Model Study of Cooperating Traction Substations at 25 kV Traction Catenary without Superior Power Distribution Control

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***Abstract*— This paper describes the results of the model study for traction system 25 kV / 50 Hz, which is built on an advanced traction substation with a rail active balancer and phase shifting device. The first part of this paper is described traction substation topology with a description of its properties. The following section describes the operation of the traction system in terms of interconnection with the distribution power grid. The important requirements for the behavior and used equipment of advanced traction stations are explained in more details here. The last part of this paper presents the proposed concept of control of individual traction substations, while superior power distribution control is not available. Therefore, each traction substation must have its own independent control algorithms, its behavior properties are presented and documented in the results of simulation models. In order to be able to explain the whole issue well, the created model is simplified only to the control of two independent traction substations.**

Keywords*— *AC traction substation, power flow control, traction catenary model, independent power distribution control

I. INTRODUCTION

AC electric traction is preferred today. Therefore, the construction of DC railways is limited and somewhere being rebuilt to an AC system. An AC system offers higher power density, reduction of the capital cost of electrification, lower number of Traction SubStations (TSSs), etc. [1]. A significant aspect is a fast cooperation with smart grids under industry 4.0, where it is possible to use the benefits of offering modern semiconductor converter structures of Traction SubStation (TSS) as a symmetrization, reactive compensation, and harmonic elimination. The reconstruction into modern smart traction grids is in the eye of European Union politics within Shift2Rail (S2R) [2]. The two most perspective topologies for this rebuild are Advanced Rail Balancer (ARB) and Static Frequency Converter (SFC). A properties description of the both mentioned topologies, including a comparison with other commonly used variants of TSS, can be found in [3].

This paper describes ARB topology with the power electronics balancer (provides symmetrical currents consumption, allows compensation, and filtering of higher harmonics, as described in [4] and [5]). The cooperation of several TSS based on ARB is provided by the Phase Shifting Device (PSD). The symmetrization method (based on the Steinmetz symmetrization circuit) and its operation with Cascaded H-Bridge (CHB) converters are described in [5] and [6]. The transformer and a hybrid topology of PSD cooperating with balancer are described in paper [7]. This paper deals with a description of TSS power control without entering the required power from a superior central control unit. It is a proposed independent (autonomous) control algorithm of each TSS, where the limitations are specified only.

II. TRACTION CATENARY AND ADVANCED COOPERATION OF TRACTION SUBSTATION

The circuit diagram of the traction catenary based on ARB technology is shown in Fig. 1. The reason for the appropriate control of the flowed power through the TSS is shown there. It is necessary that there is no undesired overloading of individual TSSs and at the same time minimal catenary losses are achieved.

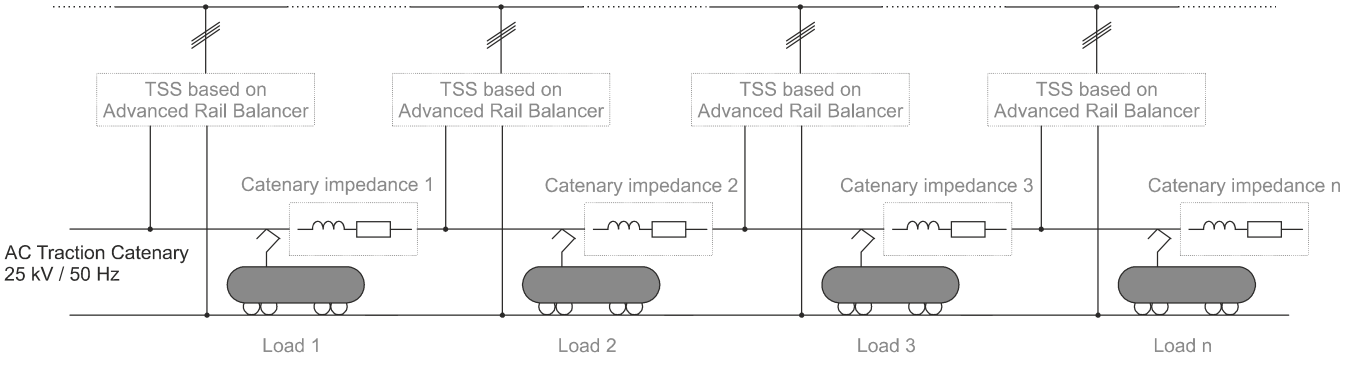

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Fig. 1. Example of possible interconnection of distribution line and traction catenary

The power circuit of TSS, based on ARB technology, is shown in Fig. 2. It is composed of the main transformer (three-phase), power electronic balancer and PSD (there are several possible variants of topologies).

