STUDY OF POWER AND RIPPLE FACTORS OF CONTROLLED THYRISTOR RECTIFIERS

Evgeniy Ivanov Popov, Liliya Ivanova Pindeva, Sergey Chavdarov Hristov

Department of Power Electronics, Technical University of Sofia, Kl. Ohridski Bul. No.8, 1700 Sofia, Bulgaria, phone: +359 2 9652642, e-mail: epopov@tu-sofia.bg

Controlled thyristor rectifiers provide regulatable output d.c. voltage, current and power necessary in many power application by phase control of the moment of turning on the devices. But at the same time the power factor in respect to the supplying mains is decreased that leads to an additional loading of the system for generation and distribution of electrical energy. That is rather important nowadays taking into account the struggle against the global warming. On the other hand the phase control causes increased pulsations of the rectifier voltage, measured by the ripple factor. To remove the undesirable ripples inflicted by the phase angle regulation larger filters are required. Different rectifiers behave differently in respect to the power and ripple factors. The aim of this article is to study the most commonly used types of controlled thyristor rectifiers and to clarify, and compare the information concerning their power and ripple factors.

Keywords: power factor, ripple factor, voltage control, thyristor rectifiers.

1. INTRODUCTION

The classical controlled thyristor rectifiers produce regulatable output d.c. voltage, current and power which are necessary in many power and high power applications. The regulation of the output rectified d.c. voltage is provided by the phase control of the moment of turning on of the power semiconductor devices in respect to the a.c. voltage(s), supplying the rectifier.

But the control of the output rectified d.c. voltage is accompanied with substantial decrease of the power factor [3] in respect to the supplying mains. This fact speaks that the system for generation and distribution of electrical energy is additionally loaded which is rather important taking into considerations the reasons, aspects and effects of the global warming.

On the other hand the control of the output d.c. voltage is provided also at the expense of increased pulsations of the rectified voltage, measured by the so called ripple factor [2], [3]. To remove the undesirable ripples inflicted by the phase control larger filters are required.

Different types of rectifiers (fully-controlled, half controlled, with or without free-wheeling diodes) behave differently in respect to the power and ripple factors. Some of the rectifiers have these parameters well known but other types have them completely unstudied because the analysis is quite complicated. Especially it is not known how different types of rectifiers compare in relation to the same degree of the output d.c. voltage control (the controlling characteristic [2], [3] – Fig.1).

Therefore this article is aimed at studying, comparing and clarifying the whole possible information concerning the power and ripple factors of the most commonly used types of controlled thyristor rectifiers. Of course to choose the proper rectifier, correctly to design it and apply it in practice its other specific features and parameters should also be taken into account.

2. PROBLEM STATEMENT

2.1 Single-phase controlled thyristor rectifiers

It is well known [3] that single-phase controlled thyristor rectifiers with phase number coefficient $m = 2$ (configuration with a central-tapped secondary winding of the supplying transformer and fully-controlled bridge configuration) without free-wheeling diode and active-inductive load causing continuous load current have power factor expressed by

$$K_P = \frac{2\sqrt{2}}{\pi}.\cos\alpha \tag{1}$$

where α is the phase control angle.

It is also known that the power factor of the same circuits with a free-wheeling diode (including the case of the half-controlled bridge configurations) is

$$K_P = \frac{2\sqrt{2}}{\pi}.\sqrt{\frac{\pi}{\pi-\alpha}}.\frac{1+\cos\alpha}{2} \tag{2}$$

The not known expression of the power factor for single-phase controlled thyristor rectifiers with active load, applicable also for single-phase thyristor regulators with active load, is deduced

$$K_P = \frac{\sqrt{(1-\frac{\alpha}{\pi}+\frac{\sin 2\alpha}{2\pi})^2+\frac{\sin^4\alpha}{\pi^2}}}{\sqrt{1-\frac{\alpha}{\pi}+\frac{\sin 2\alpha}{2\pi}}}.\cos(\arctan\frac{-\sin^2\alpha}{\pi-\alpha+\frac{\sin 2\alpha}{2}}) \tag{3}$$

