Active Elimination of Low-Frequency Harmonics of Traction Current-Source Active Rectifier

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Abstract— **In this paper, a new control approach in active suppression of low-frequency disturbances in the trolley-wire current using resonant (R) controllers is presented. It is dedicated for a single-phase active current-source rectifier (ACSR) developed within the research into a new generation of main traction converters employing the medium-frequency transformer dedicated for suburban units operating on both ac electrification systems of 25 kV/50 Hz and 15 kV/16,7 Hz. Proper function of proposed control strategy with a new compensative principle has been verified by simulations and large experimental study made on designed small-scale prototype of ACSR of the rated power of 7 kVA.**

Keywords*— *converter control, modulation strategies, power factor correction, single phase systems.

I. Introduction

Important motivation for this research has been our project dealing with the new generation of traction converters employing medium-frequency transformer – exactly the research into the matrix converter based converters on the primary side of the medium-frequency transformer [1], [2] as well as the project dealing with new topologies and control algorithms of current type of traction converters, e.g. [3], [4]. Therefore, we have been focusing on control possibilities and strategies of current-source rectifiers, their features and applicability under specific traction conditions.

Active suppression of low-frequency disturbances on the ac side of the traction active current-source rectifier (ACSR) is up to date topic. Generally, investigated disturbances can be caused by two sources: (i) oscillations caused by the input LC filter (both serial and parallel resonance), and (ii) oscillations (distortion) of the grid current caused by distorted trolley-wire voltage.

The ACSR requires a LC filter connected to its input terminals which constitutes a LC resonant mode. The lightly damped LC filter inclines to series (caused by rectifier switching) and parallel (caused by the power source) resonances when tuned to a system harmonic either from the trolley-wire or from the rectifier side. The solution of these oscillations suppression can be the selection of the filter resonant frequency out of the possible collision frequencies. This approach may result in a limited performance since the LC resonant frequency is a function of the power system impedance which usually varies with power system operating conditions such as the variation of trolley-wire inductance value caused by different position of the locomotive in a supply section. As a solution to this effect, an active damping approach appears as a most promising way. It is based on an emulation of the resistor in parallel to the filter capacitor by control. This method is very effective in LC filter oscillation suppression and it has been described e.g. in [5] and [6], but does not enable an effective compensation of the trolley-wire distortion when the trolley-wire voltage is permanently distorted.

In traction applications, sinusoidal current taken from the trolley-wire is often demanded even under strong permanent distortion of trolley-wire voltage. There are several control approaches able to deal with it. Currently, we have developed three control strategies able to effectively compensate the trolley-wire current distortion caused by the voltage distortion: (i) a correction based on direct measuring of the trolley-wire current described in [7], [8], (ii) a correction using directly the trolley-wire voltage described in [9] and (iii) the new correction approach using resonant (R) controllers tuned on particular harmonics to be described in this paper. Despite the previous controls proofed themselves functional and stable, the compensative effect they provide is not significant. Thus, a new approach operating with a high compensative effect employing R controllers has been developed. The idea of using R controllers in order to compensate distortion is not new and has been already successfully employed in voltage types of converters (e.g. in [10]). However, we did not find up to now any paper dealing with successful implementation of this control approach in a single-phase ACSR.

Topic of ACSR itself is not very common and published papers mostly deal with the three-phase version. Publications are rather theoretical, researches go into the problems connected with the control in particular using mainly the PWM modulation (e.g. [11]). Industrial applications of current-source converters are not in the power range below 10 MW very frequent at present. Nevertheless, e.g. Rockwell Company accommodates this technology in their three-phase converters [12]. Unfortunately, we did not find up to now (with exception of our research group) either complex paper dealing with the single-phase ACSR for traction applications or successful implementation in the traction vehicle. The aim of this paper is to provide an introduction of active suppression of low-frequency disturbances in the current on ac side of the traction ACSR based on R controllers. The main emphasis is given on the current distortion caused by the distorted trolley-wire voltage. The paper is organized as follows; (i) proposed control strategy with active correcting feature description, (ii) proper function of considered control strategy verification by simulations and large experimental study on a developed small-scale prototype, (iii) the behaviour and results of developed control are discussed in conclusions.

