Power Conversion Quality of AC Buck Voltage Converter in Comparison with SCR Voltage Converter

Roman L. Gorbunov
Novosibirsk State Technical University, Novosibirsk, Russia

Abstract – **This paper presents the benefits of the AC Buck voltage converter in comparison with the traditional SCR-based voltage converter in the induction drive's energy-saving application. The particular squirrel-cage induction motor is considered. The Power Factor, the Displacement Power Factor and the currents' Total Harmonic Distortion are analyzed and compared.**

Index Terms – **AC Buck converter, SCR-based converter, induction motor drive, power quality, energy saving.**

I. Introduction

AC VOLTAGE converters implement key functions in numerous industrial equipment. For a long time the well-known SCR-based converter has being used in such applications as industrial power control, heating and AC motor drive. However, despite of high reliability, compact size and low price of this converter, it creates significant problems due to poor quality of currents and voltages. Generated harmonics cause EMI problems, which are very important nowadays due to the increasing stress of widely spreading switch-mode equipment [1]. Moreover, because of intrinsic phase lag, the converter increases reactive power flow in a power system.

Aforementioned problems of the SCR-based converter have a tremendous effect on its application in the induction motor drives. In drives the main functions of a voltage converter: (1) soft-start of a motor and (2) motor's flux optimization during underloaded drive's operation. The second function's target is to increase motor's efficiency at a time it operates with reduced load. However, harmonics cause extra power losses and deteriorate the efficiency of a motor. Moreover, the Power Factor (PF) drops because of a phase lag. As the result, the SCR-based soft-starters are rarely useful in the motor's flux optimization task, so instead they are usually bypassed after a start is completed.

There are mechanisms, where the SCR-based soft-starters might be effective «Energy-Savers», but the harmonic-related EMI problems still exist, though equipment manufacturers rarely highlight them.

Since the power transistors become available, much attention has been paid to the AC Buck converter as an alternative to the SCR-based converter. The AC Buck converter, or AC Chopper, is a class of direct power electronic voltage converters, based on a well-known power circuit (Fig.1) in various implementations (see [2]). Operating with high switching frequency (much higher, than the line frequency) the harmonic distortion of the converter's currents and voltages can be easily attenuated by quite small and inexpensive filters [3] – [8]. Additionally, the switching block of the converter can operate with no phase shifting of the output voltage. These two properties lead to important benefits in AC drive application, especially for induction motor's flux optimization.

These problems of the SCR-based converter and the advantages of the AC Buck converter are considered in numerous papers [9] – [18 and more]. However, converter's performance at a stator voltage control of induction motor is simulated individually for each converter (SCR: [9], AC Buck: [11] – [16]). The comparative study is presented at a soft-start mode [17], or when the AC Buck converter operates in a non-PWM mode [10,11]. Moreover, an input filter of the AC Buck converter is rarely taken into account and its influence to a reactive power balance is never considered. Thus it often leads to the misconception, that the PF of these two converters is almost the same [18].

Due to these facts the benefits of the AC Buck converter are diminished and the detailed comparative study is necessary.

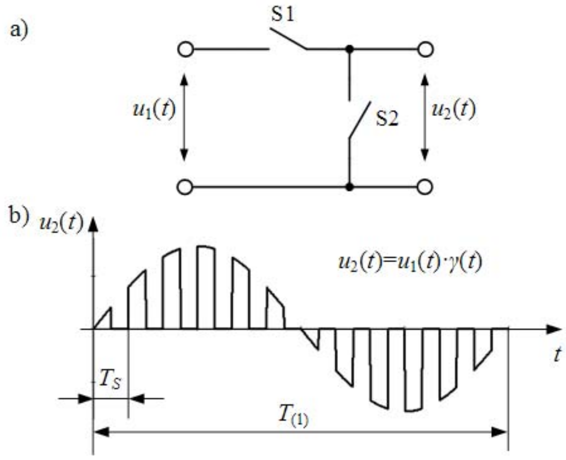

Fig. 1. a) The simplified circuit structure of AC Buck converter (switching block), b) a waveform of the output voltage

II. Problem Definition

The target of this research is to present the main benefits of the AC Buck converter in comparison with the SCR-based converter in the induction drive's energy-saving application.

