Dynamic Modeling of Six Pulse Rectifier Using MATLAB

Vikas M[1], B. K. Singh[2]

[1, 2] Electrical and Electronics Department, Manipal Institute of Technology, Manipal, India

Abstract: *A dynamic modeling of thyristor rectifier which is useful for the study of power electronics controlled rectifiers with the help of using MATLAB and SIMULINK is presented in this paper. This dynamic model is very simple, fast and effective simulation method for the output variables of thyristor rectifiers. The rectifier output voltage static and dynamic variables behavior are represented by an accurate non linear function of the pulse number (p), trigger angle control voltage* (α) *and displacement angle* $(\boldsymbol{\theta})$*. And also it allows the study in open and closed loop thyristor rectifier simulation of loads which are fed by high power thyristor rectifiers with any pulse number greater than one* $(\boldsymbol{p} > \mathbf{1})$ *or their association by solving only the differential equation(s) of the load(s). The simulation time is always small and independent of the pulse number. This paper gives an approach to establish a general pulse*$(\boldsymbol{p} > \mathbf{1})$ *thyristor rectifier dynamic model which is based on the steady state rectifier behavior and corrected to accurately represent its dynamic transients. In this paper we considered only null commutating reactances having instantaneous switching, no conduction loss and zero overlap angle.*

Keywords: SIMULINK Model, Ideal Voltage Source, 6pulse Thyristor, Sawtooth Function, MATLAB.

1. Introduction

High power high pulse number rectifiers are expensive systems to design, build and test. Therefore computer based rectifier models like MATLAB or Pspice simulation of thyristors currents and voltages, output variables, input currents and voltages with normal and abnormal working conditions must be used to evaluate the converter design and operation. For testing a newly designed controller operation for high power rectifier needs the use of rectifier simulation.

One of the most widely used computer software for the simulation of all kinds of dynamic systems is MATLAB SIMULINK model. For forced commutated power electronics converters such as inverters or choppers SIMULINK non linear blocks such as relays or switches could be used as to obtain ideal models which are required for the dynamic simulation of such power electronics converter systems. However in the case of power rectifiers SIMULINK models of the power thyristor are available. And the thyristor rectifiers are difficult to analyze and simulate with the MATLAB SIMULINK due to the line commutated semiconductors. Usually due to the thyristor inherent positive feedback, power rectifier simulation shows convergence problems even when used with the electronics circuit simulators such as Pspice. Therefore within the SIMULINK environment an ideal, simple fast and accurate thyristor rectifier input output subsystem which is not suffering from the effects of the thyristor internal positive feedback will be helpful for the designing of the output filters or closed loop control subsystems of thyristor converters [1], [2].

A dynamic model for the $\mathrm{p}(\mathrm{p} > 1)$pulse thyristor rectifier should present following properties are [1], [2];

- In the continuous mode of operation, as the output current is always greater than zero, the output voltage must be a collection of continuous sinusoidal segments, often forming a periodic discontinuous function;
- In the discontinuous mode of operation when the output current is zero, the rectifier output voltage must be equal to the load voltage. When the output current is positive, the output voltage must be equal to the source voltage;
- For mains voltage with period t and small perturbations on the triggering angle, the output voltage delay time must be in the range of 0-t/p with statistical average delay near t/2p;
- For large trigger angle variations, from 150° to 0° , the delay time of the output voltage must be essentially zero;
- Whereas from 0° to 150°, the time delay of the output voltage must be roughly t/2 (due to thyristor memory effect).

Here some of these properties are obtained at the expense of simplicity, other needs long computational times and as nearly all need a model with as many non linear equations, pulse number, pulse triggering equation for each thyristor. So therefore number of model equations depends on the pulse number, being very difficult to find a general model.

