

Theoretical, Experimental Comparison and Mathematical Modeling of AC-AC 3-phase Thyristor

Anudeep.Vurity, Harshith.Ch, S.Narendar

Abstract— This paper deals with the theoretical, experimental comparison and mathematical modeling of AC-AC 3-phase PAS series Thyristors. The 'Parallel and Series' or (PAS) - Series thyristors use a maximum current input of 600 Amps and their load is a balanced 3-phase delta connected load. By giving various command voltages at the gate terminal, we can control their input power. An experiment is conducted on "PAS Series Thyristors" to find out the measured outputs, after simulating the models of the firing circuits of these thyristors in simulation programs such as MATLAB and PSpice. A comparison was made between the simulated and the measured output voltages, with the variation of command input. After many calculations, a mathematical model was derived between the command voltage and the RMS output voltage. It was seen from the results that the experimental and the simulated results were in close agreement at all input command voltage values.

Index Terms— PAS Series Thyristor, Thermocouple, Power controller, Firing circuit, Simulink model, Curve Fitting, PSpice Simulation, RMS Voltage.

1 INTRODUCTION

We all know how the thyristors are used in the control of the output voltage by varying their input voltage given to the gate terminal at different intervals of time. This is simulated in an ideal condition using simulating softwares such as PSpice and MATLAB which will mathematically calculate the ideal voltage outputs of such a network.

However, in reality, that's not the case, as the voltage supply in either single phase or three phase is never constant and varies by some threshold. There are also other constraints which must be taken into consideration such as losses and other external factors. This results in the real output to be slightly varied compared to the output calculated through these simulating softwares. Hence, this paper deals with finding out how much is the variance between the two, using mathematical modelling of the networks involved and curve fitting the results in order to obtain a relation between the two results so that it can be used to accurately predict the results of the desired equipment, saving time and energy in this process.

2 LOAD SIMULATION SYSTEM

The load simulation system is used to simulate the working of the AC-AC 3-Phase thyristor. It is generally a closed loop feedback control system. The Voltages are measured using various types of Voltmeters (mostly digital). The heart of the system is the balanced 3-phase delta connected load which on the application of a controlled supply input, gives desired heat

output, which is used to heat the aerospace component for the simulation purposes.

To give a controlled input supply to the load, it is essential to have a power controller as well. The open loop control system mainly consists of the following subsystems -

- 3-Phase delta connected load
- Power controller for the load

2.1 3-Phase Delta Connected Load

The present system uses Line-controlled delta connection. The basic circuit for a 3-phase converter consists of a pair of anti-parallel thyristors in each phase with the necessary firing circuits.

The circuit has three identical branches each in one phase connected to one of the three phase voltages. It can be seen that the circuit has three arms, one for each phase having a pair of thyristors connected in anti-parallel scheme. During each phase half cycle in the different phases, one SCR from each unit conducts. Since we are using a purely resistive load, it dissipates energy in both the half-cycles of the AC supply. [1]

2.3 Power Controller

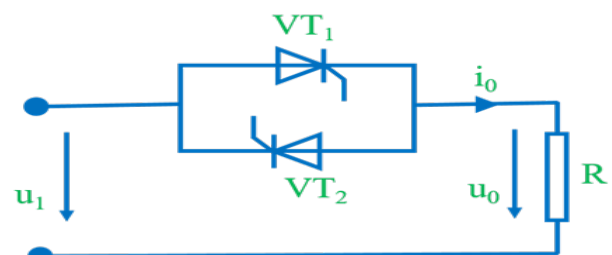


Fig.1 Single-phase Full-wave AC voltage controller

Controlled power to an EIRH (Electric Infra-red Heater) is given by this element, which is a 3-phase AC-AC converter

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based on phase control of SCRs. An AC voltage controller operating in single phase supply is shown in Fig 1. The load used is resistive in nature. The circuit uses two thyristors which are connected in parallel but are opposite in direction to each other. Here, the firing angle of these devices can be controlled separately in order to get the needed output voltage. For getting an AC voltage at the output, the firing angle of the two devices must remain equal. The operation is similar to that of a rectifier, except that instead of removing or reversing the negative half-cycle it is also controlled individually. The waveforms of the output voltage against the input current are shown in below. [2]

