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Assessment of Synchronous Generator's Influence on Transmission Network with Significant Level of Voltage Unbalance

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***Abstract*—The electrified railway systems are known as source of large voltage unbalances in the transmission network. The electrified railway connection load flow analysis provides good overview of voltage unbalance distribution over transmission network. The level of unbalance is expressed by voltage unbalance factor, which value depends on network load conditions, network strength and selected traction system solution. In this paper a fragment of Estonian transmission network is modelled in PSCAD together with perspective electrified railway system and CHP plant in order to analyse the network operation in different conditions and determine the impact of synchronous generator to distribution of voltage unbalance.**

***Index Terms*— Electric locomotives, power quality, PSCAD traction systems, voltage unbalance.**

I. INTRODUCTION

Development of Rail Baltica railway connection has been under consideration for years. In recent times this discussion has elaborated and more development is foreseen in the future. Preliminary impact analysis of AC based electrified railway to Estonian electrical network have been made and the results are given in [1]. However, further technical studies and assessments are needed. The solution to use AC based electrified railway system is fairly common around the world and substantial amount of research results are available [2]–[7].

Based on the studies and existing practices it can be concluded that the electric railway system may have negative impact on power system due to relatively high level of unbalanced load. Consequently, the impact of electrified railways on power quality has to be studied and proper countermeasures taken. Electrical network characteristics in individual European Union countries are different due to their incremental development and therefore every country may need their own solutions to address and mitigate problems caused by wider implementation of electrified railway systems in the future.

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II. GENERAL APPROACH ON SYSTEM MODELLING

This paper continues the discussion started in [5], where the operation of one part of Estonian transmission system together with railway system was modelled and analysed. The approach selected was based on the load flow analysis in order to determine the resulting level of voltage unbalance and the size of affected area of related transmission system. In this paper this discussion is elaborated further by including additional combined heat and power (CHP) plant into the model. The objective of this paper is to analyse the influence of CHP plant to voltage unbalance level and determine the size of the affected area. This type of generating unit was added to the observable network in order to determine the influence of different type of generating units and also because in real life it is foreseen that similar CHP plant will be installed in the same region.

The observable transmission network fragment was selected based on possible foreseeable connection points on two possible routes of the railway system on the Estonian territory. Detailed description of the selection and modelling of the transmission network is presented [5]. Simplified scheme of selected and modelled transmission network together with the combined heat power plant is presented in Fig. 1.

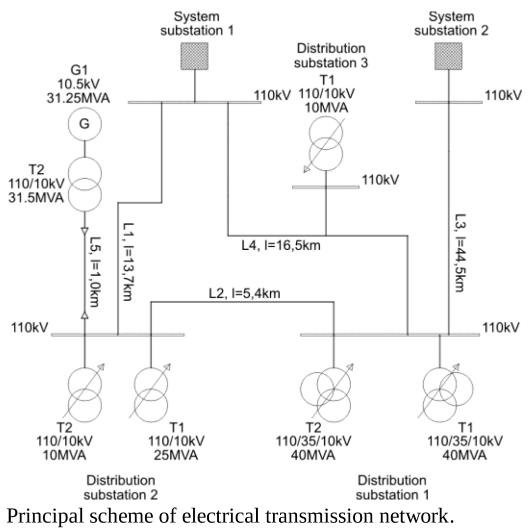

Fig. 1. Principal scheme of electrical transmission network.

The principle solution for electric railway traction system is the same as used in previous study [5]. The modelled network consists of two new 10 km overhead lines modelled as double circuit line, traction system substation with two 110/25 kV transformers, two traction system contact feeder lines and three electric trains as seen on Fig. 2. The contact feeder line is modelled in PSCAD using PI segments with longitudinal impedance 0,169 + j0,432 Ω/km and with a shunt capacitance of 0,011 μF/km at 50 Hz. Same approach for traction system modelling is used also in previous research by other authors [4].

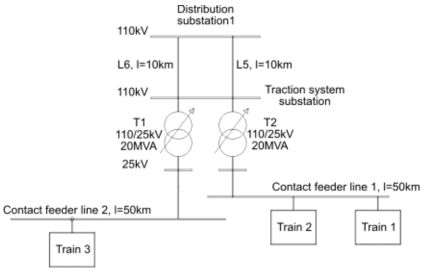

Fig. 2. Electric railway traction system connection scheme.

The contact feeder lines (Fig. 2) are modelled using PI sections with appropriate length and parameters. More details regarding the traction system model can be obtained from [5]. The traction system load was modelled consisting of three trains each with rated power 5,5 MW and power factor of 0,8 [2], [3].

III. Modelling of the CHP Plant

The technical parameters of the CHP plant selected for this study correspond to similar plants which have been built in Estonia. Considering the amount of heat consumption in the region it is very probable that the same type of plant will also be built and therefore author believe the conclusions made based on this study are applicable in the future. In the model, the CHP plant is connected to the 110 kV bus bars of distribution substation 2 via 1 km cable line L5 as seen in Fig. 1. Due to PSCAD limitations regarding the modelling of cable lines the line were modelled using coupled PI section model (Fig. 3). It is believed that the selected model provides sufficient accuracy in order to model cable line for load flow and power quality related studies. Modelled CHP step-up transformer is with rated power of 31,5 MVA and without tap changer. Transformer parameters were selected based on typical data available in the literature for similar type of power transformers.