II. Proposed Control Strategy of the Traction ACSR

The power circuit of the considered traction converter is shown in Fig. 1, the proposed control strategy in Fig. 2. Its basic control loop consists of two PI controllers: (i) R_{Id} – load current controller and (ii) R_{φ} – phase shift controller. This configuration is able to secure demanded load current and also to control a phase shift between the trolley-wire voltage and current in demanded value, in our case within the range of ± 50 º (in comparison to the conventional control making possible only zero phase shift $\varphi = 0$ º). This feature makes the rectifier able to be operated also as a reactive power compensator working either with capacitive or inductive cos φ. The position of the trolley-wire voltage vector in the "stationary" reference frame (β) and the trolley wire current vector and magnitude ($I_{(1)M}$) are estimated by the discrete Fourier transform (DFT) which is able to operate even with strongly distorted waveforms.

This basic control loop provides very good results in a case of sinusoidal trolley-wire voltage but due to common PWM switching approach, in case of distorted trolley-wire voltage the trolley-wire current distortion occurs similarly according to the voltage distortion. This behavior is a common negative of all PWM controls. Due to this reason, the original control algorithm has been completed by a compensation block "harmonic compensator" based on resonant controllers. Transfer function of resonant (R) controller is defined as follows:

$$G_r(s) = \frac{K_r.2.s}{s^2 + \omega^2} \qquad (1)$$

where K_r is the resonant control gain and ω is the fundamental angular frequency of the source current. The gain of the transfer function is infinite at ω, the output is in phase with the input signal and the amplitude is amplified with time. The function has the characteristics of a generalized integrator in a stationary frame. Therefore, with the resonant controller it is possible to track the "high frequency" sinusoidal current reference without additional synchronization with the tracked frequency.

The harmonic compensator block consists in our case of three resonant controllers with pass-frequency of 150 Hz, 250 Hz and 350 Hz (3rd, 5th, and 7th harmonic). Outputs of controllers (iv_3h, iv_5h and iv_7h) are summed and form a compensation signal / correction waveform i_{cor}. This signal is consequently summed with the basic modulation waveform (i_v^*) and build together a final modulation curve led into PWM block. The basic idea of this approach is indicated in Fig. 3 where the basic converter current i_v is summed with the correcting current i_{cor} in order to sink the current with demanded "sinusoidal" shape. This way we are able to mitigate selected harmonics of the trolley-wire current. This approach can be generally applied to any harmonic component; the limitation is given mainly by the switching frequency, we use asynchronous PWM with carrier frequency of 2 kHz.

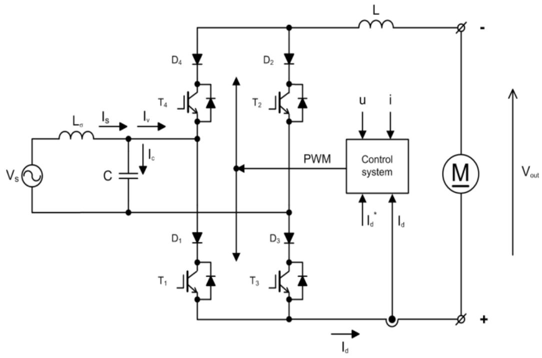

Figure 1. Power circuit of single-phase active current-source rectifier

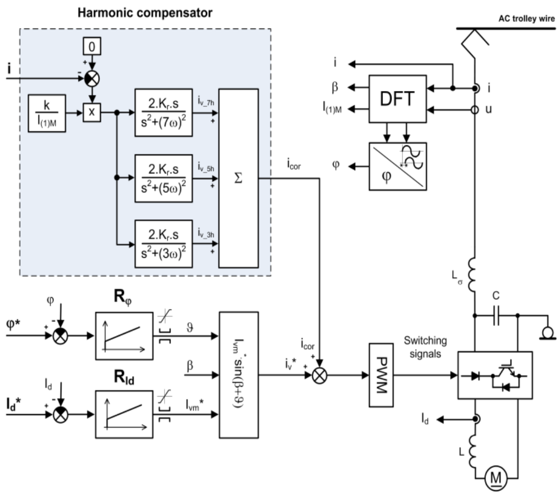

Figure 1. Proposed control strategy with the phase shift controller and active correction of the trolley-wire current waveform