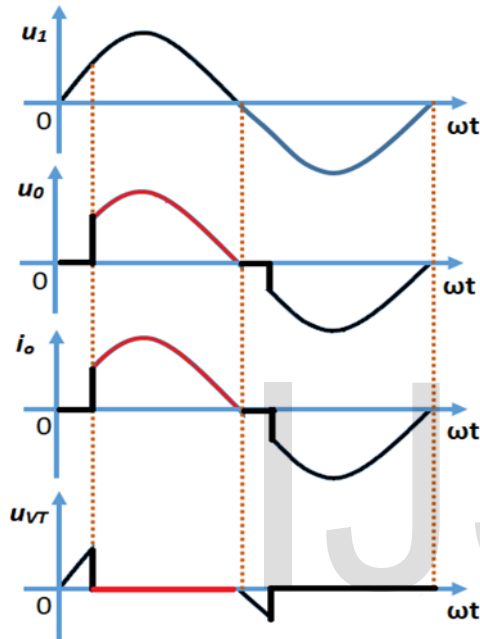


Fig.2 Waveforms of Full-wave AC voltage controller operating in single phase

The RMS value of the output voltage (L-N) is given by

$$U_o = \sqrt{\frac{1}{\pi} \int_{\alpha}^{\pi} (\sqrt{2}U_1 \sin \omega t)^2 d(\omega t)}$$

$$= U_1 \sqrt{\frac{1}{2\pi} \sin 2\alpha + \frac{\pi - \alpha}{\pi}} \quad (1)$$

The line voltage (L-L) for a three phase system is given by

$$V_o = \sqrt{3}U_o \quad (2)$$

The present system uses Line-controlled Δ connection. The basic circuit for a 3-phase converter is as shown in the figure above. It consists of a pair of anti-parallel thyristors in each phase with the necessary firing circuits. [2]

3 EXPERIMENTAL PROCEDURE

- A command voltage was applied in the form of DC voltage.

- The controller on application of the command voltage generated a controlled three-phase voltage across the load, depending on the command voltage. The phase voltages (L-N), and line currents were measured using a power analyser.
- Since the specifications of the heaters specified a continuous running duration of 20 seconds at rated voltage, it was necessary to switch off the heater periodically, after measurements were done. Command DC voltage was increased in steps of 0.5 V ranging from 1V to 5 V, signifying a power increase of 10% at each step.[3]

The quantities measured during the load test on the AC controller, have been given in the Table.1

DC Command Voltage (v)	RMS Output Voltage, L-L(v)	Alpha
1.0	40	2.7866
1.5	136	2.3078
2.0	225	1.9087
2.5	291	1.5865
3.0	365	1.1149
3.5	373	1.0459
4.0	391	0.8571
4.5	401	0.7130
5.0	410	0.5132

Table.1 Output voltage Vs command voltage

The Fig.3 & Fig.4 graph is generated from MATLAB using equation 1 where alpha is found out using this equation 1. And these figures are compared to Theoretical modeling results.

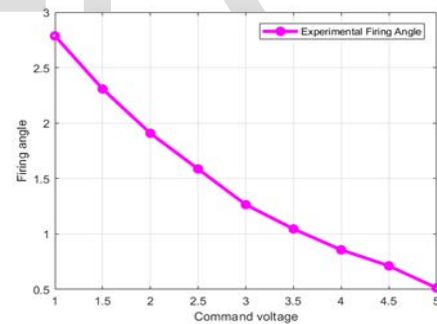


Fig.3 Firing Angle Vs Command voltage

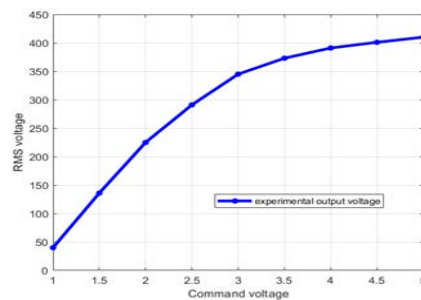


Fig.4 MS Output Vs Command voltage

4 THEORETICAL PROCEDURE

A single-phase full-wave AC controller was simulated using the SimPowerSystems/Power Electronics block-set in Simulink/MATLAB and also PSpice. The information on the firing pulses and firing angle was taken from the results of the PSpice simulation. The system was simulated for various values of Command Input Voltage ranging from 1V – 5V DC.

