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Performance Analysis of Three-Phase Controlled Rectifier in various Switching Angles

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Abstract*: *This paper discusses the performance analysis the characteristics of three-phase controlled rectifier parameters based on various switching angles. The phase delay method with various switching angles is employed to generate output voltage. Analysis of calculations is engaged to determine the various desired parameters. Voltage and current waveforms both input and output side are considered. The analysis are verified by simultion. The results show that the calculation results and simulation results are the similarly.

Keywords: Three- phase controlled rectifier, phase delay, switching angle

I. INTRODUCTION

The main function of the controlled three-phase rectifier is to convert the alternating current (AC) to the direct current (DC) with an output value that can be varied, as opposed to the uncontrolled rectifier whose output is fixed. Rectifier has many benefits, simple, robust and low cost [1]. The rectifier, especially the controlled three-phase rectifier is an important part of converter technology. Three-phase controlled rectifier is widely used in industry for speed control of DC motors, also applied in other fields such as transportation, power systems, communication systems, energy and others [2]– [4].

It is very essential to know the significant parameters of the rectifier and one way is through simulation. From the simulation, data on the parameters required is also helpful for anticipating and guiding the engineering practice [5].

Besides having benefits, the rectifier also has disadvantages such as the creation of harmonics and reactive power on the input side, resulting in distortion of the input signal, a miniscule power factor and ripples on the output signal. [6], [7]. The concept of phase voltage control is generally used by controlled rectifier circuits to control the output voltage, this type of rectifier is called a controlled rectifier [8]. The controlled rectifier utilizes major components such as the Silicon Control Rectifier (SCR) and the Insulated Gate Bipolar Transistor (IGBT) to control output voltage and current through adjustment of the switching angle. Whereas the uncontrolled rectifier uses the diode's main component and can’t regulate the voltage output.

II. THREE-PHASE CONTROLLED RECTIFIER

The rectifier is used to convert AC voltage into DC voltage, mostly used in industry and tools in households. But there are many rectifiers on the market that only generate a fixed output voltage, so the implementation of the rectifier is restricted to some apparatus. The rectifier output voltage must therefore be regulated to solve these issues. The controlled rectifier is designed specifically using a SCR thyristor, so the output voltage can vary from zero to maximum voltage by controlling the SCR's switching angle. Three-phase controlled rectifier circuit with resistive load can be shown in Fig. 1.

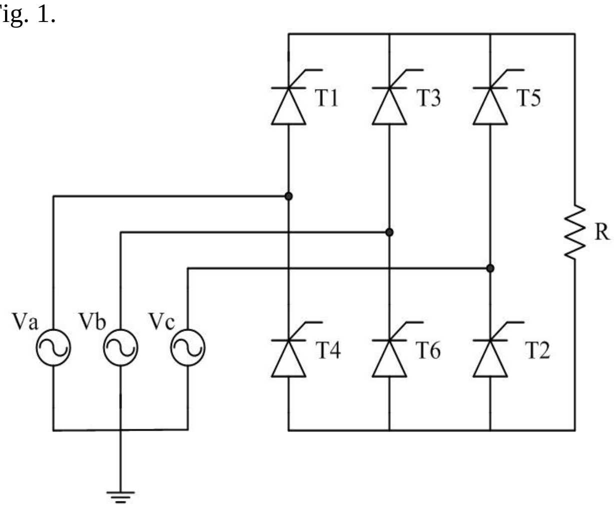

Fig. 1. Three-phase controlled rectifier

At $\frac{\pi}{6}+\alpha$, the T6 is already conducting when T1 starts conduction. So that over a period of $\frac{\pi}{6}+\alpha$ until $\frac{\pi}{2}+\alpha$, T1 and T6 are simultaneously conduced and the phase voltage V_{ab} flows to the load. At the $\frac{\pi}{2}+\alpha$, T2 is conduced and T6 gets a reverse bias voltage so that T6 is turned off or not conduced. So that during the time $\frac{\pi}{2}+\alpha$ to $\frac{5\pi}{6}+\alpha$, T1 and T2 are jointly conduced and the phase voltage of V_{ac} is flowing to the load. Fig. 2 can be a guideline for the stages of three phases-controlled rectifier control.