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The particular P_{nom}=1.7 kW squirrel-cage induction motor 4AC80B4Y3 ($n_{r.\text{nom}}$=1425 rpm) is considered.

The research is divided into the following tasks:

- analyze harmonic distortions and phase-shift properties of the AC Buck converter in the drive-oriented power circuit configuration;
- develop computer simulation model of the SCR-based converter and calculate power quality factors;
- compare power quality of these converters.

III. THEORY

A. AC Buck Converter

In the induction motor drive application the power circuit of the AC Buck converter consists of the switching block (SB) and the input low-pass filter (Fig.2). In this study the switching block operates in pulse-width regulation mode with constant switching frequency and equal time-ratio. The switching frequency is much higher than the power supply voltage frequency (f_S>>$f_{(1)}$), thus normally the output filter is not needed due to inherent current filtering properties of an inductive load.

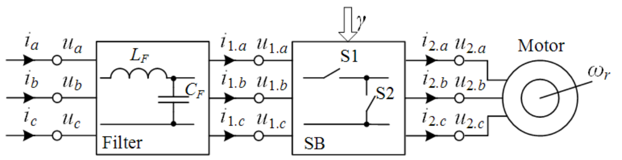

Fig. 2. AC Buck converter in motor drive application

In order to analyze converter's operation in the motor's flux optimization mode the steady-state mode is considered. The preceding research proved, that at the steady-state the harmonic distortions of this converter can be calculated using the proposed mathematical model [19]. The simplified equations for calculation of the Total Harmonic Distortion (THD) of the input $i(t)$ currents (THD_i) and the output $i_2(t)$ currents (THD_{i2}) were derived:

$$THD_i \approx \overline{K}_{\text{g.norm}} \cdot N_{F.S}^2 \cdot A \,, \qquad (1)$$

$$THD_{i2} \approx \overline{K}_{\text{g.norm}} \frac{z_{ekv(1)}}{x_{ekv.S}} \sqrt{1+\left(\frac{r_{ekv.h}}{x_{ekv.S}}\right)^2} \,, \qquad (2)$$

where $\overline{K}_{\text{g.norm}}$ is the normalized integral ratio;

$N_{F.S} = \omega_F / \omega_S$, $\omega_F = 1/\sqrt{l_F \cdot c_F}$, $\omega_S = 2\pi \cdot f_S$;

$$A = \frac{1}{\sqrt{\left(\frac{1}{x_C}\cdot\frac{r_{ekv(1)}}{\gamma_0^2}\right)^2 + \left(1-\frac{1}{x_C}\cdot\frac{x_{ekv(1)}}{\gamma_0^2}\right)^2}} \,;$$

γ_0 is the control ratio (duty cycle).

The normalized integral ratio is the characteristic of the switching block with the particular control algorithm. For the pulse-width regulation mode

$$\overline{K}_{\text{g.norm}} \approx \sqrt{\frac{1}{\gamma_0}-1} \,.$$

In these and the following equations all the variables are presented in the relative units, i.e. normalized to nominal mode values. Frequency dependence of the parameters is neglected.

Inductance l_F and capacitance c_F are parameters of the input LC-filter. x_C is an equivalent impedance of filter's capacitors at the fundamental frequency $\omega_{(1)}$.