For the present simulation, following were the parameters taken for the thyristor:

$$R_{on} = 0.45 \text{ m}\Omega$$

$$L_{on} = 0$$

$$V_f = 1.4 \text{ V}$$

Snubber Circuit – Not present ($R_s = \infty$)

These are the corresponding models in PSpice and MATLAB in Fig.5 & Fig.11. Since the system was a balanced three-phase system, it was easier to model it as a single-phase system and extend the results for a three-phase case.

4.1 Simulink Simulation Results

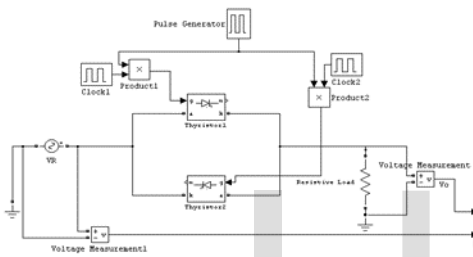


Fig.5 MATLAB Simulation model

Hence, only a single-phase model has been simulated. The output result are derived from inputs and a 5V command input voltage is shown in Fig.6 [4]

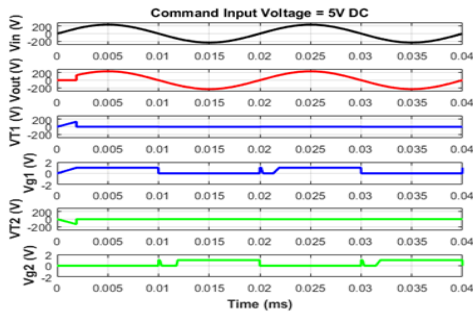


Fig.6 Output at command input voltage 5.0V ms.

Fig.7 & Fig.8 shows the results which are generated in MATLAB.

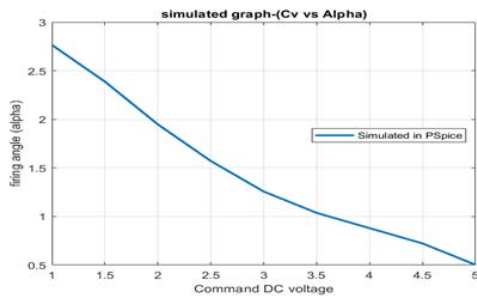


Fig.7 Firing Angle Vs Command Voltage

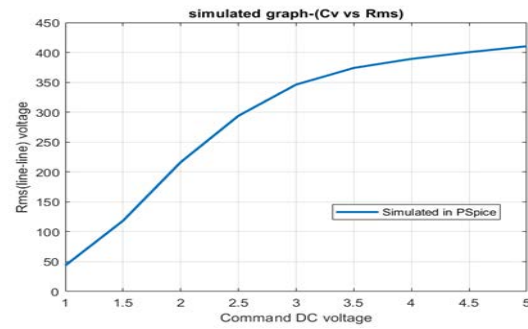


Fig. 8 RMS output voltage Vs Command Voltage

7.1 PSpice Simulation Results

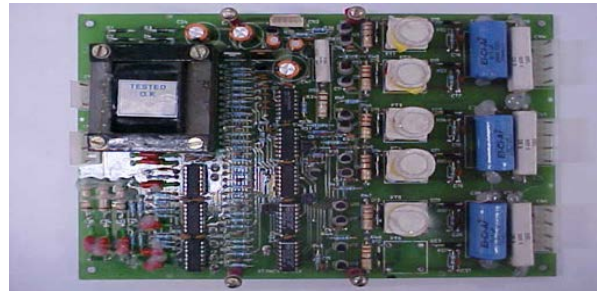


Fig.9 PAS series thyristor Open-loop firing circuit

The open loop firing circuit in Fig.9 was modeled using PSpice and its response to different values of command input voltage was simulated. The simulation gave the waveform of the pulse signals at the output of the pulse transformer circuitry. The variation of the pulse width leads to the variation of the firing angle. The Fig.10 shows output voltage at gate terminal at 5V of command voltage.[4] Many components are studied and replaced in the model with the help of their datasheets present on-internet.[5][6][7][8][9][10][11].