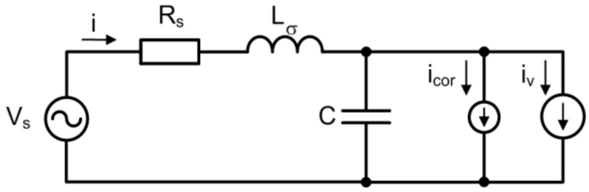

Figure 2. Simplified circuit of the active harmonic elimination applied to the active current-source rectifier

At the input of the harmonic compensator a block of the adaptive gain was accommodated. The gain depends on a magnitude of $I_{s(1)}$ current (indirectly), the constant K value was established with respect to the highest possible compensation effect. With lower I_s current we get higher gain of the control deviation led into R controllers which means higher magnitude of the compensation current. This way we can reach more effective compensation in the whole power range.

III. SIMULATION RESULTS

In the following page, selected simulation results of the new control strategy of ACSR are presented. The simulation model parameters are the same as the parameters of the designed laboratory prototype and are listed in TABLE I. The results have been divided into two groups where behaviour of rectifier under permanent trolley-wire distortion can be compared with (Fig. 4a - 6a) and without (Fig. 4b - 6b) correction feature for different supply waveforms with different harmonic distortion and load current (Id). From the comparisons it is apparent that correction feature can effectively mitigate selected harmonics under permanently distorted supply voltage. Simulations were provided in MATLAB with PLECS toolbox.

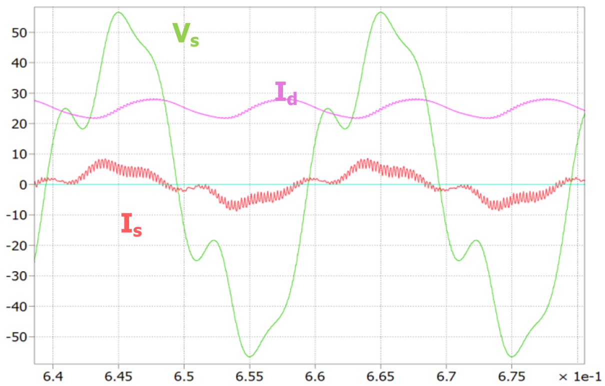

Figure 4a. Waveform 1, steady-state, without compensation, I_d= 2,5 A, φ = 0 °, V_s=50 V_{rms}/50 Hz (V_s= 10 V/DIV, I_s=1 A/DIV, I_d=1 A/DIV)

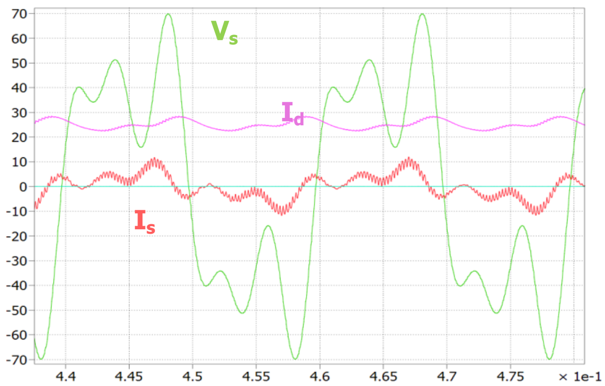

Figure 5a. Waveform 2, steady-state, without compensation, I_d= 2,5 A, φ = 0 °, V_s= 50 V_{rms}/50 Hz (V_s= 10V/DIV, I_s=1 A/DIV, I_d=1A/DIV)

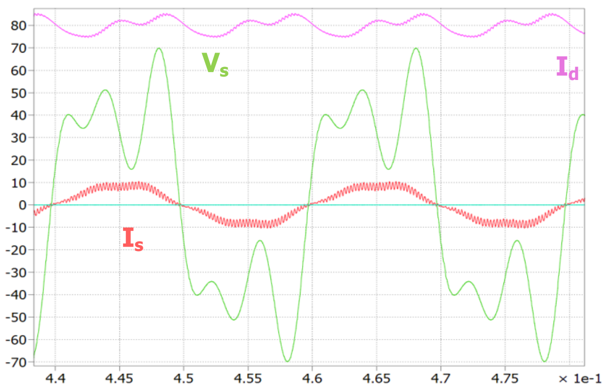

Figure 6a. Waveform 2, steady-state, without compensation, I_d=8A, φ=0º, V_s=50V_{rms}/50Hz (V_s=10V/DIV, I_s=5A/DIV, I_d=1A/DIV)