The ripple factor of the single-phase controlled thyristor rectifiers ($m = 2$) without free-wheeling diode, active-inductive load and continuous load current is well known

$$S_\alpha = \frac{2}{m^2-1}\sqrt{1+m^2\tan^2\alpha} \tag{4}$$

The ripple factor of the same rectifiers ($m = 2$) with active-inductive load and free-wheeling diode or purely active load is deduced

$$S_\alpha = \frac{\sqrt{E_{1mc}^2+E_{1ms}^2}}{V'_{d\alpha}} \tag{5}$$

where

$$V'_{d\alpha} = \frac{m}{\pi}\sin\frac{\pi}{m}.\frac{1-\sin(\alpha-\pi/m)}{2\sin\pi/m} \tag{6}$$

(7)
$$E_{1mc}=\frac{m}{\pi(m^2-1)}(-\cos\frac{m\pi}{2}+\sin\frac{\pi}{m}\cos\alpha\cos m\alpha-\cos\frac{\pi}{m}\sin\alpha\cos m\alpha+$$
$$+m\sin\frac{\pi}{m}\sin\alpha\sin m\alpha+m\cos\frac{\pi}{m}\cos\alpha\sin m\alpha)$$

(8)
$$E_{1ms}=-\frac{m}{\pi(m^2-1)}(\sin\frac{m\pi}{2}+\cos\frac{\pi}{m}\sin\alpha\sin m\alpha-\sin\frac{\pi}{m}\cos\alpha\sin m\alpha+$$
$$+m\cos\frac{\pi}{m}\cos\alpha\cos m\alpha+m\sin\frac{\pi}{m}\sin\alpha\cos m\alpha)$$

The power factors given by (1) and (2) are displayed as a function from the normalized rectified voltage in Fig.2. The power factor in (3) is drawn depending from $V_{d\alpha}/V_{d0}$ in Fig.3. (single-phase rectifiers with active load) and from V_2/E_2 in Fig.4 (single-phase a.c. thyristor regulator with active load). The ripple factors given by (4) and (5) are displayed as a function from the normalized rectified voltage in Fig.5.

2.2 Three-phase half-wave controlled thyristor rectifier

The power factor of the three-phase half-wave controlled thyristor rectifier ($m=3$) with star - star connection of the windings of the supplying transformer, active–inductive load (continuous load current) without free - wheeling diode is [3]

(9)
$$K_P=\frac{3\sqrt{3}}{2\pi}.\cos\alpha$$

and of the same circuit with free – wheeling diode and $5\pi/6=\pi/2+\pi/m\geq\alpha\geq\pi/2-\pi/m=\pi/6$ is (again original expression)

(10)
$$K_P=\frac{\sqrt{1+\frac{\sqrt{3}}{2}\cos\alpha-\frac{1}{2}\sin\alpha}}{\pi.\sqrt{\frac{2}{3}}.\sqrt{\frac{5}{12}-\frac{\alpha}{2\pi}}}.\cos(\arctan\frac{-\frac{1}{2}\cos\alpha-\frac{\sqrt{3}}{2}\sin\alpha}{1+\frac{\sqrt{3}}{2}\cos\alpha-\frac{1}{2}\sin\alpha})$$

The ripple factor of the circuit without free – wheeling diode can be calculated from (4) and of the rectifier with free – wheeling diode, and $\alpha_m=5\pi/6=\pi/2+\pi/m\geq\alpha\geq\pi/2-\pi/m=\pi/6=\alpha_{cr}$ – from (5), (6), (7), (8). In both cases the value of the phase number coefficient is $m=3$.

The power factors from (9) and (10) are displayed as a function from $V_{d\alpha}/V_{d0}$ in Fig.6. The ripple factors dependence from $V_{d\alpha}/V_{d0}$ are drawn in Fig.7.