This paper presents an approach for the simulation of the output variables of a general p pulse thyristor rectifiers. Using just one of non linear function describing the effects of all the triggering pulses for all the thyristor, coupled to a non linear block, both the static and transients dynamic of the rectifier output voltage and current are accurately represented. The simulator in the section 2 does not suffer the effects of the thyristor internal positive feedback as on purpose it does not describe the input or internal currents and voltages, being well suited for the simulation study of feedback controlled systems with very high power rectifiers, using MATLAB SIMULINK program or even with the Pspice as the total number of its equations does not increase with the pulse number p [1], [2].

2. Ideal voltage source

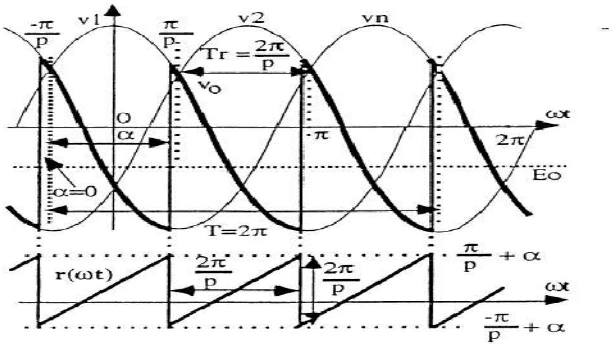

Figure 1: Mains and output voltages of an ideal rectifier, and also showing the sawtooth function r (ωt) waveforms [1].

Line commutated rectifiers are discrete and highly non linear. Electronic power converters due to the semiconductor behavior. All their thyristors are fired and synchronized with the mains power supply, with trigger pulses delayed by the trigger angle. Once conducting, each thyristor only turns off when its current falls below holding level. Furthermore the rectifier response to small variations of the trigger angle presents a random delay which endows some minimum phase behavior to the rectifier. Firing the thyristors of a p pulse rectifier with the pulse phase control divides the mains period T in p ramps and can be simulated by a sawtooth wave $\mathrm{r}(\omega\mathrm{t})$ with frequency $\mathrm{f}=\frac{\mathrm{p}}{\mathrm{T}}$ and with triggering angle α. Considering the figure 1, the maximum value of the sawtooth wave $\mathrm{r}(\omega\mathrm{t})$ must be $\alpha+\frac{\pi}{\mathrm{p}}$. And the minimum value of the sawtooth wave $\mathrm{r}(\omega\mathrm{t})$ must be $\alpha-\frac{\pi}{\mathrm{p}}$ [1], [2].

The ideal relationship between the triggering angle α and the rectifier control voltage u_c with individual phase control is can be given by

$$\alpha=\frac{\pi}{2}-\frac{\pi}{2}\frac{\mathrm{u_c}}{\mathrm{u_{c\,max}}} \tag{1}$$

Then a new sawtooth function $r(\omega\mathrm{t})$ outlining the thyristors triggering instants are introduced and it can be mathematically described by the following non linear function is given by

$$r(\omega\mathrm{t}) = \alpha-\frac{\pi}{\mathrm{p}}+\ \mathrm{REM}(\omega\mathrm{t}+\mathrm{d_1}\,,\frac{2\pi}{\mathrm{p}}) \tag{2}$$

Where the function $\mathrm{REM}\left(\omega\mathrm{t}+\mathrm{d_1}\,,\frac{2\pi}{\mathrm{p}}\right)$ is the remainder of the division of $\omega\mathrm{t}+\mathrm{d_1}$ by $\frac{2\pi}{\mathrm{p}}$.

The sawtooth function $r(\omega\mathrm{t})$obeys two boundary conditions;

Case (i). When $\omega\mathrm{t} = \alpha-\frac{\pi}{\mathrm{p}}$

The value of $r(\omega\mathrm{t}) = \alpha-\frac{\pi}{\mathrm{p}}$ from figure 1 which means that REM function of equation (1) is zero.