In the three-phase controlled rectifier circuit there are two SCR groups, positive groups (T1, T3, T5) and negative groups (T4, T6, T2). The positive SCR group will be conducive if it receives a positive voltage source voltage, conversely, if the received source voltage is negative then the SCR group will be negative.

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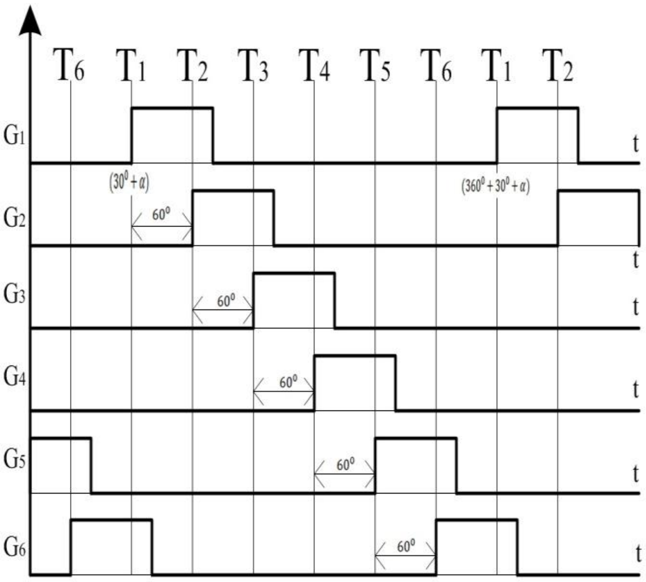

Fig. 2. The setting of the phase angle of a three-phase controlled rectifier

Three-phase controlled rectifier consisting of six SCRs connected in the form of a full wave bridge configuration. Operated using trigger signals with intervals of each SCR of $\pi/3$ or 60^0 [9]. The desired output voltage value depends on the active time of the trigger signal (t_{on}). The desired output voltage value depends on the active time of the trigger signal (t_{on}). The longer the active time value, the smaller the average output voltage value generated, while the less active time of the trigger signal, the greater the average voltage output of the rectifier.

The three-phase controlled rectifier can be operated in two modes, Continuous Conduction Mode (CCM) and Discontinuous Conduction Mode (DCM). To determine the average voltage and current value and the value of the effective voltage and current output of a three-phase controlled rectifier can be used equation (1) to (10)[10].

$$V_{dc} = \frac{3}{\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} \sqrt{3}V_m \sin\left(\omega t+\frac{\pi}{6}\right) d\omega t \quad (1)$$

$$= \frac{3\sqrt{3}V_m}{\pi}\cos\alpha \quad (2)$$

$$I_{dc} = \frac{V_{dc}}{R} \quad (3)$$

$$V_{rms} = \sqrt{\frac{3}{\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} 3\left(V_m sin\left(\omega t+\frac{\pi}{6}\right)\right)^2 d\omega t} \quad (4)$$

$$= \sqrt{3}V_m\sqrt{\left(\frac{1}{2}+\frac{3\sqrt{3}}{4\pi}cos2\alpha\right)} \quad (5)$$

$$I_{dc} = \frac{V_{rms}}{R} \quad (6)$$

The maximum value of the output voltage is when the value $\alpha = 0$. Equations (1) and (4) can be used if the value $\alpha \leq 60^0$ where the output voltage is in CCM mode. As for the value $\alpha > 60^0$, the output voltage is in DCM mode and to calculate the output voltage equations (6) and (8) can be used.

$$V_{dc} = \frac{3}{\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}} \sqrt{3}V_m \sin\left(\omega t+\frac{\pi}{6}\right) d\omega t \quad (7)$$

$$= \frac{3\sqrt{3}V_m}{\pi}\left[1+cos\left(\frac{\pi}{3}+\alpha\right)\right] \quad (8)$$

$$V_{rms} = \sqrt{\frac{3}{\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} 3\left(V_m sin\left(\omega t+\frac{\pi}{6}\right)\right)^2 d\omega t} \quad (9)$$

$$= \sqrt{3}V_m\sqrt{1-\frac{3}{4\pi}\left(2\alpha-cos\left(2\alpha+\frac{\pi}{6}\right)\right)} \quad (10)$$

Table 1 shows in detail the sequence of switching angles for SCRs in a three-phase controlled rectifier.