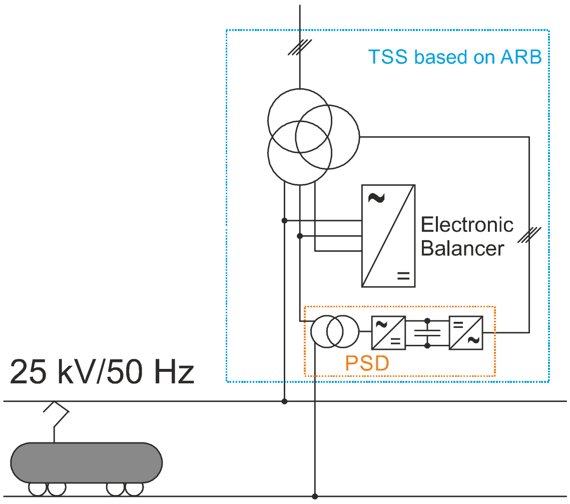

Fig. 2. The electric topology of analyzed traction substation with Advanced Rail Balancer including phase shifting device

An example of AC traction catenary equivalent circuit is shown in Fig. 3. There is the voltage source u_{TR} that represents the single-phase voltage of the main transformer, the controlled single-phase source (u_{PSD}) represents the controlled PSD voltage, inductance (L_{TSS}) and resistance (R) as representing the replacement of the real behavior of both sources. A primary key of this paper is concerned with PSD voltage control and thus a possibility to control the power distribution of the individual TSSs.

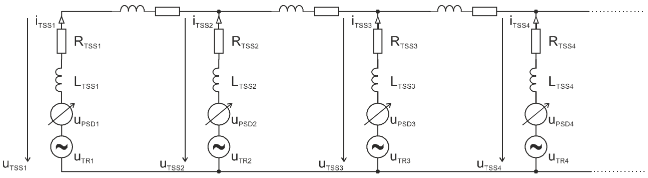

Fig. 3. The electric topology of analyzed traction substations with Advanced Rail Balancer including phase shifting device

The described control of the PSD unit can be tested on the proposed low-voltage mathematical model, which is shown in Fig. 4 (reduced to low-voltage mathematical and laboratory model of two TSSs with reality/model voltage scale 25kV/400V=62.5, nominal current scale 200A/12.5A=16, nominal power scale 5MVA/5kW=1000 and impedance scale circa 125Ω/32Ω=3.9). This model allows the testing of many different types of load. However, were selected the three situations. The first load situation belongs Z_{load_case1} there is a load right in the middle between TSS1 and TSS2 (ratio of catenary impedance is 2:2). The second load situation belongs Z_{load_case2} there is a load located closer to station TSS1 (ratio of catenary impedance is 1:3). The third load situation belongs Z_{load_case3} there is a load located directly at station TSS1 (ratio of catenary impedance is 0:4).

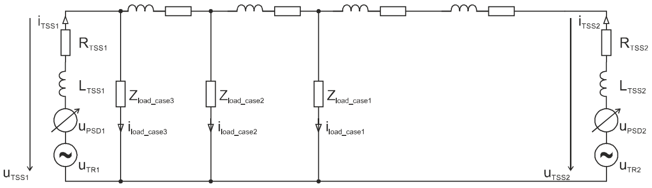

Fig. 4. The electric circuit of low-power mathematical model of two TSSs with moveable load

III. LOW-VOLTAGE MODEL RESULTS

The created mathematical model for two TSSs (Fig. 4) is used for the tests of behavior and analysis of power distribution between two TSS. The proposed control algorithm respects the minimization of catenary line losses. This fact is natural for the situation of the normal operation of AC traction catenary without control. However, when the selected TSS is overloaded, then it is necessary assistance from the other TSS. By the overload state is meant the load higher than the rated power of TSS, which is 5 kW for each TSS for our low-voltage model. The method of assistance (during overload) is based on the idea of droop control for the single-phase sources described in [8] and [9]. That is meant as independent management and distribution of power between individual sources.