Equivalent parameters of the induction motor's model

$$r_{ekv.h} = r_s + r_r \frac{l_m^2}{l_r^2} \,,$$

$$x_{ekv.S} = \omega_S \cdot \left(l_s - \frac{l_m^2}{l_r}\right) = \omega_S \cdot \sigma \cdot l_s \,,$$

$$r_{ekv(1)} = r_s + \frac{r_{r.nom}}{s_{r.norm}} \cdot \frac{x_m^2}{\left(r_{r.nom}/s_{r.norm}\right)^2 + x_r^2} \,,$$

$$x_{ekv(1)} = x_s - x_r \frac{x_m^2}{\left(r_{r.nom}/s_{r.norm}\right)^2 + x_r^2} \,,$$

$$z_{ekv(1)} = \sqrt{r_{ekv(1)}^2 + x_{ekv(1)}^2} \,,$$

where

r_s, r_r are the resistance of stator and rotor windings, correspondingly;

l_s, l_r are the total equivalent inductance of stator and rotor windings, correspondingly;

l_m are the equivalent main flux (magnetizing) inductance;

σ is the scattering coefficient;

x_s, x_s are the synchronous reactive impedance of stator and rotor windings, correspondingly;

x_m is the equivalent magnetizing impedance at $\omega_{(1)}$;

$s_{r.norm}$ is the relative slip, normalized to the nominal slip;

s_r is the slip at the rotor frequency ω_r;

$r_{r.nom}$ is the equivalent rotor winding resistance at the nominal slip s_{nom};

$r_{r.nom} = r_r / s_{nom}$, $s_{r.nom} = s_r / s_{nom}$, $s_r = 1 - \omega_r / \omega_{(1)}$.

The equations (1), (2) and values at the following graphs are presented relative to the switching frequency ratios: $N_{F.S}$ for input distortion and N_S for output distortion. This form makes it possible to analyze the distortions in general form with no particular frequency and then apply the results to its specified value. For example, according to the Fig.3 at γ_0=0.8 the relative value is equal to 0.4. It means, that at the $N_{F.S}$=1/4 the *THDi*=0.025 (less than 3 %), while at $N_{F.S}$=1/8 the *THDi*=0.0063.

Taking into account the input filter, the Displacement Power Factor (DPF) of the converter is approximated by the following equation

$$DPF_i \approx \frac{1}{\sqrt{1+\frac{1}{PF_{i2}^2}\left(\sin(\varphi_2)-\frac{1}{k_x\cdot\gamma_0^2\cdot\sin(\varphi_2)}\right)^2}},$$

where $PF_{i2}=\cos(\varphi_2)$ is the motor's power factor.

It is important to note, that when THD<0.1 the distortion factor is at least 0.995. Therefore it is possible to assume $PF_i \approx DPF_i$.

The motor's power factor

$$PF_{i2}=1\Big/\sqrt{1+\left(x_{ekv(1)}/r_{ekv(1)}\right)^2}$$

depends on the voltage applied to the stator (Fig.4), because the magnetic curve of the motor is not linear.

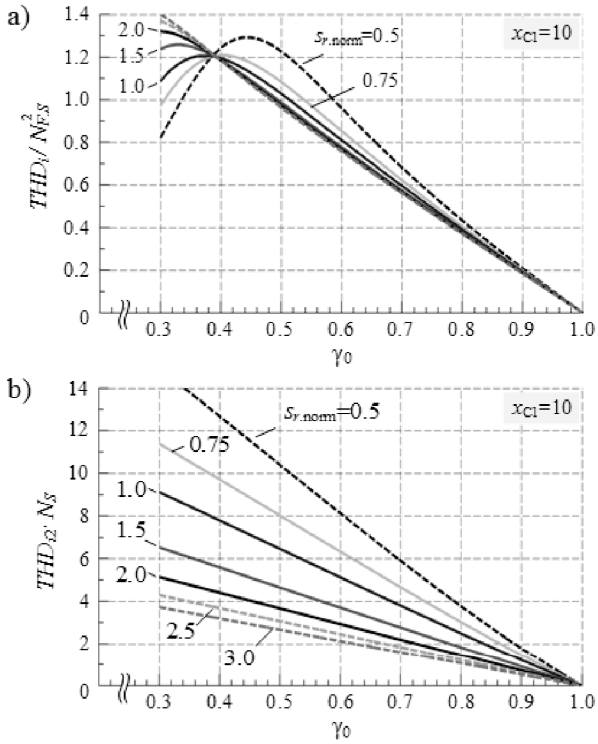

Fig. 3. Variation of the currents' THD of the AC Buck converter

B. SCR-based Converter

The SCR-based converter with an equivalent RL-load is simulated in Matlab. The power circuit of the converter is based on the three pair of SCR (Fig.5). Parameters of the load correspond to the steady-state model of the motor 4AC80B4Y3.