TABLE I

PARAMETERS OF LOW-VOLTAGE LABORATORY PROTOTYPE OF ACSR

ACSR rated power P_n	7 kVA
Trolley-wire voltage V_s	50 V
Trolley-wire voltage frequency	50 Hz
Input filter: L_σ C	1.6 mH 11 μF
Load inductance	30 mH
Switching frequency of IGBTs	2 kHz

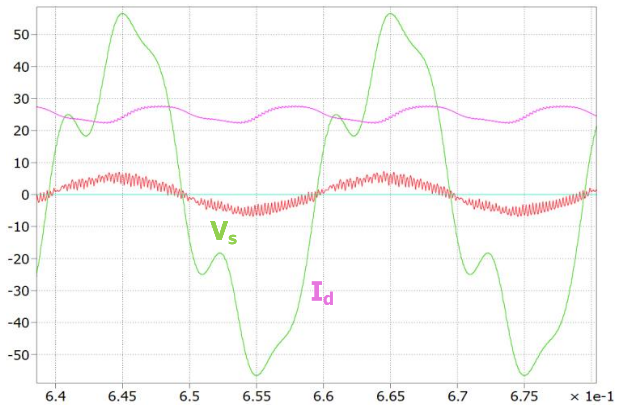

Figure 4b. Waveform 1, steady-state, with compensation, I_d = 2,5 A, φ= 0 °, V_s= 50 V_{rms}/50 Hz (V_s= 10 V/DIV, I_s= 1 A/DIV, I_d= 1 A/DIV)

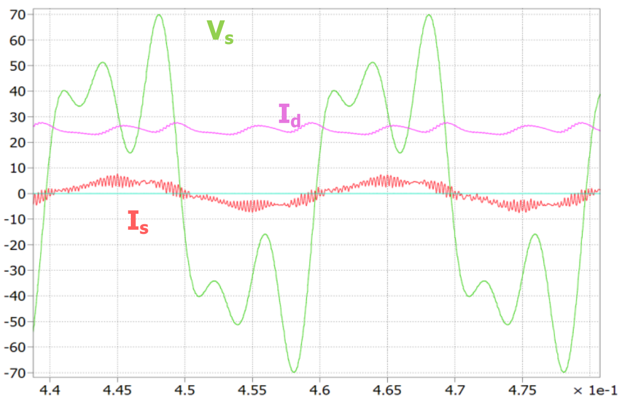

Figure 5b. Waveform 2, steady-state, with compensation, I_d= 2,5 A, φ=0 °, V_s= 50 V_{rms}/50 Hz (V_s= 10 V/DIV, I_s= 1 A/DIV, I_d=1 A/DIV)

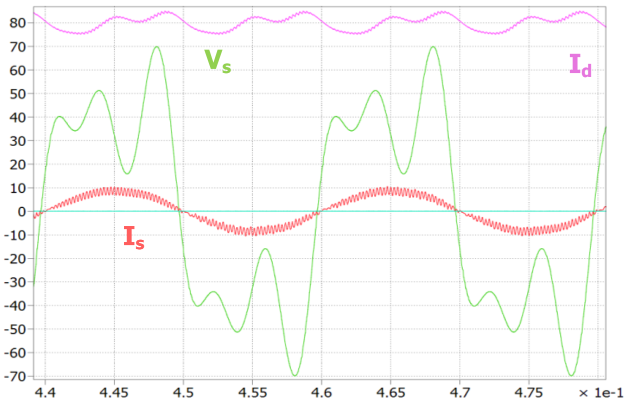

Figure 6b. Waveform 2, steady-state, with compensation, I_d= 8 A, φ=0º, V_s= 50 V_{rms}/50 Hz (V_s=10 V/DIV, I_s=5 A/DIV, I_d= 1 A/DIV)