2.3 Three-phase bridge controlled thyristor rectifiers

The power factors of the three-phase bridge fully - controlled thyristor rectifier ($m=6$), active–inductive load (continuous load current) without ($\pi/2\geq\alpha\geq0$, [3]) and with ($2\pi/3\geq\alpha\geq\pi/3$ - original expression) free - wheeling diode are as follows:

(11)
$$K_P=\frac{3}{\pi}.\cos\alpha$$

$$K_P = \frac{\sqrt{2}.\sqrt{(-3/2.\cos\alpha - \sqrt{3}/2.\sin\alpha)^2 + (\sqrt{3} + \sqrt{3}/2.\cos\alpha - 3/2.\sin\alpha)^2}}{\pi.\sqrt{4/3 - 2\alpha/\pi}}. \tag{12}$$

$$.\cos(\arctan\frac{-3/2.\cos\alpha - \sqrt{3}/2.\sin\alpha}{\sqrt{3} + \sqrt{3}/2.\cos\alpha - 3/2.\sin\alpha})$$

The power factor of the three-phase bridge half - controlled thyristor rectifier ($m = 6$), active–inductive load (continuous load current), $\pi/3 \geq \alpha \geq 0$ and $\pi \geq \alpha \geq \pi/3$ are respectively (original expressions):

$$K_P = \frac{3}{\pi}.\frac{\sqrt{1+\cos\alpha}}{\sqrt{2}}.\cos(\arctan\frac{-\sin\alpha}{1+\cos\alpha}) \tag{13}$$

$$K_P = \frac{\sqrt{3}}{\pi}.\sqrt{\frac{\pi}{\pi-\alpha}}.\sqrt{1+\cos\alpha}.\cos(\arctan\frac{-\sin\alpha}{1+\cos\alpha}) \tag{14}$$

The ripple factor of the fully – controlled rectifier without free – wheeling diode can be calculated from (4) and of the rectifier with free – wheeling diode, and $\alpha_m = 2\pi/3 = \pi/2 + \pi/m \geq \alpha \geq \pi/2 - \pi/m = \pi/3$ – from (5), (6), (7), (8). In both cases the value of the phase number coefficient is $m = 6$. The ripple factor of half – controlled rectifier [4] for the ripples with the fundamental harmonic frequency (three times the mains frequency) is $S_\alpha = 1 - \cos\alpha$ and for ripples with twice the fundamental harmonic frequency (six times the mains frequency) is

$$S_\alpha = \frac{2\sqrt{2(\frac{1+\cos 5\alpha}{100} + \frac{1+\cos 7\alpha}{196} - \frac{\cos 2\alpha + \cos 5\alpha + \cos 7\alpha + 1}{140})}}{1+\cos\alpha} \tag{16}$$

The power factors of the three – phase bridge controlled thyristor rectifier for the variants without, with free – wheeling diode and half – controlled circuit are displayed as a function from the normalized rectified voltage $V_{d\alpha}/V_{d0}$ in Fig.8.

The ripple factors of these three – phase bridge controlled thyristor rectifiers are displayed as a function from $V_{d\alpha}/V_{d0}$ in Fig.9 (especially for the half – controlled case the first and second harmonic ripple factors are given).

3. RESULTS

MATLAB programs for exact graphical representation of the already mentioned functions of the power and ripple factors of different controlled thyristor rectifiers and for precise computer calculation of a specified case have been created. The graphics are presented in Fig.1 to Fig.9, as it has been already explained.

4. CONCLUSIONS

A study of the power and ripple factors of the most commonly used circuits of controlled thyrisror rectifiers with phase - angle regulation has been carried out. The original analytical expressions of the power factor of the single - phase rectifiers with active load, the three – phase half – wave configuration with free – wheeling diode and the three – phase bridge circuit with free – wheeling diode, and the half –

controlled connection are derived. The ripple factors of the already mentioned cases together with the single – phase variant with free – wheeling diode have been determined. A MATLAB program for exact graphical representation of the functions of the controlling characteristic, power and ripple factors, and their comparison and improvement has been created. It can be downloaded from the following link: http://mail.dir.bg/~epopov/KpSa13.m. Another MATLAB program that does the same together with the precise numerical calculation of a specified case can be downloaded from http://mail.dir.bg/~epopov/KpSa13c.m. In respect to the power factor it can be seen that for the three – phase bridge controlled thyristor rectifier the half controlled variant is better than the case with the free – wheeling diode. Results are confirmed by other possible means. The study helps to clarify qualitatively and quantitatively the additional loading of the mains when controlled thyristor rectifiers are connected to it. That fact is rather important nowadays taking into account the struggle against the global warming.

