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*COMMUNICATIONS*

# ADVANCED CONTROL STRATEGY FOR SINGLE–PHASE VOLTAGE–SOURCE ACTIVE RECTIFIER WITH LOW HARMONIC EMISSION

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This paper introduces the advanced control of single-phase voltage-source active rectifier. This control provide direct control of trolley-wire current and active damping of low-frequency disturbances at the converter ac side. Our proposed control strategy combines PR controller with feed-forward model and low-frequency harmonic compensator based on resonant controllers. Achieved experimental results show excellent converter behavior, where converter is fed by strongly distorted supply voltage.

K e y w o r d s: single-phase voltage-source, control strategy

## 1 INTRODUCTION

The single-phase voltage-source active rectifiers are utilized in many industrial systems, *eg* electric traction, active power filters, power factor controllers and photovoltaic converters. The power circuit of single-phase voltage-source active rectifier is composed of four IGBTs, input inductor and output capacitor (power circuit is shown in Fig. 1). This power converter allows the precise control of DC-link voltage $U_c$ to constant value and the current control on ac side of converter $i_t$ (the quality of flowing current is very dependent on selected control). Control of the active rectifier is a very popular issue and it is possible to find many interesting articles with different control methods: i) hysteresis control method [1, 2], ii) model based control [3, 4], iii) vector control [5], iv) direct current control based on PR controller [6, 7]. This type of power converter (H-bridge) is basic component for multilevel power converters [8–11] and especially for multilevel traction converter [12–14]. The main advantages of this control algorithm are satisfactory behaviour under steady-state conditions and very fast transient responses. On the other hand, this control algorithm does not compensate sufficiently the low-frequency harmonic distortion of the current on ac side of converter which is thus transferred to the trolley wire. This phenomenon is observable mainly under strongly distorted trolley wire voltage conditions. Therefore, the original control algorithm has been completed by a compensation block (so-called harmonic compensator) which compensates namely the 3rd, 5th and 7th harmonic components of the current on ac side of converter. This paper describes in detail the enhanced control strategy and presents the simulations and experiments made on developed small-scale converter prototype.

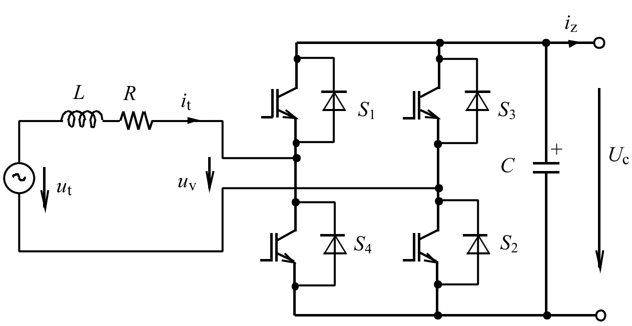


**Fig. 1.** Power circuit of voltage-source active rectifier

## 2 PROPOSED CONTROL OF VOLTAGE–SOURCE ACTIVE RECTIFIER

The proposed control of single-phase voltage-source active rectifier use PI controller for dc-link voltage control, PR controller for direct control of the fundamental harmonic of trolley wire current and resonant (R) controllers for suppression of selected harmonics of trolley-wire current. Proposed configuration of designed control is depicted in Fig. 2.

The dc-link voltage controller ($PI_{U_c}$) commands the magnitude of required current $I_m$. From this value, a trolley-wire current command $i_w$ is calculated and compared with measured current $i_t$. A resulting error signal $e_i$ enters into a PR controller ($PR_{i_t}$). This controller generates as its output a modulation signal $u_{\mathrm{v\_PR}}$ which is summed in next step with both a feedforward term

