Application of Power Electronic Converter for Actual Topologies AC Traction Substation

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Abstract – **This paper describes the typical field of power electronic converter in the branch of traction substation. The main attention is paid to problematic of AC-traction substation. This topic is solved here due to the just started conversion from DC-traction system to AC-traction system in Czech Republic. These new AC-traction substations use semiconductor power converters for purpose to minimize un-symmetrical unbalance of input current consumption, to compensate reactive power, to filtrate high-order harmonics etc. This article describe and compare basic attributes of these modern topologies of AC-traction substation.**

Keywords-railway substation; traction substation; power semiconductor converter; power symmetrization

I. INTRODUCTION

Public transport is traditional field of application of power electronic converters (see for example [1]-[3]).

DC-traction substations use special configuration power rectifiers - nowadays mostly twelve-pulse non-controlled rectifiers (with silicon diodes). Some older special configurations of DC-traction substations use silicon controlled rectifiers (SCR-thyristors bring the possibility of relatively low-cost solution with functionality of very quick over-current protection DC-traction substations for urban public transport). Historical configuration of DC-traction substations use mercury arc rectifiers (from 1920s to 1970s).

AC-traction substations for low-frequency alternating current (16.7 Hz etc.) use central or local traction current converter plants with frequency converter for connection to 50 Hz public electricity grid with rotating or static frequency converter. For example: application of controlled rectifiers with mercury arc rectifiers brings the cycloconverter topology (since 1936) with constant value of output-input frequency ratio (1:3). Modern configuration of these AC-traction substations use high-power frequency converter with voltage DC-link (so called "static frequency converter" SFC – see chapter V.) brings many advantages (above all easy cooperation between different substations with optimization of its active and reactive power output).

Traditional AC-traction substations for standard frequency alternating current (50 Hz or 60 Hz) use "only" transformer without semiconductor converters. But these traditional substations in Czech Republic was reconstructed by installation of additional filter and static compensator FKU with de-compensating device powered by semiconductor converter. This static compensator with de-compensating device minimize consumed lagging wattles power and produced high-order harmonics of current (above all third harmonics 150 Hz). Chapter III. shows the possibility of using this device for another purpose in these AC-traction substations (i.e. symmetrization of input current). Nowadays many countries prefer installation of new AC-traction systems over their traditional DC-traction systems (for example special high speed railways in Italy and Spain) and some countries (Czech Republic, Slovakia etc.) starts the long-time process of replacement from extensive railway networks with traditional DC-traction systems to modern AC-traction systems.

This paper is focused on problematics of using modern power semiconductor converters for AC-traction substations for purpose to minimize negative effects on the energy network (i.e. non-symmetrical input current, lagging wattles power etc.), to make easy cooperation between different substations and to achieve many other advantages (fast response controlled output).

II. DESCRIBED VARIANTS

This paper compare these variants of modern variants configuration AC-traction substations:

- Advanced static compensator (resp. dynamic load balancer) see chapter III.

- Active Steinmetz's balancer realized by semiconductor converter - see chapter IV.

- Static frequency converter SFC for full power- see chapter V.

- Minimized balancer (some power flow via balancer and rest part of power flow out of converter) - see chapter VI.

This division into these categories is only approximate. Because some these variants have many similar proprieties with small differences between them, but this division make described principles very illuminate.

III. Static Compensator

Figure 1 shows basic idea of topology, which is used for classical AC-traction substation TSS so called "open delta connection" (the most common configuration, in Czech Republic is used illuminate term "V-connection" of "traction transformer substation"). This figure 1 describes typical situation with two substations and two sections of the railway line between them and two sections to another substations (outside this figure).

Both substations have two single-phase transformers (for purpose to achieve low-cost solution with relatively symmetrical input currents). Two output feeders (two feeders from each substations) fed own sections of traction catenary. This configuration brings disadvantage of relatively high number of disconnection traction catenary, which are realized by neutral section position NP (i.e. NP near each traction substation and NP in special switching station SwS between these traction substations).
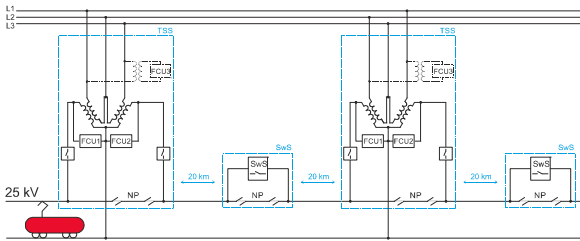

Figure 1.   The principle of substation for 25 kV /50 Hz railway traction system with electronic balancer for power symmetrization.