Table 1. Sequence of SCR switching angles in controlled three-phase rectifiers

Switching angles	SCR couple
$\alpha + 30^0$ to $\alpha + 90^0$	SCR 1 and SCR 6
$\alpha + 90^0$ to $\alpha + 150^0$	SCR 1 and SCR 2
$\alpha + 150^0$ to $\alpha + 210^0$	SCR 2 and SCR 3
$\alpha + 210^0$ to $\alpha + 270^0$	SCR 3 and SCR 4
$\alpha + 270^0$ to $\alpha + 330^0$	SCR 4 and SCR 5
$\alpha + 330^0$ to $\alpha + 360^0$ and $\alpha + 0^0$ to $\alpha + 30^0$	SCR 5 and SCR 6

III. RESULTS AND DISCUSSION

The three-phase AC source with Vrms 380V and frequency 50 Hz and 10 Ω resistor are engaged to the three-phase controlled rectifier circuit (see Fig. 3). The simulation is carried out with several variations of switching angles for CCM and DCM conditions, the simulation results are analyzed and compared with the calculation results.

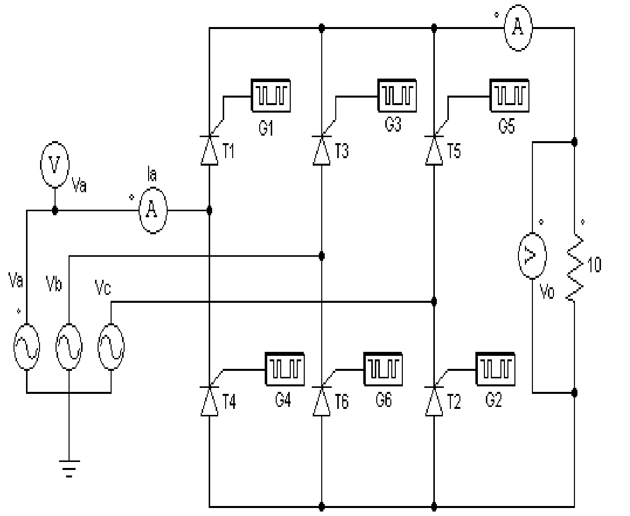

Fig. 3. Simulation of three phases controlled rectifier

Fig. 4 shows the three-phase controlled voltage input waveform. Differential voltage each phase with other phase is 120^0, and RMS phase-neutral voltage is 220 Volt. The switching pattern for gating signal to SCRs at $\alpha = 0^0$ is seen in Fig. 5.

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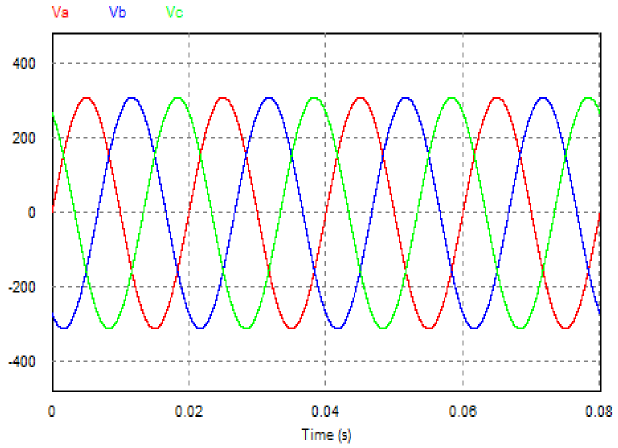

Fig. 4. Three-phase input voltage waveform

Fig. 6 is a form of signal switching at$\alpha = 0$. While Fig. 7 is the current signal and input voltage then the output current and voltage where the output signal will be after a time delay of 30^0. Fig. 7, 8 and 9, respectively, current waveforms and the input and output voltages for switching angles $30^0, 45^0$ and 60^0. for input voltage waves, there is no difference between the three images.

However, the input current waveform, the greater the value of the switching angle, the more distorted the waveform. Whereas for output voltage waves have the same pattern, it's just that the greater the switching angle value, the greater the ripple value. Another difference that can be seen is the presence of time delay at the beginning of the output voltage and the greater the value of the switching angle delay time also increases. For the output current waveform follows the pattern of the output voltage waveform.