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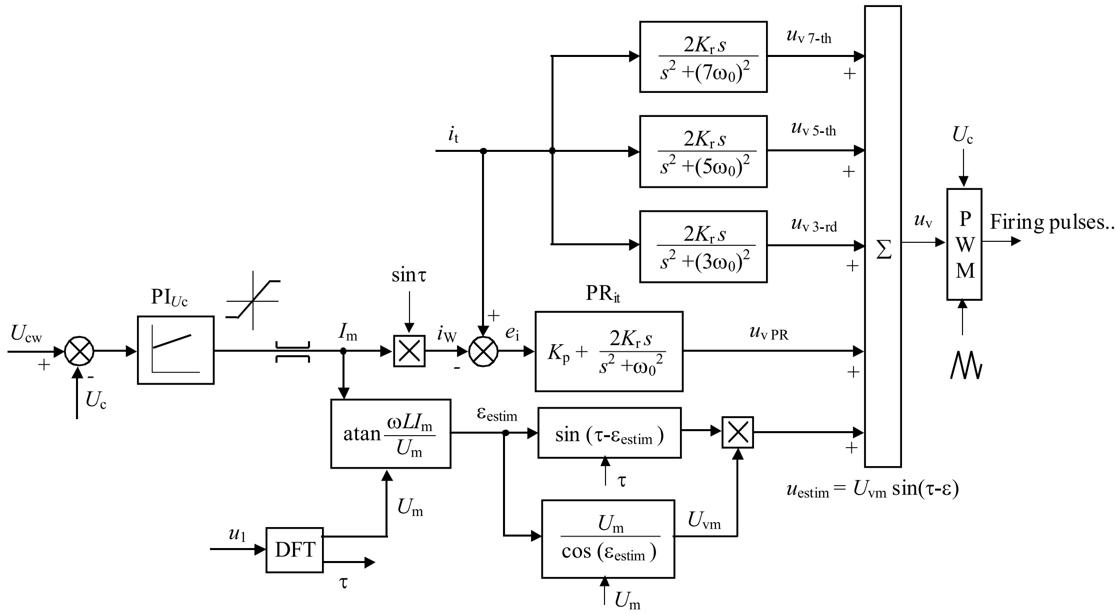


**Fig. 2.** Proposed control of voltage-source active rectifier

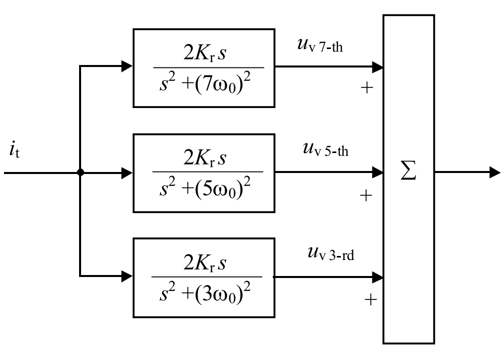


**Fig. 3.** Proposed low-frequency harmonic compensator reducing harmonic distortion of trolley-wire current

**Table 1.** Harmonic order contains in heavily distorted trolley-wire voltage

| Harmonic order | Voltage shape1 | Voltage shape2 | Voltage shape3 |
|---|---|---|---|
| | Magnitude (%) | | |
| basic ... (50Hz) | 100 | 100 | 100 |
| 3. ... (150Hz) | 20 | 20 | 17.72 |
| 5. ... (250Hz) | 1.2 | 15 | 16.88 |
| 7. ... (350Hz) | 2 | 1 | 5.49 |
| THDu | 40.27 | 50.04 | 50.16 |

$u_{v\_estim}$ estimated by a predictive model and the signals from harmonic compensator block which compensate low-frequency harmonic distortion of trolley wire current. In our case we use three resonant controllers with pass-frequency of 150 Hz, 250 Hz and 350 Hz ($3^{rd}$, $5^{th}$, and $7^{th}$ harmonic). Thus, the harmonic compensator block generates the signals $u_{v\_3h}$, $_{uv\_5h}$, and $u_{v\_7h}$. The resulting sum of $u_{v\_PR}$, $u_{v\_estim}$, $u_{v\_3h}$, $_{uv\_5h}$, and $u_{v\_7h}$ represents the final modulation signal for PWM ($u_v$).