That is the sawtooth function $r(\omega\mathrm{t})$ is at the minimum position waveform.

$$\therefore \omega\mathrm{t}+\mathrm{d_1} = \frac{2\mathrm{k}\pi}{\mathrm{p}} \tag{3}$$

Considering k=0,

And also $\omega\mathrm{t} = \alpha-\frac{\pi}{\mathrm{p}}$

Now the equation (2) becomes

$\mathrm{d_1} = -\,\omega\mathrm{t}$

$$\therefore\ \mathrm{d_1} = -\alpha+\frac{\pi}{\mathrm{p}} \tag{4}$$

Case (ii). When $\omega\mathrm{t} = \alpha+\frac{\pi}{\mathrm{p}}$

The value of $r(\omega\mathrm{t}) = \alpha+\frac{\pi}{\mathrm{p}}$ from the figure 1 which means that REM function of equation (1) is $\frac{2\pi}{\mathrm{p}}$.

That is the sawtooth function $r(\omega\mathrm{t})$ is at the maximum position of the waveform.

Considering for odd k=1,

And also $\omega\mathrm{t} = \alpha+\frac{\pi}{\mathrm{p}}$

Now the equation (2) becomes

$$\omega\mathrm{t}+\mathrm{d_1} = \frac{2\mathrm{k}\pi}{\mathrm{p}}$$

$$\alpha+\frac{\pi}{\mathrm{p}}+\mathrm{d_1} = \frac{2\pi}{\mathrm{p}}$$

$$\therefore\ \mathrm{d_1} = -\alpha+\frac{\pi}{\mathrm{p}} \tag{5}$$

So the equations (4) and (5) are same, and the parameter $\mathrm{d_1}$ can be calculated.

$$\therefore\ \mathrm{d_1} = \frac{\pi}{\mathrm{p}}-\alpha$$

Usually star-delta connected power transformer supply source voltage is required system simulation facility to connect several parallel or series connection of the rectifiers. The synchronization of $r(\omega\mathrm{t})$ with the mains source voltages that have a phase lag or lead of the value θ which is relative to the synchronization phase. The displacement angle θ introduces the phase shift in the sawtooth function and consequently in the output voltage of the rectifier. Here the value of θ will be used when series or parallel rectifier connection. So therefore a new time reference is required and it can be included by using in the value of variable d which is obtained from the $\mathrm{d} = \mathrm{d_1}+\theta$.

The new value of the sawtooth function $r(\omega\mathrm{t})$ is given by

$$r(\omega\mathrm{t}) = \alpha-\frac{\pi}{\mathrm{p}}+\ \mathrm{REM}(\omega\mathrm{t}+\theta+\frac{\pi}{\mathrm{p}}-\alpha\,,\frac{2\pi}{\mathrm{p}}) \tag{6}$$

This sawtooth function $r(\omega\mathrm{t})$ gives that the period T is dividing in p ramps and all the values are synchronized with the mains source voltage.

3. SIMULINK Model of Ideal Rectifier

In this section the SIMULINK model of thyristor rectifier is assumes an ideal thyristor and null commutating reactances means that no conduction losses, instantaneous switching and zero overlapping angle. The inputs for the SIMULINK model include the trigger angle in degrees, the pulse number, the mains peak voltage in volt, the displacement angle in radians. The displacement angle θ introduces the phase shift in the sawtooth function and consequently in the output voltage of the rectifier. The SIMULINK model of thyristor rectifier is based on the fact that in the case of steady state behavior the output voltage of the ideal rectifier is a sinusoidal wave repeated with the frequency p/T as shown in the figure 1. The SIMULINK model of the 6pulses Rectifier in the figure 2 must contain a ramp function with the repetition frequency $\frac{\mathrm{p}}{2\pi}$ and synchronized with the mains voltage. Here the ramp generates the argument for sinus or cosines function [1], [2].