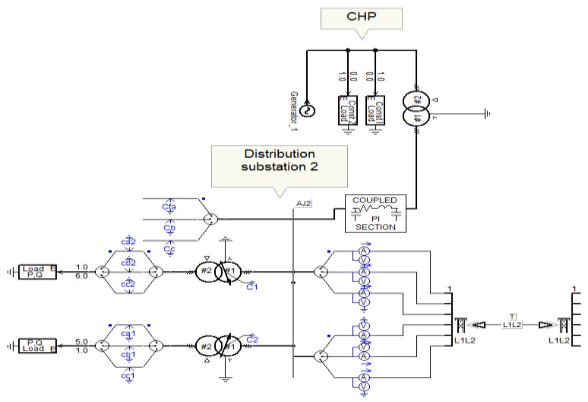

Fig. 3. PSCAD model fragment of distribution substation 2 and CHP plant.

The maximum designed electrical power output of the CHP is 25 MW. In addition, for realistic power output of the power plant 1 MW and 1 MVAr auxiliary loads were modelled as seen on Fig. 3.

Simplified PSCAD model of the CHP plant generator is shown in Fig. 4. The model consists of models of generator, excitation system and power system stabilizer. The parameters used in the model correspond to similar type of generators and their control systems.

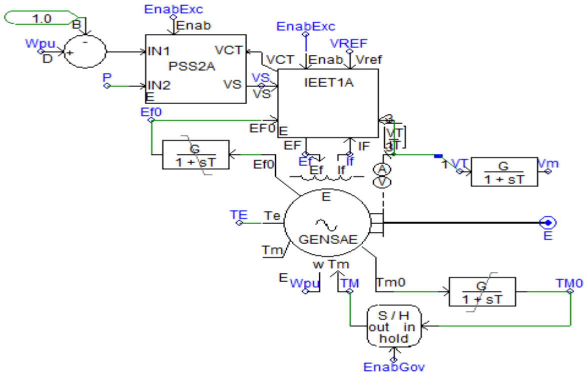

Fig. 4. PSCAD model of CHP generator.

IV. Case Study and Analysis

The purpose of this analysis was to assess the influence of CHP plant to network power flow and voltage unbalance. Analysis regarding system stability and control interaction between different types of network devices is not covered in this paper. Results of that study will be published in the future.

In this study the simulations performed were divided into four cases. In the first case, the transmission network with disconnected CHP plant and typical loads was simulated. In the second case the CHP plant was switched into the model. In the third case the CHP was disconnected and the level of loads was increased and in the fourth case the CHP model was included in the simulation. The level of unbalance was analysed according to the recommendations provided in [8]. It is suggested to use the following expression

$$k_a = \frac{U_2}{U_1} 100\%, \tag{1}$$

where k_a is unbalance factor, U_2 is voltage negative sequence component and U_1 is voltage positive sequence component.

In order to calculate accurate unbalance factor a simple measuring scheme was composed using the PSCAD standard library components (Fig. 5).

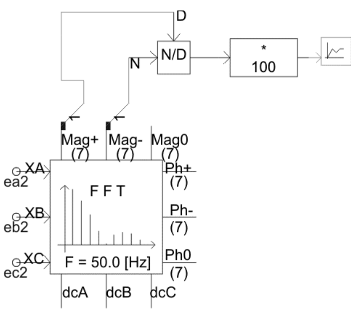

Fig. 5. Unbalance measuring scheme in PSCAD.

The component measures voltage negative and positive sequence component and automatically calculates unbalance factor.

Transmission network substation loads used are presented in Table I. The loads have high power factor ranging from 0,92 on 10 kV bus of distribution substation 3 to 0,98 on 10 kV bus of distribution substation 2.

TABLE 1. TRANSMISSION NETWORK TYPICAL SUBSTATION LOADS.

Distribution substation 1	***S* (MVA)**	***P* (MW)**	***Q* (MVAr)**
T1/T2 (35 kV side)	7,91	7,50	2,50
T1/T2 (10 kV side)	8,98	8,75	2,00
Distribution substation 2	***S* (MVA)**	***P* (MW)**	***Q* (MVAr)**
T1/T2 (10 kV side)	5,10	5,00	1,00
Distribution substation 3	***S* (MVA)**	***P* (MW)**	***Q* (MVAr)**
T1 (10 kV side)	3,68	3,40	1,40

The simulation results for traction system without CHP plant are presentend in Table II. The simulations without CHP plant are important in order to provide the base for further simulation cases and to highlight any changes caused by introducing the CHP plant into transmission network and by changing the consumption in the grid. The study results after connection of CHP plant into the network are given in Table III.

TABLE II. FIRST CASE SIMULATION RESULTS.

