.

The difference for this specific substation shows that active power is higher, the reactive power is lower, and the complex power is lower. The result could be different for other grid and other traction power system.

VUF2 in % is one of the most important factors need to be calculated in any unbalance load flow study including AC traction power system analysis. In Russia the limits of this factor are described in the standard [1]. The values of VUF2 calculated for the first substation are shown on the Fig.13.

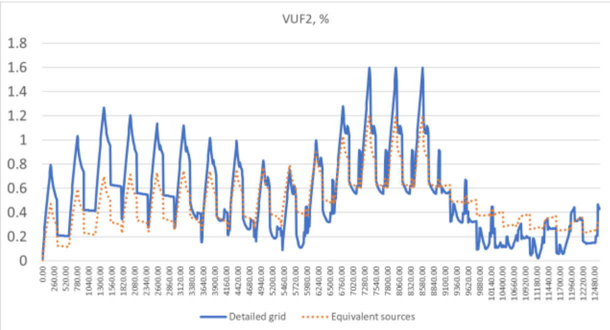

Fig.13. VUF2 calculated at 220 kV bus of 1st substation for the model with the detailed grid and the model with equivalent sources.

This plot shows that the model with equivalent sources provides underestimated values of VUF2. The results for peak loads differs more almost 3 times.

Plots for other substation (Fig.14-17) shows the same effect – VUF2 is higher for the model with the detailed grid.

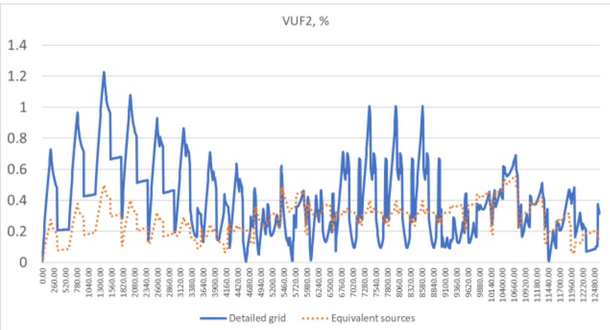

Fig.14. VUF2 calculated at 220 kV bus of 2nd substation for the model with the detailed grid and the model with equivalent sources.

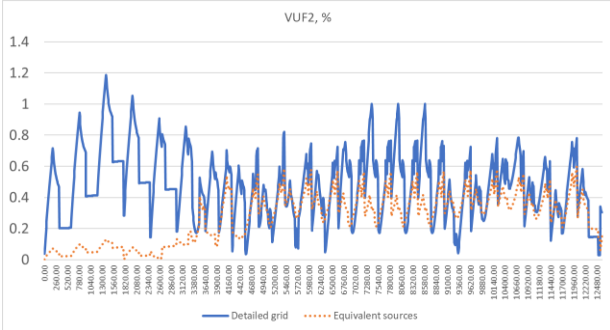

Fig.15. VUF2 calculated at 220 kV bus of 3rd substation for the model with the detailed grid and the model with equivalent sources.

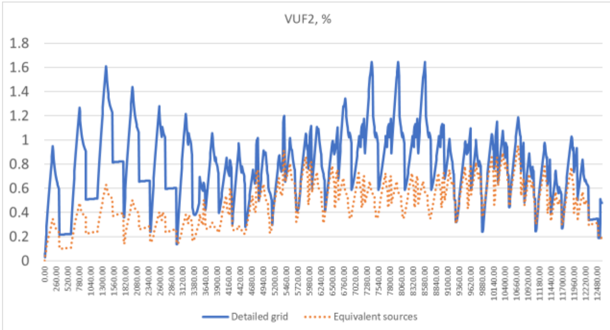

Fig.16. VUF2 calculated at 220 kV bus of 4th substation for the model with the detailed grid and the model with equivalent sources.

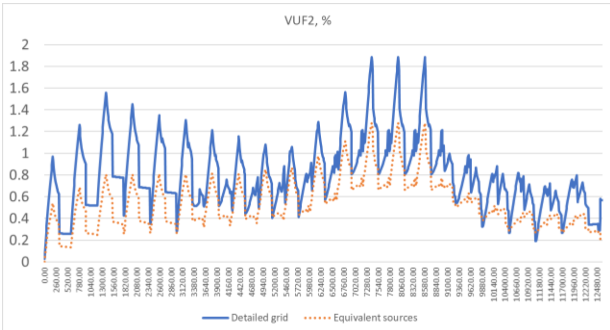

Fig.17. VUF2 calculated at 220 kV bus of 5th substation for the model with the detailed grid and the model with equivalent sources.