The output voltage of the ideal rectifier is given by

$$V_0 = V_m \cos(r(\omega t)) \tag{7}$$

Where V_m is the maximum peak value of the output voltage of the ideal rectifier. This maximum peak value depends on the particular topology of each rectifier. The equation (6) and (7) represent only steady state rectifier behavior and the memory effect of the individual conducting thyristor is not included in this paper. This memory effect of the individual conducting thyristor only influences the transient behavior for increasing the triggering angles. If the triggering angle is increasing, the delay time of the rectifier T/2 is longer than that of sawtooth wave r(ωt) because the thyristors are line commutated devices. If the triggering angle is decreasing, the delay time of the rectifier is same as that of sawtooth wave r(ωt)(=0). Therefore the ideal rectifier simulation block must include an additional non linear function to represent the thyristor memory effect.

The above SIMULINK model of 6pulses Rectifier should include blocks to represent the transient behavior. The output voltage of an ideal rectifier is a sinusoidal function with the discontinuous period of $\frac{2\pi}{p}$ and negative first order derivatives not greater than MAX$[\frac{d(V_m \cos(\omega t))}{dt}] = \omega V_m$. Now Considering that the r(ωt) positive time derivatives correspond to the output voltage first order negative derivatives, a positive rising slope of the sawtooth to the output $\frac{d(r(\omega t))}{dt}$ must be added which limits the rising slope of the ramp to the value S_r [1], [2].

$$S_r = \omega V_m \tag{8}$$

Using this S_r, the instantaneous variations on the output voltage are avoided when the trigger angle is advanced as for an example from 30° to 90°. Here the falling slew rate is not limited figure 3 as it corresponds to decreasing trigger angles as for example 120° to 40° where the rectifier delay time is almost null.

Therefore the rectifier simulation block must contain the sawtooth function, the rising slope limiter. The resulting rectifier simulation block for a p pulse converter called as “Ideal Rectifier” is shown on figure 5.

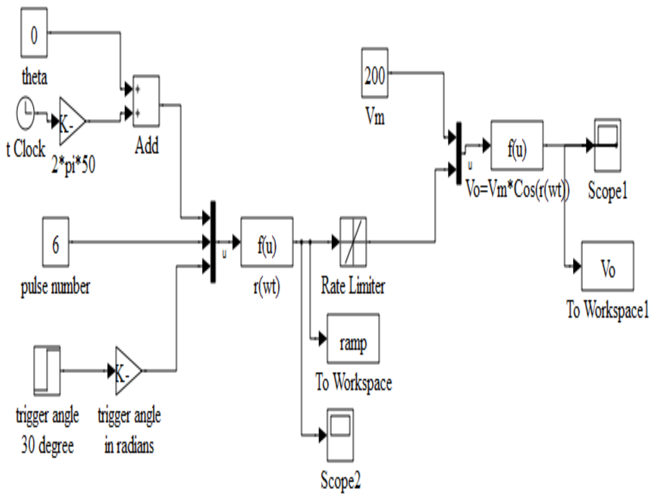

Figure 2: Generalized model of 6 Pulse Rectifier using equations [1], [2].

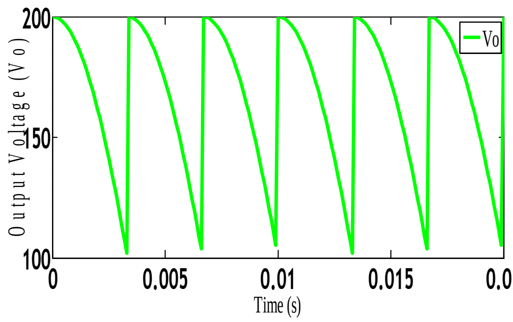

Figure 3: Output Voltage of 6 Pulse Rectifier for $\alpha = 30°$

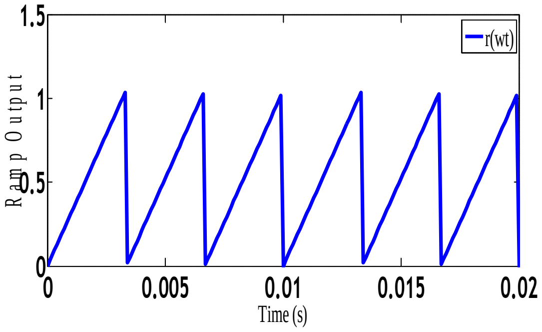

Figure 4: Ramp Output r(ωt)