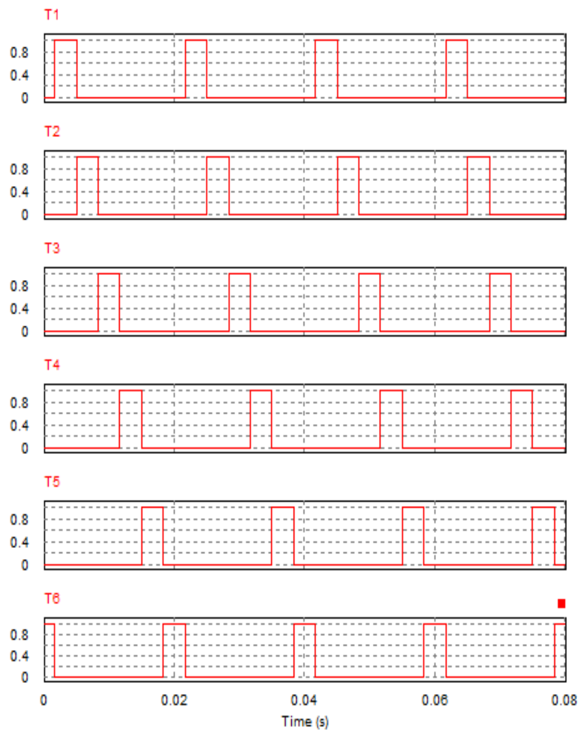

Fig. 5. Switching signals for $\alpha = 0^0$

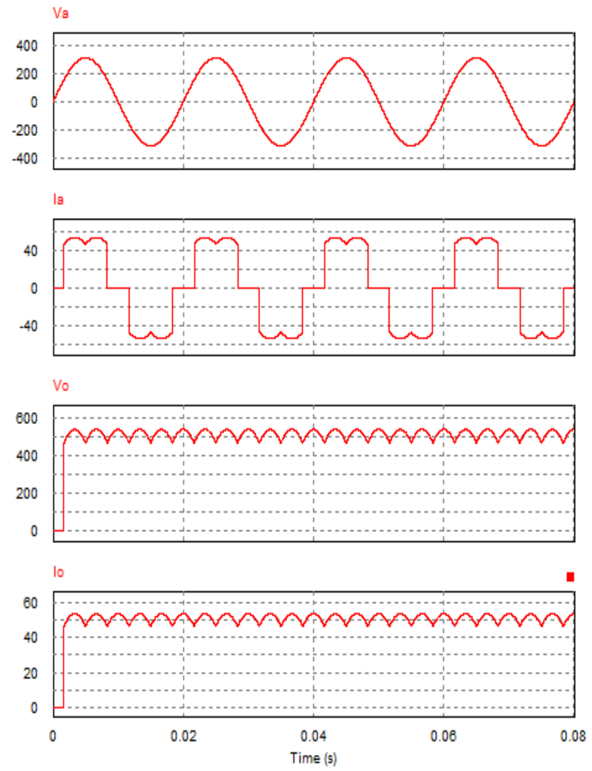

Fig. 6. Three-phase controlled input and output voltage and current waveforms when $\alpha = 0$