A. Model study for the load situation 1

The first model study (we consider the load Z_{load_case1} only) presented the same load for the TSS1 a TSS2, because the ratio of catenary line impedance is the same.

In Fig. 5 is shown the behavior of both TSSs during load changes (1 kW, 6 kW and overload 10.9 kW). For all loads size, the power is evenly distributed, this fact is given by an equal impedance ratio (2:2). The shown powers P1, Q1 and P2, Q2 are about one period (20ms) delayed, due to the reconstruction from the power calculation and subsequent filtering. In Fig. 6 can be observed the real-time current response behavior.

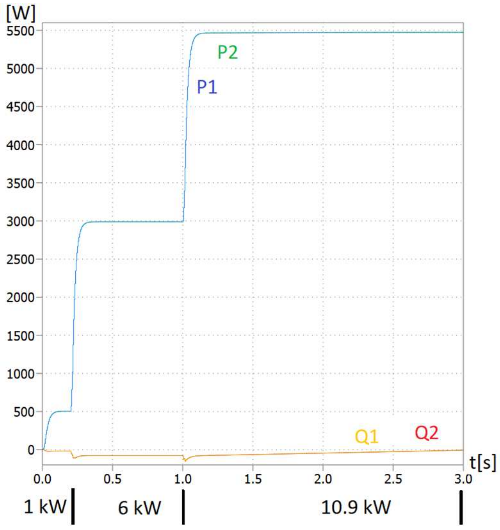

Fig. 5. TSSs load change response for the load situation 1 (symmetrical load - load in the middle TSS1 and TSS2)

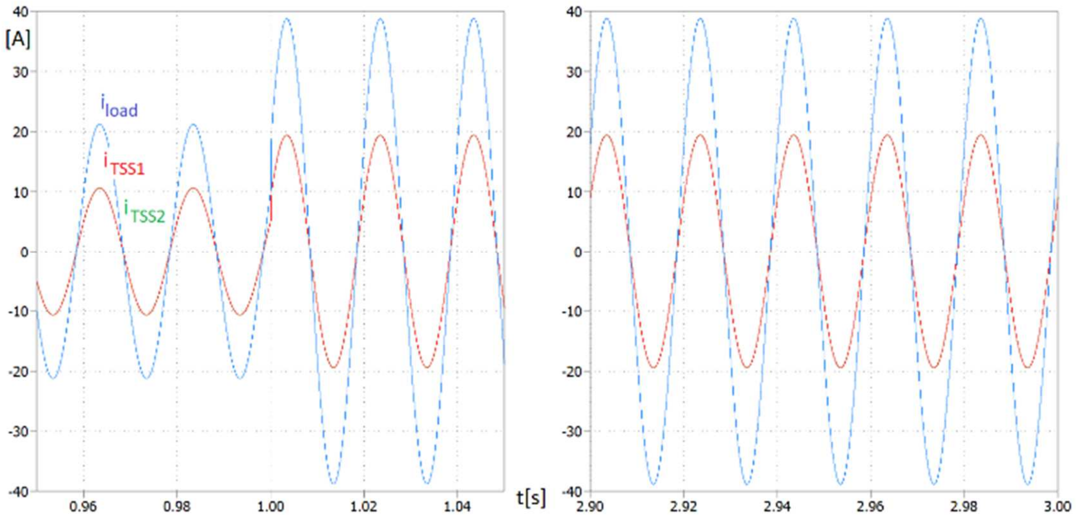

Fig. 6. The currents distribution for the load situation 1 (step change from load 6 kW to overload 10.9 kW and stabilization)

B. *Model study for the load situation 2*

The second model study (we consider the load Z_{load_case2} only) presented the different load for the TSS1 a TSS2 because the ratio of catenary impedance is different. Fig. 7 shows the behavior of both TSSs during load changes (1 kW, 6 kW and overload 10.9 kW). The 1 kW and 6 kW load are distributed according to the impedance ratio (1:3). However, for the 10.9 kW load are both stations overloaded and therefore the load is distributed equally between the TSS1 and TSS2. This current condition transient is captured in Fig. 8.