IV. EXPERIMENTAL RESULTS

Experiments (Fig. 7 – Fig. 15) were carried out on small-scale laboratory ACSR prototype of the rated power of 7 kVA for the supply waveforms with the same harmonic distortion as in the simulations in order to compare theoretical expectations and practical results. Parameters of the converter are the same as in the simulation and are listed in TABLE I. Waveforms with and without compensation are placed under the same number next to each other in order to see the compensation effect. In order to see the behaviour under different load currents, values of 2.5 A and 8 A have been chosen. The value of 2.5 A is very close to minimum converter current (given by the input filter capacitor value) under which it is unable to control the phase shift and also very difficult to control the shape of the trolley-wire current due to low value of the fundamental harmonic. Figures with compensation also include the correcting waveform (see section II) so that the effect of the harmonic compensator could be easily seen. If we compare the phase shift between the trolley-wire voltage and current with and without compensation, it is not the same. Because the synchronization of both is secured by DFT (which provides the magnitude and phase of the fundamental harmonic), distorted current is not in phase with voltage despite the fact that the synchronization operates properly (the fundamental harmonic $I_{s(1)}$ is in phase with V_s). This is caused by harmonics, which summed with a fundamental one, change the final shape and phase of the current waveform (with shape close to sinusoidal) has demanded zero phase shift. The selected waveforms are supported by harmonic analyses which clearly confirm the compensation effect on the 3rd, 5th and 7th harmonics. They are provided in a way of particular harmonics as well as by THD_i comparison placed on the top of every harmonic analysis. It can be seen that the compensation effect grows significantly with the trolley-wire voltage distortion and also with the decreasing trolley-wire current. Therefore, with the low trolley-wire current (I_s) and strongly distorted voltage (when the value of the fundamental current harmonic is significantly lower than an amount of higher harmonics), the THD_i can reach very high values (see Fig. 11 and Fig. 12). In these cases, the contribution of harmonic compensator to a power quality is very significant. The compensation effect can be seen even with the sinusoidal supply voltage where a drop of THD_i can be also observed (see Fig. 9 and Fig. 13). This THD_i drop in sinusoidal shape is caused by the I_d controller, which (when tuned on faster response) tries to compensate the load current ripple (100 Hz). This natural behaviour of the PI controller can consequently influence also the I_s current shape even in case of purely sinusoidal waveform. In Fig. 15, transient of the trolley-wire voltage shape is shown. It is apparent that the resonant controllers are able to tune within a few periods on a new voltage shape without any disturbing effect.

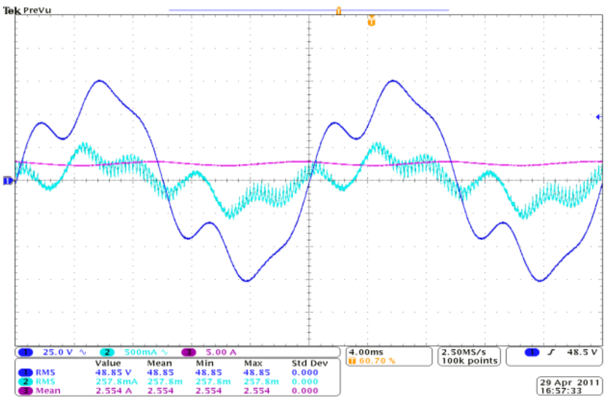

Figure 7a. Waveform 1, steady-state, without compensation, I_d = 2.5 A, φ = 0 °, V_s = 50 V_{rms}/50 Hz (Ch1-v_s, Ch2-i_s, Ch3-I_d)

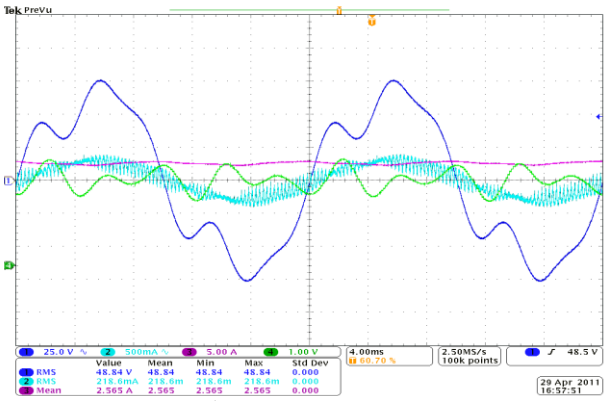

Figure 7b. Waveform 1, steady-state, with compensation, I_d= 2.5 A, φ = 0 °, V_s = 50 V_{rms}/50 Hz (Ch1-v_s, Ch2-i_s, Ch3-I_d, Ch4 (i_{cor})-0.5A/DIV)