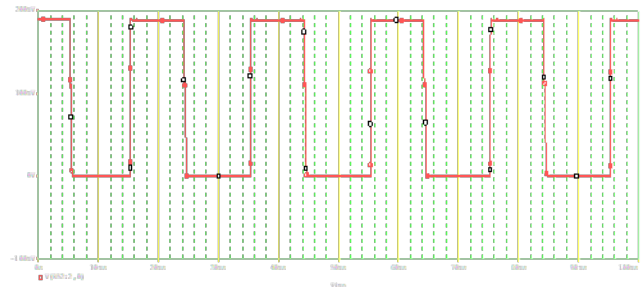


Fig.10 Outputs at G1 of R – phase at a Command Voltage of 5V

The firing angle, α can be calculated from the following relationship:

$$\alpha = \pi - \frac{2\pi}{T} t_p \tag{3}$$

Where,

t_p : pulse width of the signal

T : time period of the signal

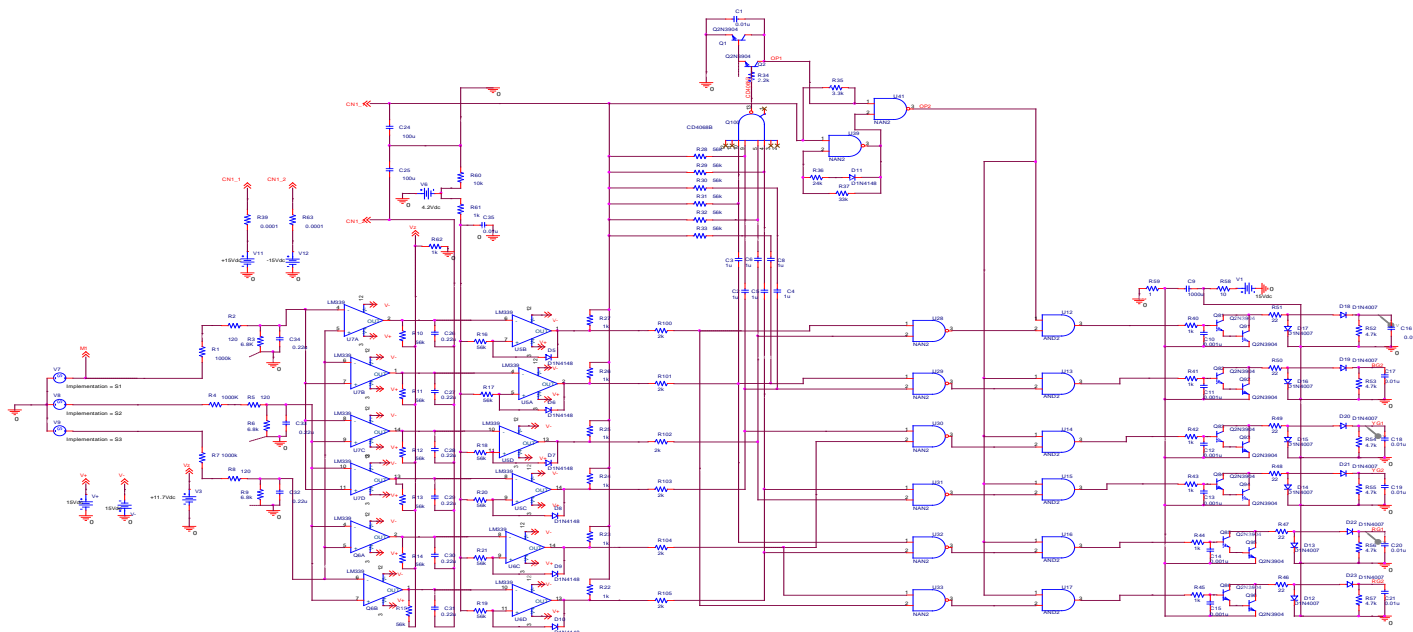


Fig.11 Simplified PSpice Model of the Firing Circuit

The variation of pulse width, firing angle and RMS value of the output voltage (L-N), with the command input voltage has been presented in Table.2

Command Input Voltage (V)	Pulse Width Duration (ms)	Firing Angle, α (Radians)	RMS value of Output Voltage L-L (V)
1	1.2	2.7646	43.6990
1.5	2.4	2.3876	118.4242
2	3.8	1.9478	216.4200
2.5	5	1.5708	293.9388
3	6.4	1.1310	363.0188
3.5	6.7	1.0367	374.0002
4	7.2	0.8796	389.1412
4.5	7.7	0.7226	400.4262
5	8.4	0.5072	410.3324

Table.2 Variation of Pulse width, firing angle and RMS simulated value

From the pulse width we got a desired firing angle which is substituted in Eq.1 using MATLAB to get our desired RMS output voltage.