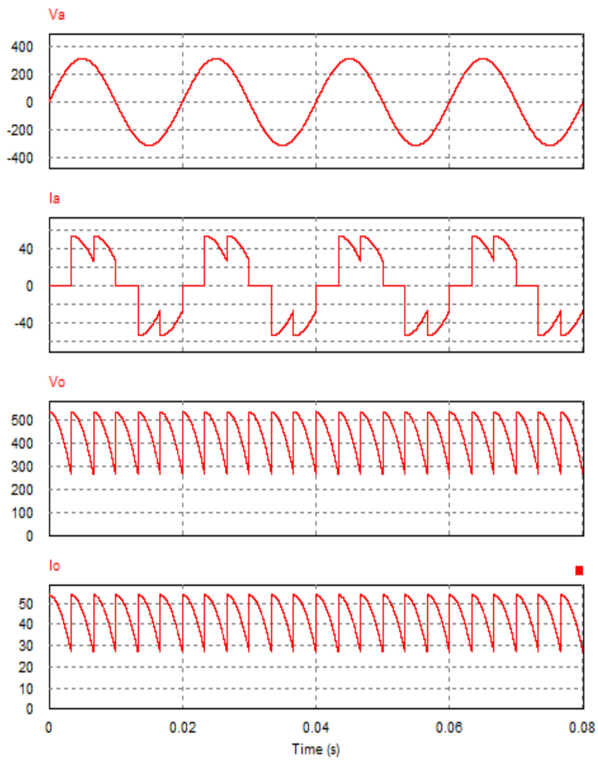

Fig. 7. Three-phase controlled input and output voltage and current waves when $\alpha = 30^0$

The waveforms generated from the simulation, both the input and output current and voltage are in the Continuous Conduction Mode (CCM) because the value of$\alpha \leq 60^0$.

Fig. 10, 11 and 12 are the waveforms produced by the Discontinuous Conduction Mode (DCM) where the angle of delay $\alpha > 60^0$. Input voltage waves are no different from input voltage waves in CCM mode, while current waves are

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more distorted when the switching angle value is higher. The output voltage and current value decreases as the switching angle value increases. Whereas the conduction time that is cut off (zero value) in the output current and voltage is proportional to the increase in the value of the switching angle. The higher the switching angle, the longer the conduction time (discontinuous conduction) is interrupted, this occurs continuously until the source voltage is switched off.

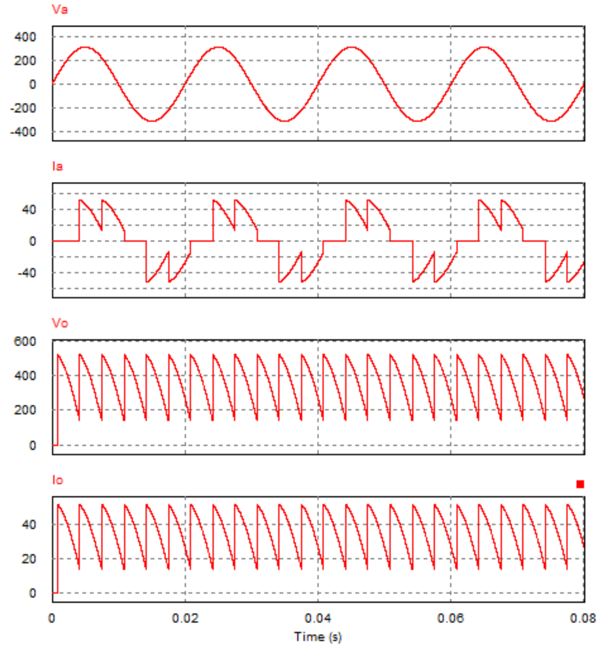

Fig. 8. Three-phase controlled input and output voltage and current waves when $\alpha = 45^0$

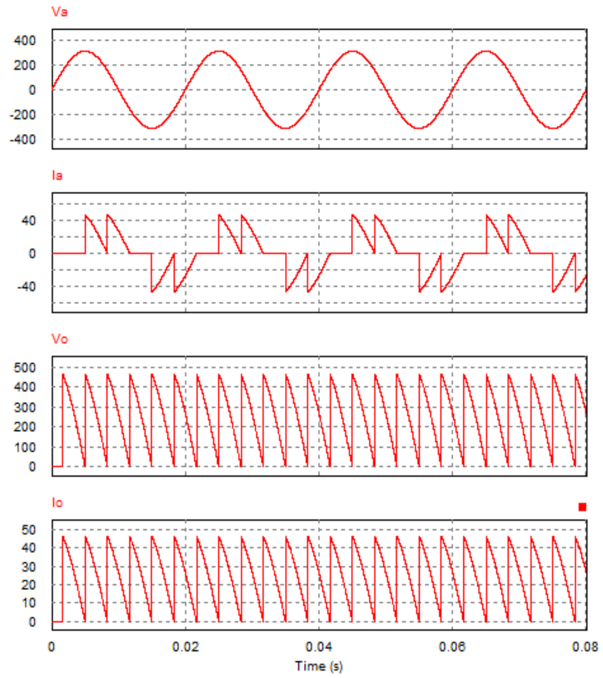

Fig. 9. Three-phase controlled input and output voltage and current waves when $\alpha = 60^0$