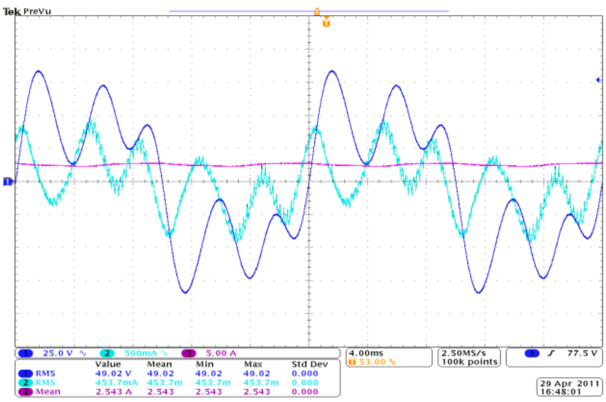

Figure 8a. Waveform 2, steady-state, without compensation, I_d= 2.5A, φ = 0 °, V_s = 50 V_{rms}/50 Hz (Ch1-v_s, Ch2-i_s, Ch3-I_d)

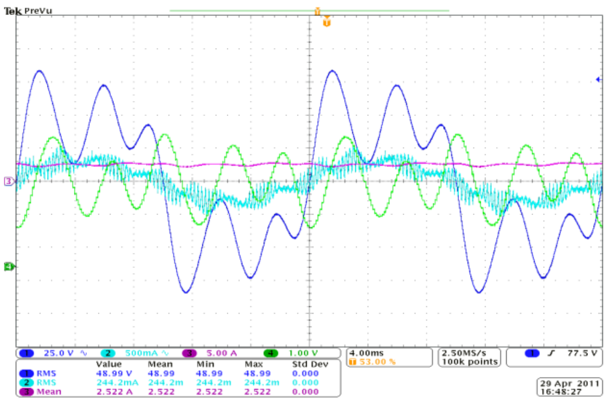

Figure 8b. Waveform 2, steady-state, with compensation, I_d= 2.5 A, φ=0 °, V_s = 50V_{rms}/50 Hz (Ch1-v_s, Ch2-i_s, Ch3-I_d, Ch4 (i_{cor})-0.5 A/DIV)

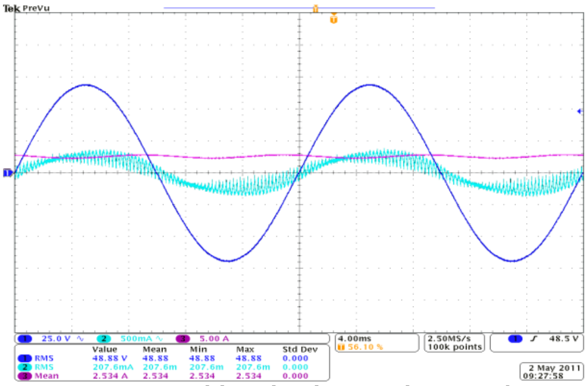

Figure 9a. Sinusoidal supply voltage, steady-state, without compensation, I_d=2.5 A, φ = 0 °, V_s = 50 V_{rms}/50 Hz (Ch1-v_s, Ch2-i_s, Ch3-I_d)