## 3 COMPENSTAION OF LOW–FREQUENCY DISTURBANCES

The main advantage of proposed control is using of harmonic compensator block. This block consists of three resonant controllers to compensate 3-rd (150 Hz), 5-th (250 Hz), and 7-th (350 Hz) harmonics. The input signal to the controllers is the current it, each resonant controller works as a filter for appropriate frequency. The output signals are subtracted from the modulation signal. It is a progressive compensation, because the resonant controller contains a double integration of (compensation rate is dependent on the selected gain $K_r$). The proposed low-frequency harmonic compensator is shown in detail in Fig. 3.

## 4 EXPERIMENTAL RESULTS

The converter control has been tested by simulations and after them implemented in the fixed-point digital signal processor Texas Instruments TMS320LF2812.

The highest benefit of the proposed control is shown in the converter behavior when fed by strongly distorted supply voltage. The proposed control provide the elimination of basic low-frequency disturbances produced directly by the converter. The dead-time and circuit nonlinearities caused further (higher harmonics) disturbances that are very difficult to compensate, especially for single-phase power converters.

Figures 4–9 present the experimental results of developed voltage-source active rectifier prototype under steady-state conditions. Converter loaded by 1kW, is fed by heavily distorted voltage, see channel 1, in steady-state and rectifier mode, $f_{\text{switch}} = 4$ kHz. The main benefit of proposed control can be seen in Fig. 4, Fig. 6 and Fig. 8, where the compensated 3-rd to 7-th harmonics of

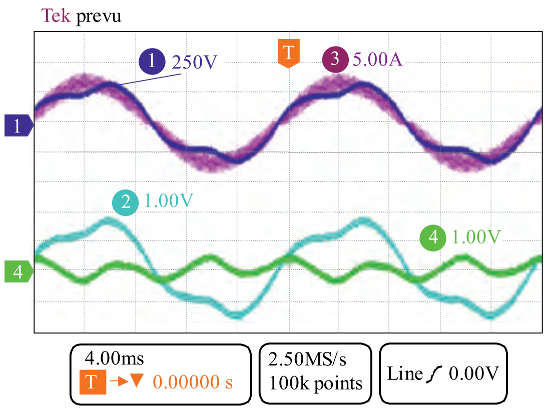


**Fig. 4.** ch-1 voltage harmonics: 1-st 100%, 3-rd 20%, 5-th 1.2%, 7-th 2%, ch-4: sum of compensation blok signals (200V/div)

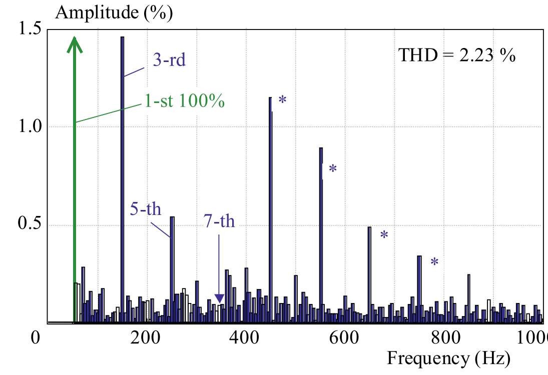


**Fig. 5.** Harmonic analysis and THDi of trolley-wire current, ch-3 in Fig. 4, fed by distorted voltage, ch-1 in Fig. 4

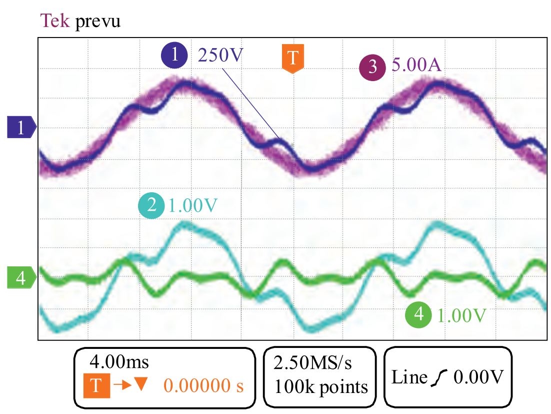


**Fig. 6.** ch-1 voltage harmonics: 1-st 100%, 3-rd 20%, 5-th 15%, 7-th 1%, ch4: sum of resonant control output signals (200 V/div)