Fig.13-17 concludes that the model with equivalent sources underestimates voltage unbalance. The SVC sized using those results will not compensate unbalanced currents in the appropriate state.

It is need also to mention that recent researches described in [2] shows that it is need to consider the relative phase angle between the negative and the positive sequence of voltage at any bus feeding induction motors.

The model with the detailed grid provides the possibility to see values the difference between phase angles of negative and positive sequence of voltage. Fig. 19 shows the function of that angle for Substation 2 (SS2) 220 kV bus (see Fig.18).

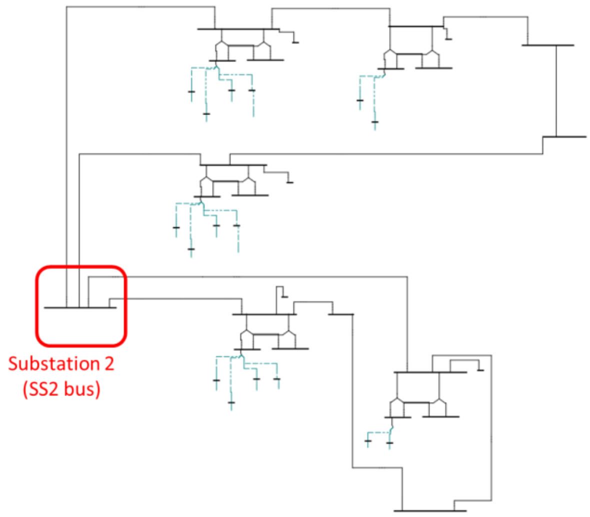

Fig.18. Substation 2 in the model with the detailed grid.

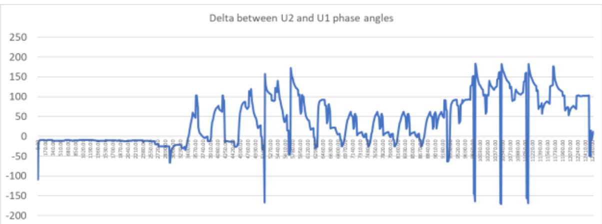

Fig.19. The relative angle between positive and negative sequence of voltage at 220 kV bus of Substation 2 (SS2).

This value also is a good example for comparison of the model with detailed grid to the model with equivalent sources. Fig.20 describes the difference between the relative phase angle between negative and positive sequences.

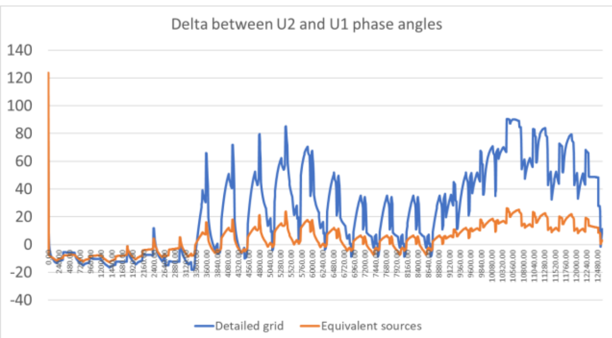

Fig.20. The relative angle between negative and positive sequence of voltage at 220 kV bus of Traction Substation 2 (TSS2).

5 Conclusions

Based on the foregoing, the following conclusions can be made:
1. There is the difference between train current calculated for the compared models with the detailed grid and the equivalent sources at the input bus of traction substations.
2. The compared models show the difference in power flows versus time for each traction substations. It could affect the sizing of traction substations transformers.
3. The model with equivalent sources shows underestimated value of VUF2. It could cause to incorrect sizing of SVC devices.
4. The model with the detailed grid provides the possibility to analyze the value of the relative phase angle between the negative and the positive sequence of voltage at any bus in the system. It is important due to recent studies including [2].
5. The model with equivalent sources shows the lower the value of the relative phase angle between the negative and the positive sequence of voltage at buses of traction substations.
6. The model with the detailed grid is recommended for all studies related to substation transformer and SVC sizing.

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