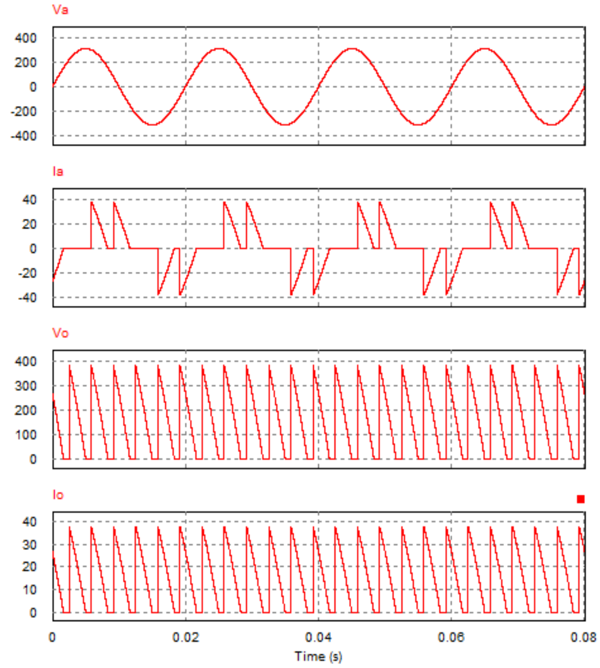

Fig. 10. Three-phase controlled input and output voltage and current waves when $\alpha = 75^0$

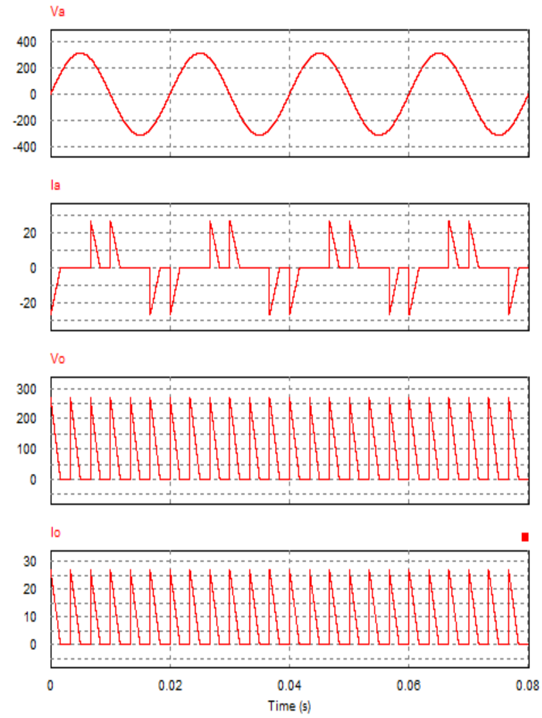

Fig. 11. Three-phase controlled input and output voltage and current waves when $\alpha = 90^0$

Based on equations (7) and (9), it can be obtained that the output voltage will be zero if the switching angle is 120^0. It shows that the value of the output voltage at the 120^0 switching angle is be zero as in Fig. 13. For more clearly the results of the comparison between the output voltage and current both from the calculation results and simulation between CCM and DCM modes with varying switching angle variations can be shown in table 2 and 3.

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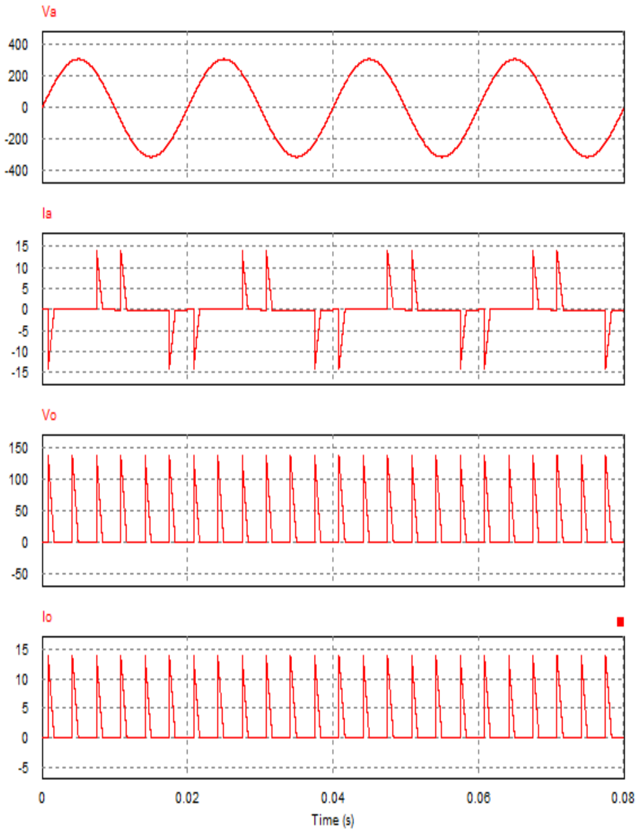