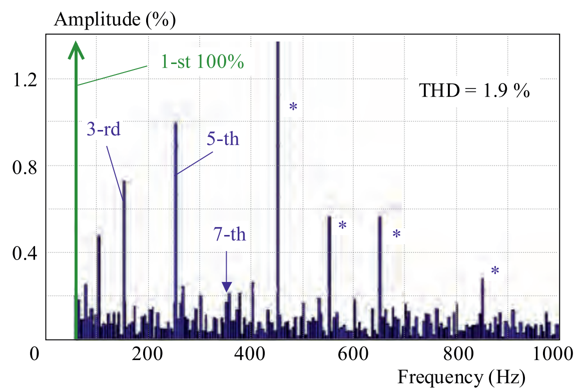


**Fig. 7.** Harmonic analysis and THDi of trolley-wire current, ch-3 in Fig. 6, fed by distorted voltage, ch-1 in Fig. 6

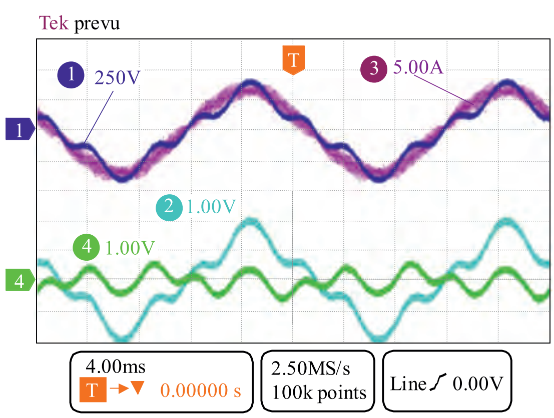


**Fig. 8.** ch-1 voltage harmonics: 1-st 100%, 3-rd 17.72%, 5-th 16.88%, 7-th 5.49%, ch4: sum of resonant control output signals (200V/div)

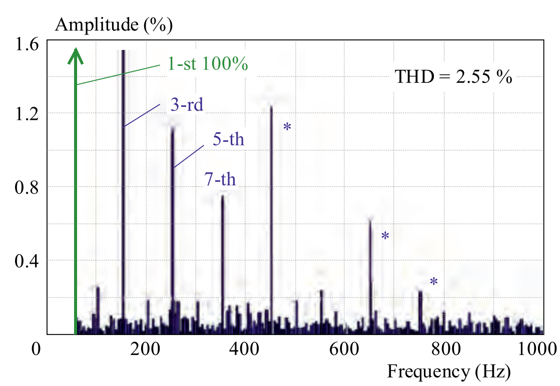


**Fig. 9.** Harmonic analysis and THDi of trolley-wire current, ch-3 in Fig. 8, fed by distorted voltage ch-1 in Fig. 8

current, see channel 3, are shown, followed by the non compensated higher components (denoted by asterisk) that are approximately of same magnitude as the compensated ones. Channel 2 in Fig. 4, Fig. 6 and Fig. 8 is showing the control-modulation signal $u_v$ (200V/div). The trolley-wire voltage is distorted by 3-rd (150 Hz), 5-th (250 Hz), and 7-th (350 Hz) harmonics as listed in Table 1.

## 5 CONCLUSIONS

- Proposed control strategy of single-phase voltage-source active rectifiers combines the model predictive feed-forward term with the PR controller of the fundamental harmonic of trolley-wire current.
- The direct control of the trolley wire current via PR controller enables a powerful limitation of the trolley wire

current under hard transient conditions and also during the converter start-up.

• Due to used resonant controllers compensating 3th, 5th, and 7th harmonics of the trolley wire current, we have achieved a significant reduction of the trolley wire distortion in low-frequency range

• The experimental results show excellent power converter behavior, even for converter fed by strongly distorted supply voltage

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