Figure 2 shows input three phase system of phase-phase voltages (u_{L1L2}, u_{L2L3}, u_{L3L1} in Czech Republic nominal voltage on primary side of transformer is 3x110kV+10%), phase voltages (u_{L1}, u_{L2}, u_{L3}), input currents (i_{L1}, i_{L2}, i_{L3}) and output currents (i_d, $-i_d$, i_e, $-i_e$). This phasor diagram shows unsymmetrical input currents and phase shift of these currents. Even if the output currents have power factor PF=1, so input currents have reactive components. For example input current i_{L1} from first phase L1 has leading power factor. And input current i_{L3} from third phase L3 has lagging power factor.
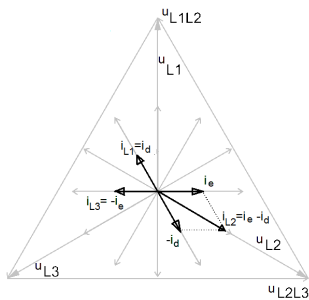

Figure 2.   The phasor's diagram of open delta AC-substation for 25 kV /50 Hz railway traction system

Real railroad transport brings unbalance between power consumption in booth output section "d" and "e". This situation is described in phasor's diagram in Figure 3. It is for example situation of high power consumption in first section "d" (supplied from voltage L1-L2) and low consumption in second section "e" (supplied from voltage L2-L3). Black solid arrows describes output currents - high power current is shown as superposition of balanced part and rest part of current (i.e. as subtraction between total value of current and balanced part: $|i_d'|=|i_d|-|i_e|$ and $|i_d''|=|i_e|$). Gray additional arrows inside triangle show the possibility how to obtain balanced input currents (violet arrows) with power factor PF=1 from balanced output currents. Additional gray arrows (outside of triangle) show the possibility how to obtain balanced input currents (black solid arrows) with power factor PF=1 from rest part of unbalanced output currents (i.e. black dotted arrows) and additional currents flows thru additional "filter-compensator units" FCU2 and FCU3.
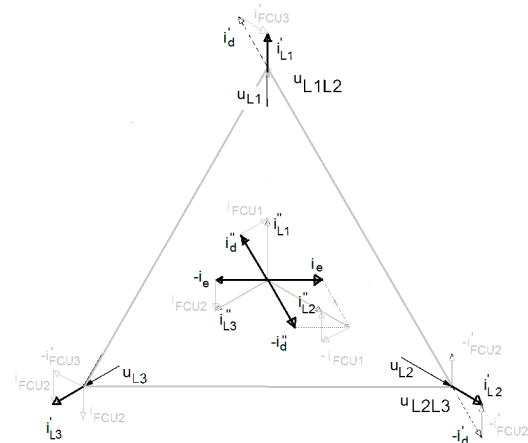

Figure 3.   The phasor's diagram of open delta AC-substation for 25 kV /50 Hz railway traction system.

All these additional currents have only wattles reactive power – it brings possibility to realize these additional currents by passive components (i.e. with using of capacitances or inductances in additional "filter-compensator units" FCU1, FCU2, resp. FCU3 in Figure 1). Practical railroad transport (with variety of actual value of current consumption of both sections) need the possibility to control actual value of currents flow thru these passive components.
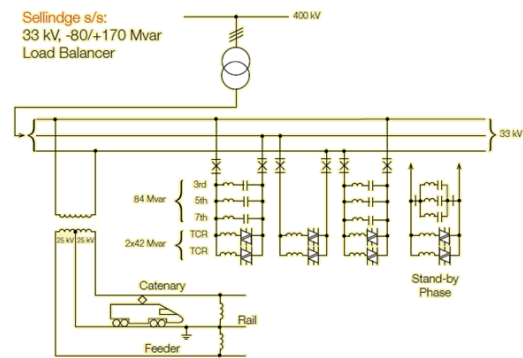

Figure 4.   Real example (high-speed railroad in Euro-chanel) of practical realization of single section AC-substation with additional controlled static compensator (so called "dynamic load balacer"). Figure from [4].