Fig. 12. Three-phase AC source and DC output voltage and current waveforms when $\alpha = 105^0$

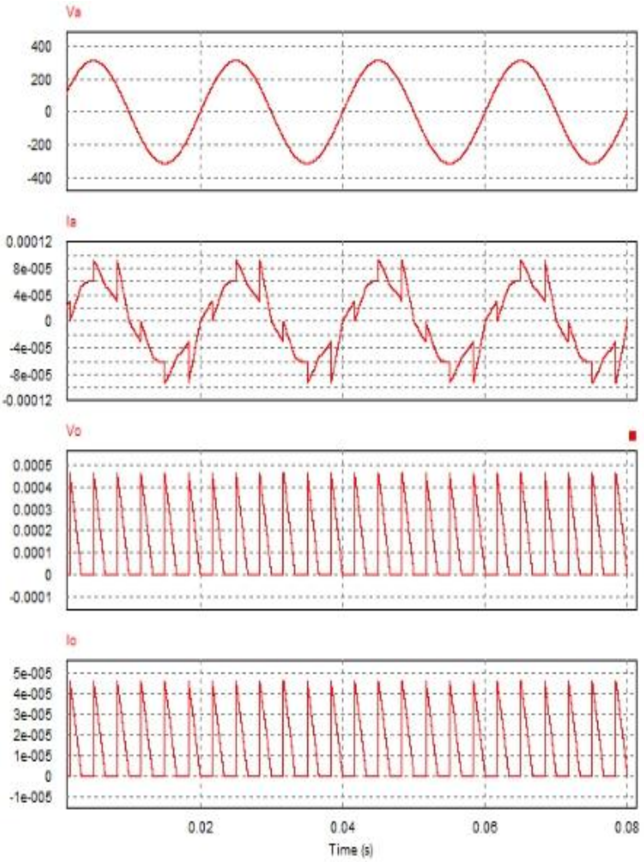

Fig. 13. Three-phase AC source input and DC output voltage and current waveforms when α=120^0

Table 2. Comparison of output voltage and current with various switching angle variations based on calculation

α	Vdc	Vrms	Idc	Irms
0	513,2	513,6	51,3	51,4
15	495,74	497,84	49,574	49,784
30	444,5	451,8	44,5	45,2
45	363,0	380,1	36,3	38,0
60	256,8	291,2	25,7	29,1
75	150,8	198,3	15,1	19,8
90	69,1	111,3	6,9	11,1
105	17,69	38,51	1,769	3,851
120	0	0	0	0

Table 3. Comparison of output voltage and current with various switching angle variations based on simulation

α	Vdc	Vrms	Idc	Irms
0	502,5	508,3	50,2	50,8
15	495,68	497,79	49,568	49,779
30	444,4	451,8	44,4	45,2
45	360,7	379,4	36,1	37,9
60	253,6	290,0	25,4	29,0
75	150,3	198,3	15,0	19,8
90	68,7	111,7	6,9	11,2
105	17,49	40,31	1,749	4,031
120	0	0	0	0

The difference in voltage and current output from a controlled three-phase rectifier with a varying switching angle can be seen in Table 2 and 3. From the findings of the calculation, the output voltage is inversely proportional to the switching angle. The greater the switching angle, the lower the output voltage. The largest output voltage is when the value α = 0^0

Fig. 14 and 15 are the calculation and simulation results of output voltages respectively. It shows that the highest output voltage value is when the smallest switching angle value and the lowest output voltage value is when the highest switching angle. Meanwhile in Fig. 16 and 17 are calculation and simulation results of output current on varying switching angle.