Substation	**Unbalance factor (%)**		
	110 kV bus	**35 kV bus**	**10 kV bus**
System substation 1	0,00	-	-
System substation 2	0,00	-	-
Distribution substation 1	1,35	1,35	1,35
Distribution substation 2	0,65	-	0,65
Distribution substation 3	1,15	-	1,15

TABLE III. SECOND CASE SIMULATION RESULTS.

Substation	**Unbalance factor (%)**		
	110 kV bus	**35 kV bus**	**10 kV bus**
System substation 1	0,00	-	-
System substation 2	0,00	-	-
Distribution substation 1	1,34	1,34	1,34
Distribution substation 2	0,56	-	0,56
Distribution substation 3	1,14	-	1,14

According to the transmission system operator requirements for power quality the maximum allowable voltage unbalance limit for single connected load is 1% and overall voltage unbalance in transmission network should be below 2% [10]. In case the limits are reached then due to the continuous nature of the voltage unbalance it is prone to cause problems in nearby distribution networks as seen from simulation results where the unbalance factor is equal in HV and MV side. Therefore this type of power quality phenomenon should be observed and appropriate countermeasures used when necessary.

Comparison of the first and second case simulation results show that CHP plant model connected to the transmission system improves the voltage unbalance factor on substation buses. Improvement is clearly seen on distribution substation 2 where the voltage unbalance reduction was the highest. However, one should consider that on the distribution substation 2 the voltage unbalance was already on acceptable level and overall change of voltage unbalance in other buses was almost unnoticeable.

In order to assess the influence of load increase in the future, the substation loads were changed based on forecast obtained from Estonian transmission system operator. Only distribution substation 3 load was not changed because it is expected that the level of that substation will remain the same. New values of loads are given in Table IV.

TABLE IV. TRANSMISSION NETWORK ELEVATED SUBSTATION LOADS.

Distribution substation 1	***S* (MVA)**	***P* (MW)**	***Q* (MVAr)**
T1/T2 (35 kV side)	15,81	15,00	5,00
T1/T2 (10 kV side)	17,95	17,5	4,00
Distribution substation 2	***S* (MVA)**	***P* (MW)**	***Q* (MVAr)**
T1/T2 (10 kV side)	7,65	7,50	1,50
Distribution substation 3	***S* (MVA)**	***P* (MW)**	***Q* (MVAr)**
T1 (10 kV side)	3,68	3,40	1,40

The results of the third case simulation where the loads where increased and the CHP plant was disconnected is presented Table V. It can be observed that together with the increased loads in transmission network also the level of voltage unbalance in the network increased.

The increase of voltage unbalance in distribution substations 1 and 3 compared to the first case simulation results are caused by higher load flows in lines L3 and L4 which lowers the voltage at distribution substations bus bars. Lower supply voltage at the traction system terminal causes additional power losses in the traction system and consequently the level of total unbalanced load and level of voltage unbalance are increased. The comparison of first and third case simulation results show that in the distribution substation 2 the voltage unbalance has decreased. This was caused by load flow redistribution between transmission network lines, i.e. the redistribution caused increased load flow in line L1 and decreases the load flow in L2.

TABLE V. THIRD CASE SIMULATION RESULTS.

Substation	**Unbalance factor (%)**		
	110 kV bus	**35 kV bus**	**10 kV bus**
System substation 1	0,00	-	-
System substation 2	0,00	-	-
Distribution substation 1	1,40	1,40	1,40
Distribution substation 2	0,62	-	0,62
Distribution substation 3	1,19	-	1,19

Fourth case simulation results (Table VI) indicate that the influence of reconnecting the CHP plant into transmission network is relatively same as in case three but due to increased loads the level of voltage unbalance is higher.

TABLE VI. FOURTH CASE SIMULATION RESULTS.

Substation	Unbalance factor (%)		
	110 kV bus	35 kV bus	10 kV bus
System substation 1	0,00	-	-
System substation 2	0,00	-	-
Distribution substation 1	1,39	1,39	1,39
Distribution substation 2	0,55	-	0,55
Distribution substation 3	1,18	-	1,18

V. CONCLUSIONS

In this paper, a case study analysing the influence of CHP plant to network with significant level of voltage unbalance was discussed.

The results of the study showed that in the modelled transmission network segment the traction system with trains caused an unacceptable level of voltage unbalance. By adding the synchronous generator into the network only minor changes occurred. Nevertheless, it can be concluded that the CHP plant generator strengthens the distribution substation 2 node by increasing the short-circuit power there and therefore providing largest improvement of voltage unbalance. The overall effect from stronger node to the rest of the network is modest due to weak connection between substations 1 and 2. It can also be concluded that the stronger the network node the more it is prone to manage different influences from other network parties.

The analysis in case of increased loads in the network confirmed that distribution of voltage unbalance in the transmission network is affected by the load flow in the lines L2 and L4, i.e., load flow in line L2 defines the voltage unbalance in distribution substation 2 and load flow in L4 affects the voltage unbalance in distribution substation 1 and 3.

However, the presented model should be extended to allow more precision in order to analyse the traction system influences to CHP plant generator and to network also during locomotive coasting and recuperative braking regime. Further studies are currently performed and the results will be published in near future

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