Practical realization ([4], [5]) is shown in Figure 4. This AC-traction substation supply only one section (only one single phase traction transformer i.e. "half" of described open delta connection with). This added advanced controlled static compensator (so called dynamic load balancer) consist of three arms with

inductances controlled by AC-regulator with SCRs (for controlled decompensation) resp. with passive LC filters (filters eliminate produced high-order harmonics and make leading factor of current for fundamental harmonic 50 Hz). Modification of this connection is solution how to solve problems of AC-traction substations in Czech Republic (i.e. with using additional filter-compensator unit FCU3 shown in Figure 1 in input side of transformer). But next chapters show more modern solutions.

IV. ACTIVE STEINMETZ'S BALANCER

Figure 5 shows the possibility how to obtain symmetrized input currents for single phase load (very similar situation is in Figure 4 as Figure 3 for only one output section). Theoretically (see [6]) three passive components R,L,C obtain symmetrized input currents (i.e. black arrows in phasor's diagram in Figure 5b). Practical loads in output section (locomotives with transformers) brings lagging power factor compensated by capacitance C_2 (shown in Figure 5c).
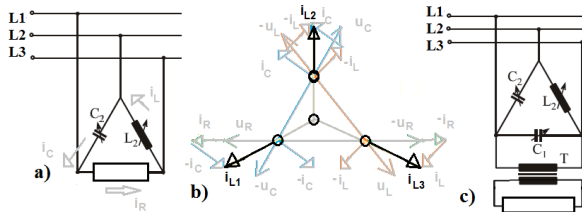

Figure 5. Steinmetz's triangle applied on to example of one-section AC-substation

Modern solution use realization all these L, C passive components by semiconductor converter. Figure 6 shows the practical realization by three arms of high-voltage converters (based on long chain by high number of serial connection of basic elements "cascade of H-bridges CHB") with inductance. Control algorithms of these arms make these converter the same function as inductance or as capacitance.
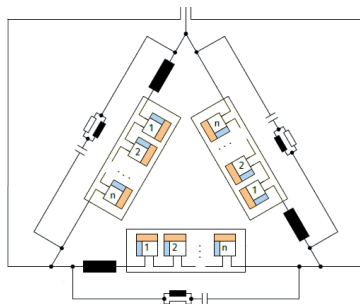

Figure 6. Active Steinmetz's balancer. Figure from [7].

V. STATICIC FREQUENCY CONVERTER

Another solution is based on using of full frequency converters (for this application operated as 3-phase 50Hz/50Hz 1-phase). The same type of these converters were traditionally used in Germany (etc.) for purpose discussed on chapter I. Figure 7 shows typical internal configuration of this converter, which consist of combination of multilevel frequency converter with 3-phase voltage source active rectifier VSAR, DC-link and 1-phase voltage source inverter. Application for Germany (etc.) need to use DC-link

with 33Hz filter 2nd for harmonics and converter for breaking resistor. Application in Czech Republic need 100 Hz filter 2nd for harmonics (braking resistors are implemented in vehicles).
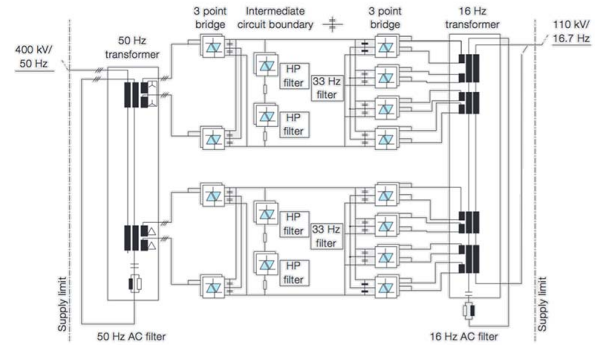

Figure 7. Static frequency converter SFC. Figure from [1].

This type of converter brings very expensive solution (step down input transformer, step up output transformer, input rectifier, output inverter and all these components are sized onto full power).