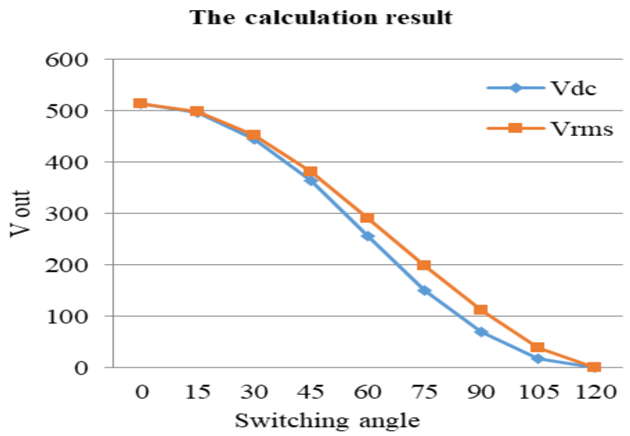

Fig. 14. Graphic output voltage values by calculations

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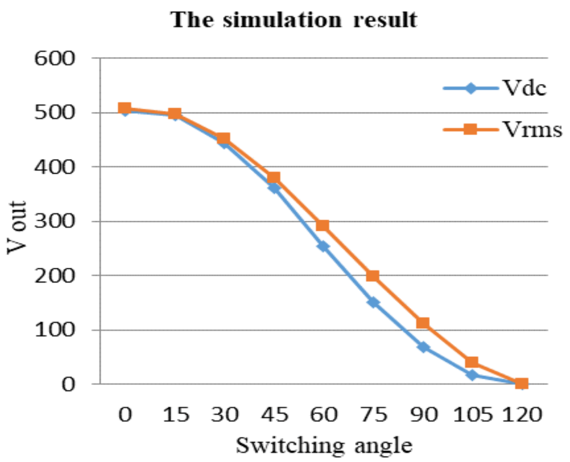

Fig. 15. Graphic output voltage value by simulation

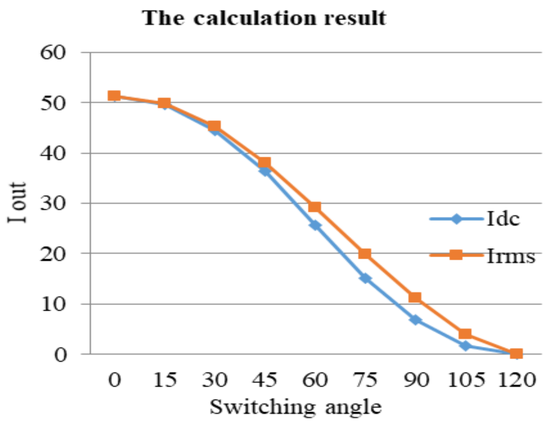

Fig. 16. Graphic output current value by calculation

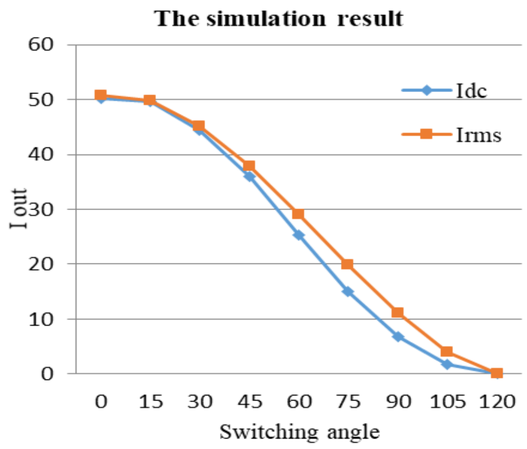

Fig. 17. Graphic output current value by simulation

IV. CONCLUSION

The performance analysis of three-phase controlled rectifier on varying switching angles has been conducted. The converter was operated with phase delay method with various switching angles. From calculations and simulations, it can be proven that the greater switching angle, the smaller the output voltage and current. Conversely, if the switching angle is smaller, the output voltage and current is greater. The calculation and simulation results shows similar results.

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