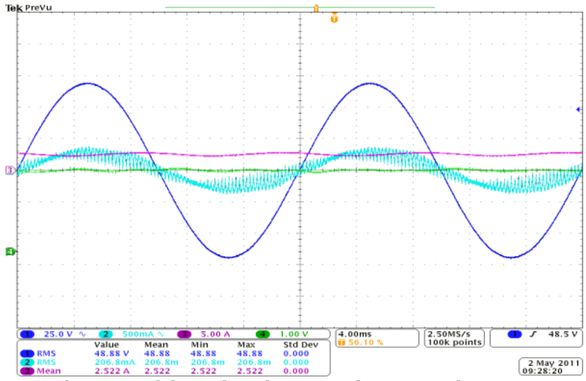

Figure 9b. Sinusoidal supply voltage, steady-state, with compensation, I_d= 2.5 A, φ = 0 °, V_s = 50 V_{rms}/50 Hz (Ch1-v_s, Ch2-i_s, Ch3-I_d, Ch4 (i_{cor})-0.5A/DIV)

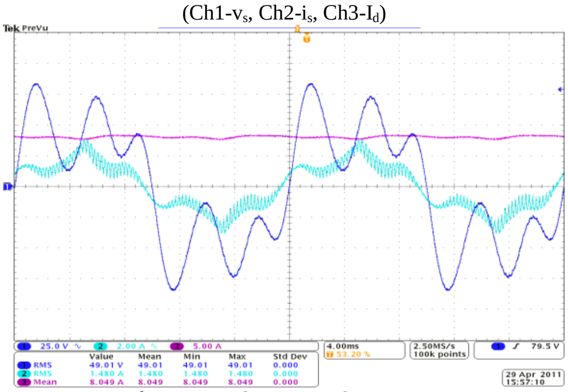

Figure 10a. Waveform 2, steady-state, without compensation, I_d= 8 A, φ = 0 °, V_s = 50 V_{rms}/50 Hz (Ch1-v_s, Ch2-i_s, Ch3-I_d)

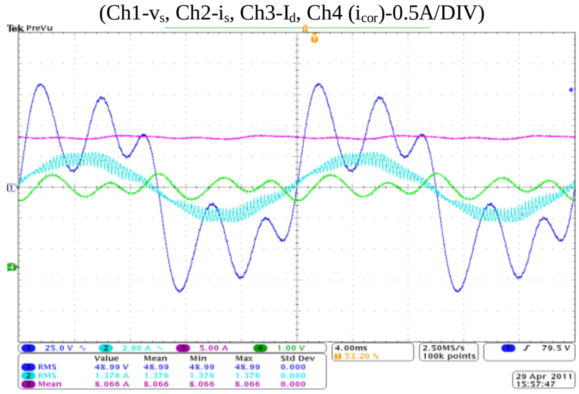

Figure 10b. Waveform 2, steady-state, with compensation, I_d= 8A, φ=0º, V_s = 50 V_{rms}/50 Hz (Ch1-v_s, Ch2-i_s, Ch3-I_d, Ch4 (i_{cor})-0.5 A/DIV)

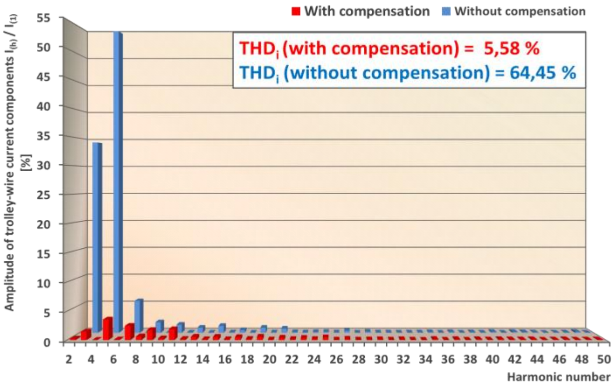

Figure 11. Comparison of harmonic analysis of trolley-wire current from Fig. 7a (without compensation) and Fig. 7b (with compensation)

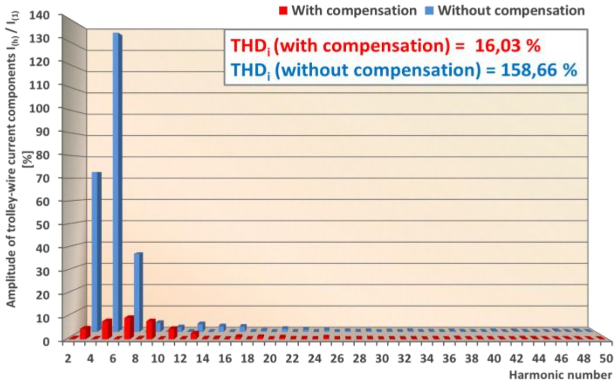

Figure 12. Comparison of harmonic analysis of trolley-wire current from Fig. 8a (without compensation) and Fig. 8b (with compensation)