VI. POWER MINIMIZED BALACER

Figures 8 and 9 show some variants of low cost solution used power minimized balancers. These configuration brings some parallel ways for power flow from input to output. These parallel ways bring the advantage of minimization of size of these components (static frequency converter has serial connection of these components – each component is sized for full power). These converters can operates in many modes (resp. as combination of many modes). The main function of these converters are:

- Way for power from input to output
- Way for current flows between sections
- Symmetrization (i.e. balancing of input currents from unbalanced output currents)
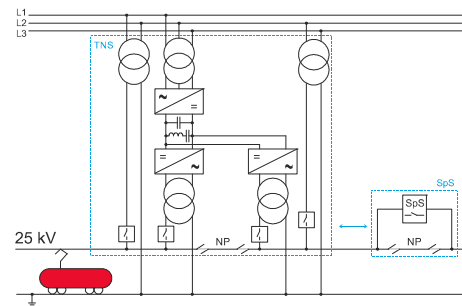- Filtration and compensation

Figure 8. Modification of open delta connection.

Open delta connection modified with additional "low-power" static frequency converter (see Figure 8) brings many advantages for actual older AC-substations, for balanced load in both sections (for substation with fluent public transport), the biggest part of power flows directly thru transformer (with minimized power losses on converter), possibility of emergency operation without converters etc. Disadvantage of this solution is two section with phase

shifted output voltage (the same principle as configuration described in chapter I.). Reconfiguration of this connection brings the Figure 9.

Figure 9 shows the modification which brings the way for biggest part of power flow thru converters and only rest of power flow thru transformer. This connection has advantage of possibility of commonly outputs (all outputs without phase shift). This configuration brings the possibility of emergency operation by disconnection of this common output and operating regime as previous Figure 8 or Figure 1. Papers [8]-[11] show other alternatives.
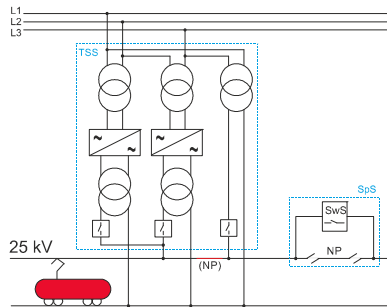

Figure 9.   Modification of AC-substation with single output.

Sizing of converter depend on many factors of operating regimes of traction substation. For example many operators in some countries (for example Czech Republic etc.) use older vehicles which product relatively high wattles power with lagging power factor (these vehicles use transformer and diode or SCR-thyristor input converter).
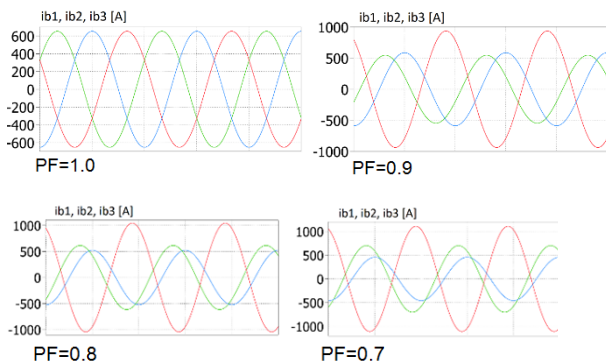

Figure 10. Current flows into converter (see Figure 8) for purpose to obtain symmetrical input currents.

Modern vehicles use active voltage source rectifier, with possibility to compensate wattles reactive power of own transformer for purpose to obtain power factor PF=1 with minimization of wattles reactive power. Older vehicles with low power factor need the compensation of this wattles reactive power by converters or compensation unit in traction substations. It brings non symmetrical input currents flows into these converters (see Figure 10) and it brings the problems of optimal sizing.

VII.   Conclusion

Public transport is traditional field of application of power electronic converters. This paper shows now field of practical application for power semiconductor

devices (i.e. in AC-traction substations). Chapter III. shows older solutions used in older construction of traction substations used in Czech Republic and in other countries. Chapter IV. shows the principle and practical realization of "balancer" which is able to achieve symmetrical current consumption. Chapter V. shows the modern configuration of traction substation used for traction system 15kV/16.7Hz etc. Using of this topology for system 25kV/50Hz bring many additional advantages (possibility of cooperation between neighboring substations) but it brings relatively expensive solution. Chapter VI. shows cheaper solution (with possibility to minimize size of power converter).

This applications nowadays are very important due to the strict requirements for the quality of electricity consumption and with regard to the already beginning conversion of the DC-traction system to AC-traction system in Czech Republic and other countries.

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