At the steady-state operation the currents and voltages include numerous low-frequency harmonics and in the output voltage control range 1:2 the currents' THD exceeds 20 % (Fig.6). The most prominent are the harmonics with the number n=5,7,11,13 (Fig.7). The 5th harmonics is of the highest magnitude and it increases when the output voltage $U_{2(1)}$ reduces (Fig.7a). This harmonic has a great influence on the motor, while its attenuation is very problematic due to low frequency and proximity to the 1st harmonic.

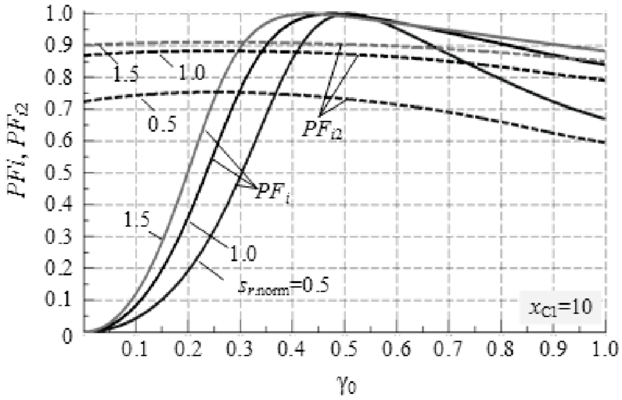

Fig. 4. Variation of the power factor of the AC Buck converter

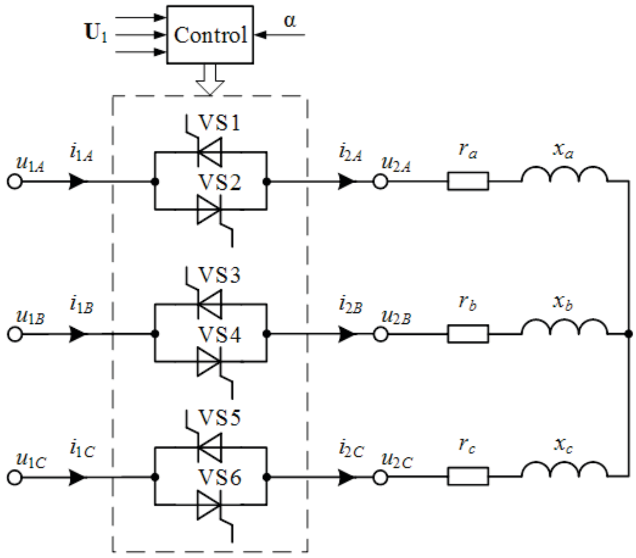

Fig. 5. The power circuit of the SCR-based converter

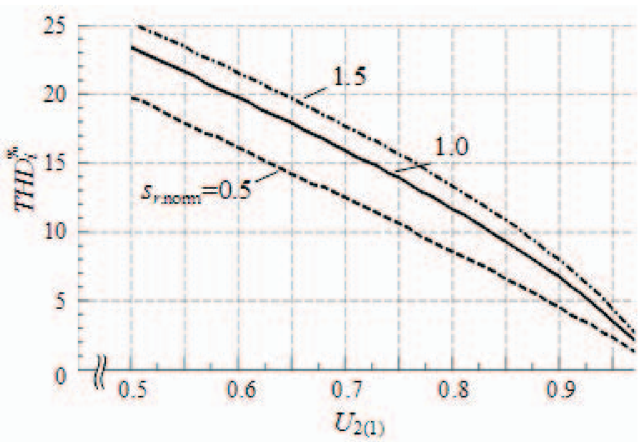

Fig. 6. Variation of the currents' THD of the SCR-based converter

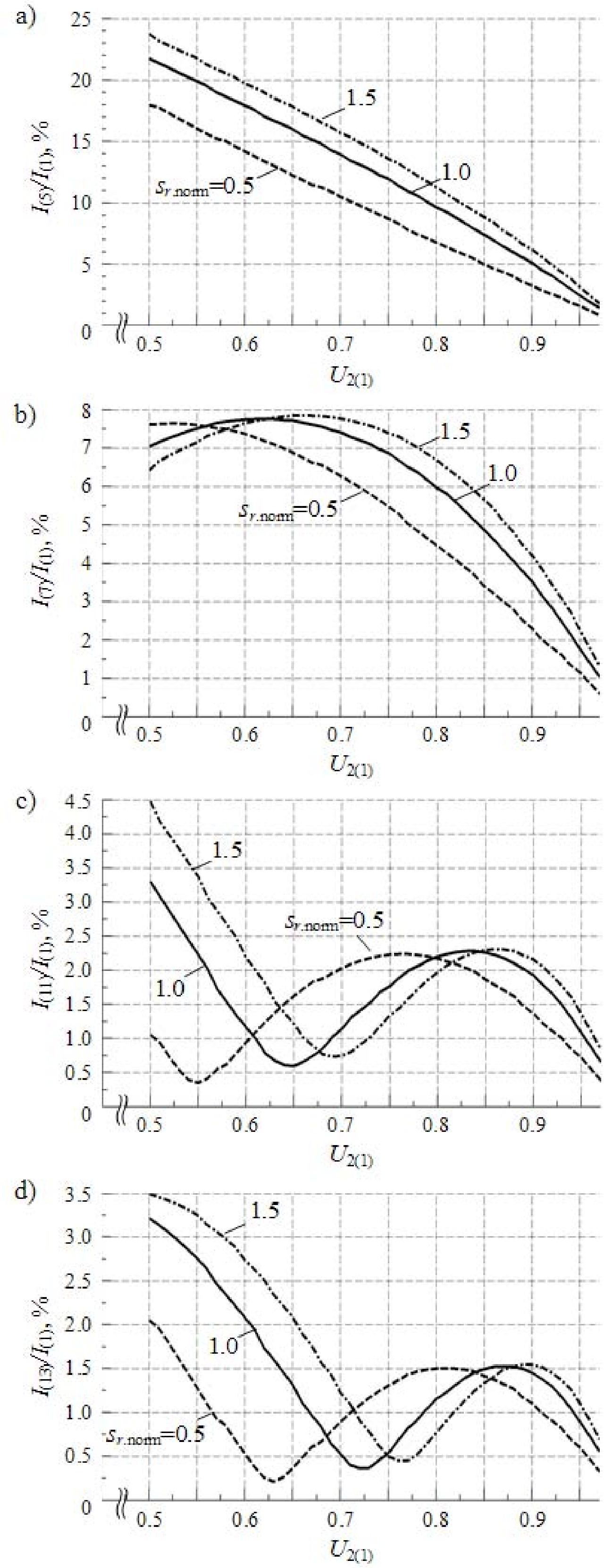

Fig. 7. Variation of the current harmonic's magnitudes (magnitudes are relative to the 1st harmonic's magnitude) of the SCR-based converter

IV. Discussion of Results

At the nominal rotor's slip the THD of the output currents of the AC Buck converter doesn't exceed 10 % even at the switching-to-fundamental frequency ratio N_S=100 (f_S=5 kHz at the $f_{(1)}$=50 Hz), while in the control range γ_0>0.8 the THD is less than 3 %. At the filter crossover frequency ratio $N_{F.S}$=1/4 the THD of the input currents is less than 5 % in the control range γ_0>0.6. The distortion power is negligible.

By contrast, the currents of the SCR-based converter include numerous low-frequency harmonics. At the control range 1:2 the magnitude of the 5th harmonic reaches 20 % and the 7th harmonics – 8 %. So the magnitude of the 7th harmonic alone is higher than the currents' THD of the AC Buck converter.