5 Comparison of Simulated Results

The experimental and simulated results have been compared below. Fig.12 shows the variation of output voltage for both experimental and simulated results and Fig.13 shows the variation of firing angle for both experimental and simulated result.[12]

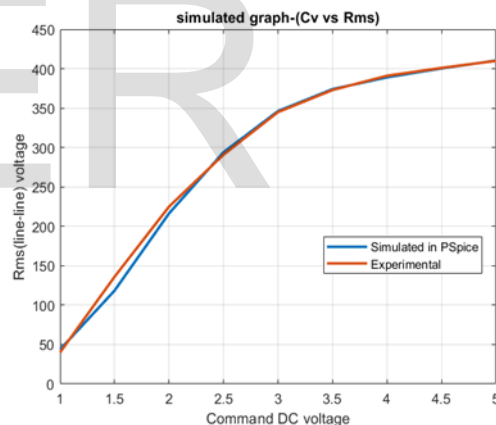


Fig.12 Variation of Output Voltage with Command Voltage

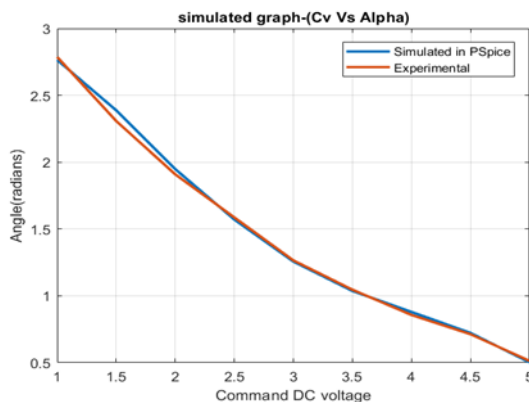


Fig.13 Variation of Firing angle with Command Voltage

Fitting a curve for the variation in both firing angle and output voltage with the command voltage gives us a mathematical relationship between the input and output quantities. Fig.14 shows the curve fit for the variation of output voltage with the command voltage input.[12]

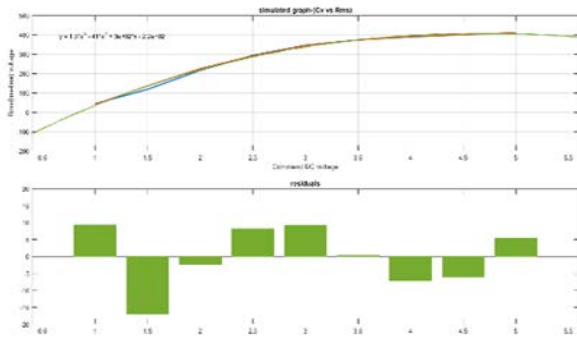


Fig.14 Curve Fit for variation of Output voltage with firing angle and their residuals.

After mathematically fitting the curve of the variation of firing angle with the command voltage, we then fit the curve for the variation of output voltage with the firing angle. Then we finally fit the curve between output and command voltage. From Fig.14 we got the below equation:

$$V_o = 1.3V^3 - 41V^2 + 300V + 220 \quad (4)$$

Where,

The variation of the RMS value of the output voltage with the command voltage of the "PAS Series" 3-phase AC-AC thyristor can be expressed in the above Equation 4. [13]

V_o = Output RMS Voltage = Input Command Voltage

6 Conclusion

A load test on the actual hardware was performed, to validate the simulated results. The command input voltage was applied to the firing circuit in an open loop configuration. Since the load was a balanced load, the output voltage across only the R-Y phases was measured as being a balanced system, the other two line voltages, Y-B and B-R would also be equal to that of the R-Y phases.

A comparison was made between the simulated and the measured output voltages, with the variation of command input. The simulated output voltages being phase voltages, needed to be multiplied by a factor of $\sqrt{3}$ to convert it into line voltage, for comparison purpose. A Mathematical model was generated which was very much useful for generating a required-profile without any further calculations.

It was seen from the results, that the experimental and the simulated results were in close agreement at all input command voltage values.

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