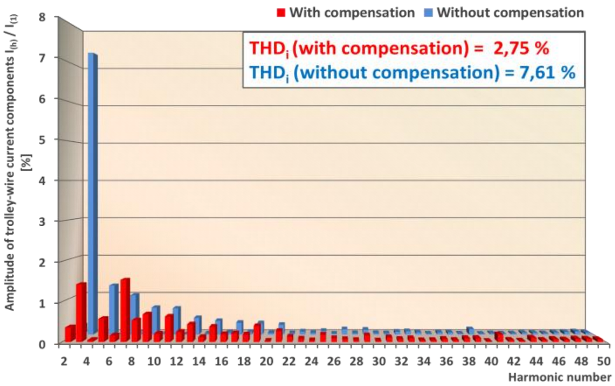

Figure 13. Comparison of harmonic analysis of trolley-wire current from Fig. 9a (without compensation) and Fig. 9b (with compensation)

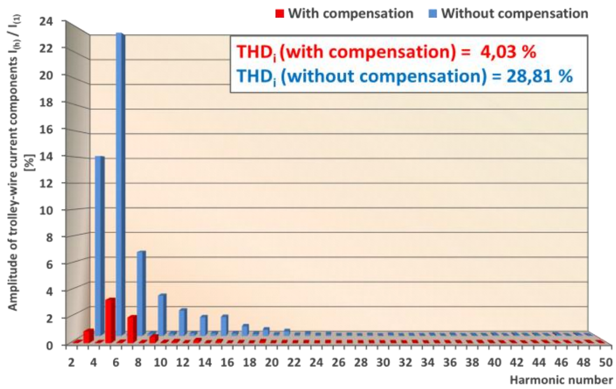

Figure 14. Comparison of harmonic analysis of trolley-wire current from Fig. 10a (without compensation) and Fig. 10b (with compensation)

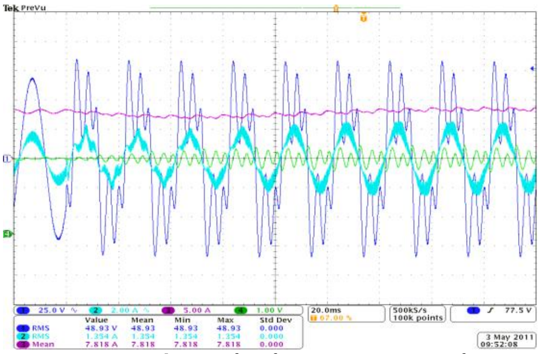

Figure 15. Step change of V_s from sinwave to waveform 2, with compensation., I_d = 8A, φ = 0 °, V_s = 50 V_{rms}/50 Hz (Ch1-v_s, Ch2-i_s, Ch3-I_d, Ch4 (i_{cor})-0.5 A/DIV)

V. Conclusions

This paper introduced the new approach in active suppression of low-frequency disturbances on ac side of the single-phase ACSR based on resonant controllers tuned on particular harmonics. The main attention has been paid to elimination of the current distortion caused by the distorted trolley-wire voltage. New control strategy making possible to suppress these disturbances is proposed and verified by simulations and experiments made on the developed ACSR prototype of the rated power of 7kVA. Main conclusions of this paper can be summarized into following points:

- New control approach in suppression of low-frequency disturbances on the ac side of the ACSR caused by the permanently distorted trolley-wire voltage using unwanted harmonics compensator with resonant controllers has been developed and described.
- The main contribution of this paper consists particularly in an introduction of the new control strategy based on resonant controllers able to significantly reduce the trolley-wire current harmonic amount. The proposed strategy can be easily widespread for arbitrary harmonic component of the trolley-wire current according to demand.
- The ACSR can be also operated as a reactive power compensator working with capacitive or inductive cos φ.
- Proper function of the proposed control has been verified by simulations and experiments made on designed small-scale prototype of the ACSR of the rated power of 7 kVA.

Acknowledgment

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