C. *Model study for the load situation 3*

The third model study (we consider the load Z_{load_case3} only) presented the different load for the TSS1 a TSS2. The impedance ratio (0:4) is entire to the detriment of the TSS1 and this fact leads to TSS1 overloading. In Fig. 9 and Fig. 10 is shown the behavior of both TSSs during load change (1 kW, 6 kW and 10.9 kW) for the monitoring of filtered powers (P1, Q1 and P2, Q2) and for the current values. For the 6 kW load, is TSS1 overloaded, and therefore is occurs assistance from TSS2. The result is an overload minimalization of TSS1 to close the nominal load of 5 kW (Fig. 10 time 1 s). During the subsequent load change to the 10.9kW, the load will be gradually distributed to the same values for both TSS.

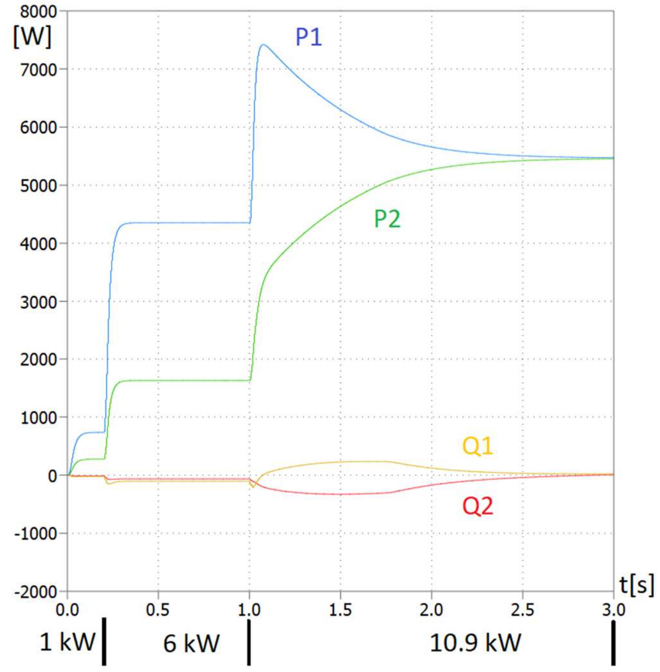

Fig. 7. TSSs load change response for the load situation 2 (non-symmetrical load - load is closer to the TSS1)

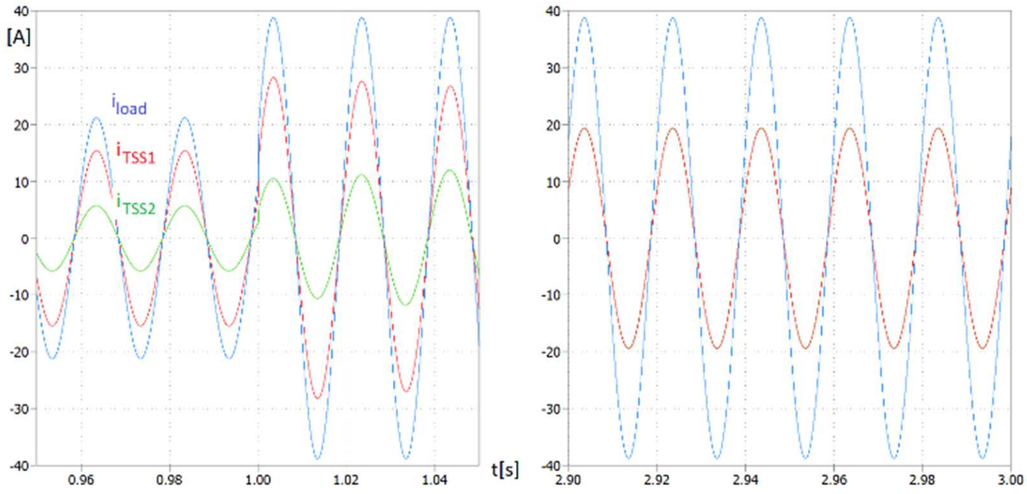

Fig. 8. Current distribution for the load situation 2 (step change from load 6 kW to overload 10.9 kW and stabilization)