The very important feature of the AC Buck converter with the input filter is that at the specified voltage control range the converter's DPF is always higher, than the motor's DPF (Fig.8). Even at the light load the converter's DPF reaches its maximum value *DPF*=1.

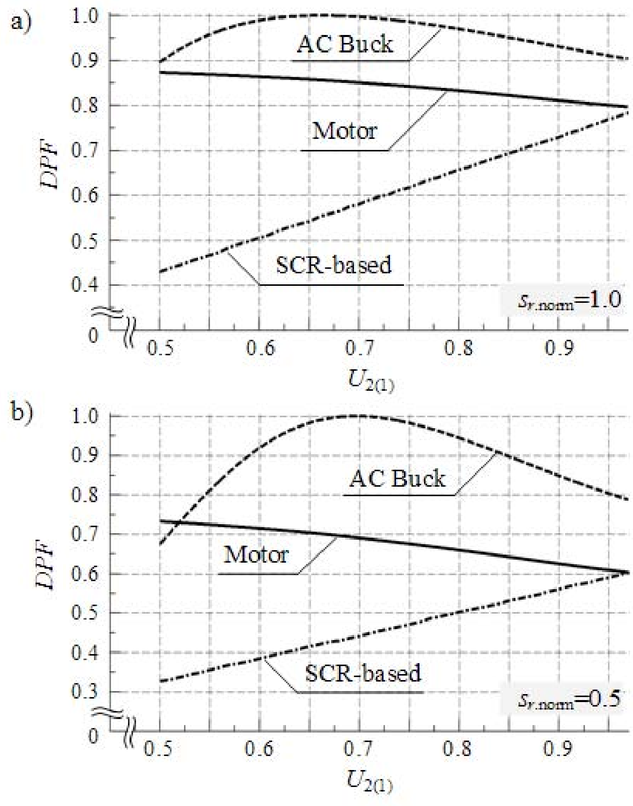

Fig. 8. Variation of the DPF of different converters

By contrast, the DPF of the SCR-based converter is always lower than the load's DPF (Fig.8). At the output voltage $U_{2(1)}$=0.5 (50 % of the input voltage) the DPF drops down to 0.4. This is unacceptably low value for power systems.

V. Conclusion

Both converters can be used as the induction motor's Energy-Savers. However, the SCR-based converter significantly increases reactive power flow of a drive. For example, the 20 % voltage reduction causes 0.10-0.15 DPF drop. Moreover, the currents' harmonic distortion might exceed 20 %. That makes ineffective the reactive power optimization of the motor and leads to the motor's extra power losses.

The AC Buck converter has no one of the aforementioned problems. Even at the relatively low switching frequency the motor's currents distortion is almost negligible. The input currents' harmonics are attenuated by the high-crossover-frequency filter and this filter provides an extra degree of freedom to control/limit input currents' distortion.

The power efficiency of these two converters is not considered in this study. Nevertheless, it is the well-known fact, that the efficiency of the SCR-based converter exceeds 98 %, while in [2] it is shown, that the AC Buck converter's efficiency is lower (at the 4 kVA load it equals to 96.5 %). Thus, the very important task is to improve the AC Buck converter's efficiency. It is possible, but the solutions are not discussed in this paper. Anyway, much attention is given today, by the utilities, to the PF [12] and EMI, which are significantly better in case of the AC Buck converter.

Another important task for the future research is to compare power quality of the converters in high-voltage drive application (3, 6 and 10 kV).

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Roman L. Gorbunov was born in Russia in 1991. He received an engineering degree in "Industrial Electronics" from Novouralsk Technological Institute NRNU MEPhI in 2013. In 2013-2016 he studied towards a PhD degree in "Power Electronics" in National Research Tomsk Polytechnic University and in 2016 got a PhD degree with the topic of research: "AC Voltage Converter with Improved Energy Quality". His interests include AC Voltage Converters and AC Drives.

E-mail: romangorbunov91@gmail.com