5. REFERENCES

[1] Nachev N. A., G. Yu. Mallev, *Power Electronics*, Technica, Sofia, 1979 (in Bulg.).

[2] Nachev N. A., G. G. Krastev, N. P. Gradinarov, E. I. Popov, M. Hr. Anchev, *Industrial Electronics*, Sofia, Technical University, 1995 (in Bulg.)

[3] Bobcheva M. L., N. P. Gradinarov, G. Yu. Maleev, E. I. Popov, M. Hr. Anchev, *Power Electronics*, Sofia, Technical University, 1998 (in Bulg.)

[4] Stefanov N. Y., E. I. Popov, *Ripples of the Rectified Voltage with Fundamental Harmonic Frequency of Three – Phase Bridge Controlled Rectifiers*, Proceedings of the Scientific Conference Radio's Day, Sofia, 7.5.1975. (in Bulg.)

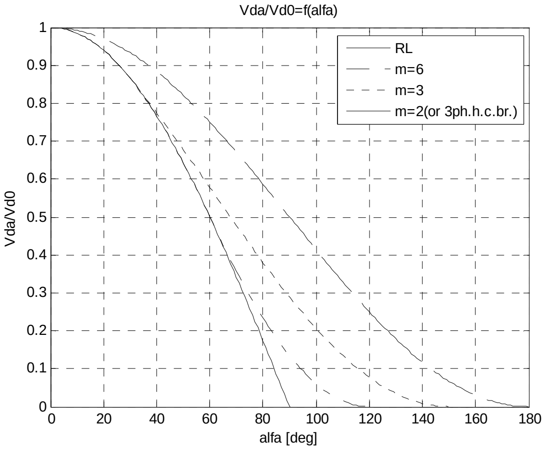

Fig.1. $V_{d\alpha}/V_{d0} = f(\alpha)$.

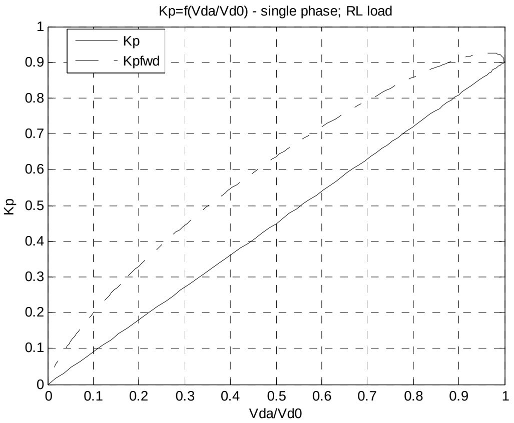

Fig.2. $K_P = f(V_{da}/V_{d0})$.

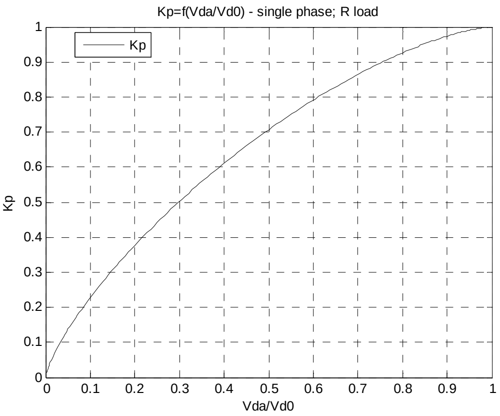

Fig.3. $K_P = f(V_{da}/V_{d0})$.

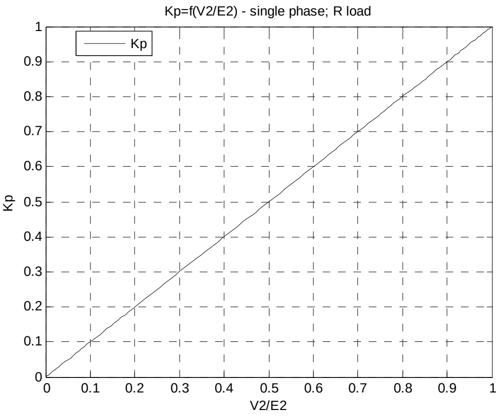

Fig.4. $K_P = f(V_2/E_2)$.