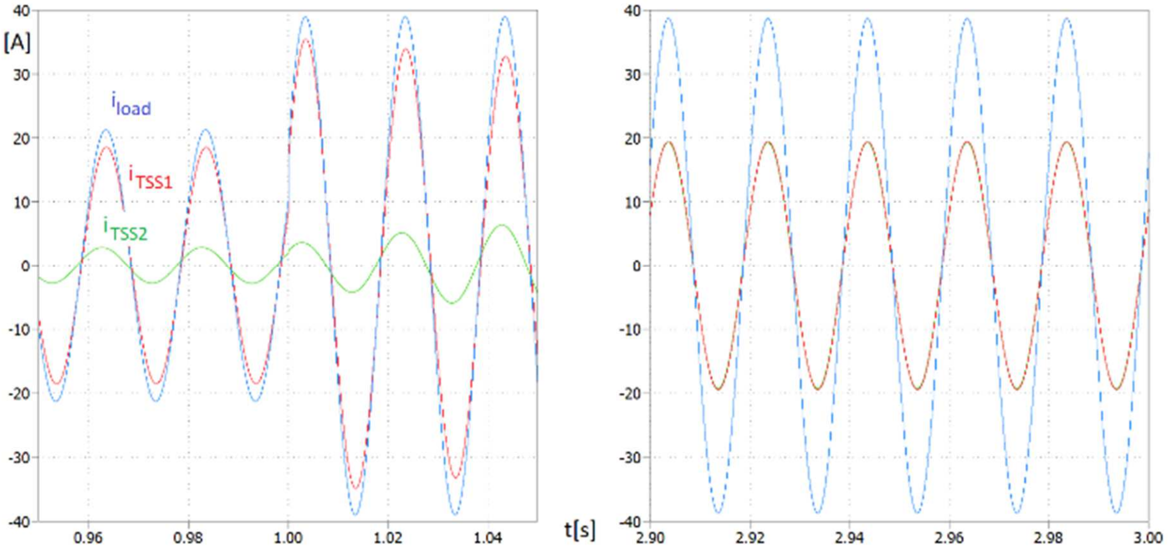

Fig. 9. Current distribution for the load situation 3 (step change from load 6 kW to overload 10.9 kW and stabilization)

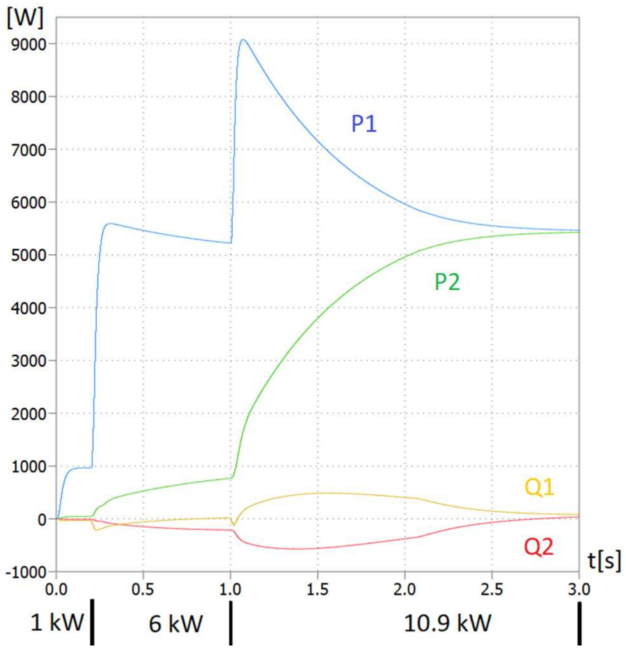

Fig. 10. TSSs load change response for the load situation 3 (non-symmetrical load - load is directly at the TSS1)

IV. CONCLUSION

The paper presented the proposed behavior of TSS with an electronic balancer and PSD (called ARB topology) for a situation without superior power distribution control. The behavior was tested for three different types of loads (Z_{load_case1}, Z_{load_case2} and Z_{load_case3}) on the designed low-voltage mathematical model of the traction catenary.

The TSS operation shows the achievement of specified requirements, which are a catenary loss minimization and power distribution between stations during overload.

Another advantage of the tested ARB configuration is the possibility of a higher short-term overload of this topology in comparison to the SFC topology. However, in this situation, the consumed power will not be fully balanced (the nominal power of the power balancer will not be enough), but it will be possible to keep running the traction catenary. This is closer to the possibilities of the existing traction catenary operation, when it is possible to overload transformers (old TSS without semiconductor converters) for.

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