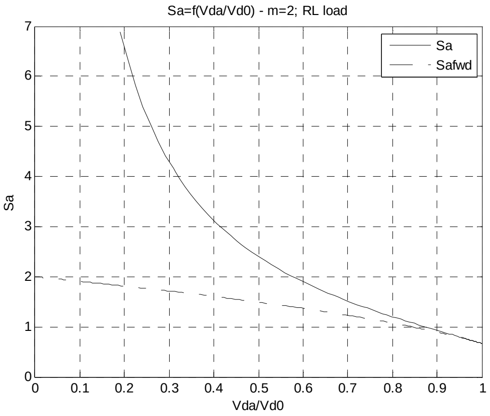

Fig.5. $S_a = f(V_{da}/V_{d0})$.

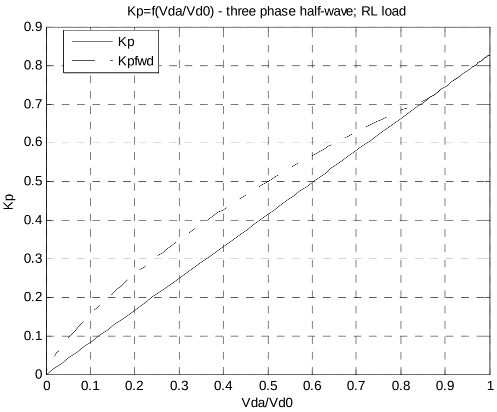

Fig.6. $K_P = f(V_{da}/V_{d0})$.

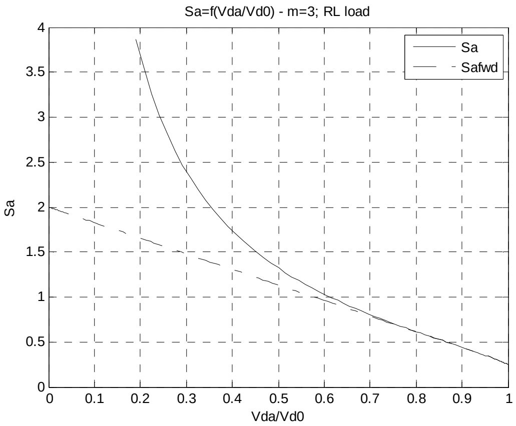

Fig.7. $S_a = f(V_{da}/V_{d0})$.

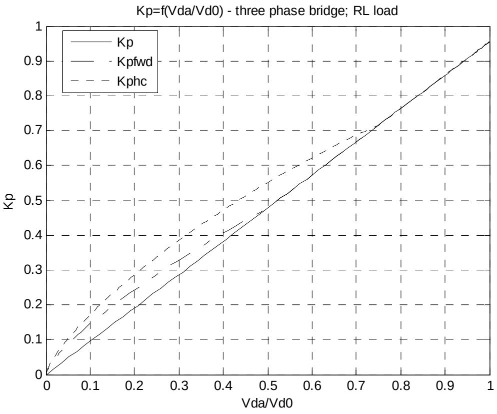

Fig.8. $K_P = f(V_{da}/V_{d0})$.

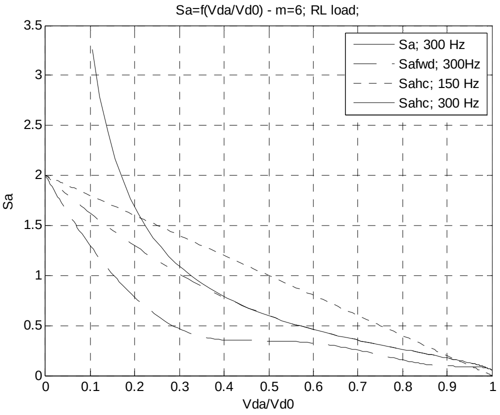

Fig.9. $S_a = f(V_{da}/V_{d0})$.