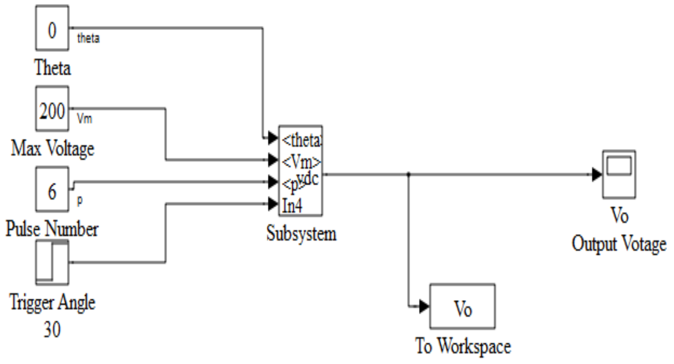

Figure 5: SIMULINK Model of 6 Pulse Rectifier [1], [2]

4. Simulation result with the loads

Here the open loop simulation of thyristor rectifiers shows the operation in the discontinuous mode and the dynamic behavior were made with the block diagram figure 7 which are suitable for the zero overlapping angles three phase half wave rectifier with RL load, RLEo load. The simulation result gives a good representation of the transient behavior.

4.1 With RL Load

Considering the output voltage of the thyristor rectifier across the RL load is given by

$$V_0 = IoR + L\frac{dIo}{dt} \tag{9}$$

V_0 = Output Voltage of the thyristor rectifier.
Io = Output Current across the RL Load.
L = Inductance connected across the thyristor rectifier.
R = Resistance connected across the thyristor rectifier.

By rearranging the equation (9)

$$-\mathrm{IoR} = \mathrm{L}\frac{\mathrm{dIo}}{\mathrm{dt}}$$

The output current equation becomes

$$\mathrm{Io} = \frac{1}{\mathrm{L}}\int (\mathrm{V}_0 - \mathrm{IoR})\mathrm{dt} \qquad (10)$$

By looking the above equation number (10), we can write the SIMULINK block diagram.

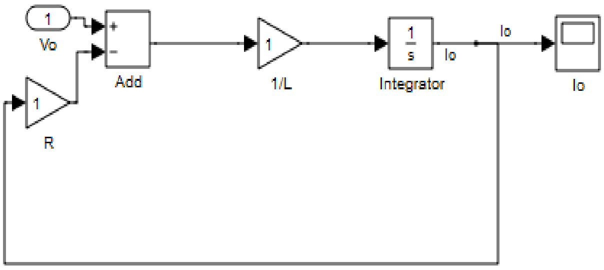

Figure 6: Block diagram of RL load

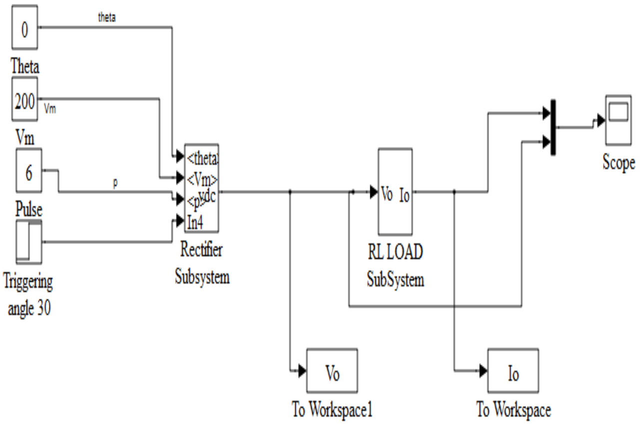

Figure 7: SIMULINK Model of 6 Pulse Rectifier with RL load subsystem.

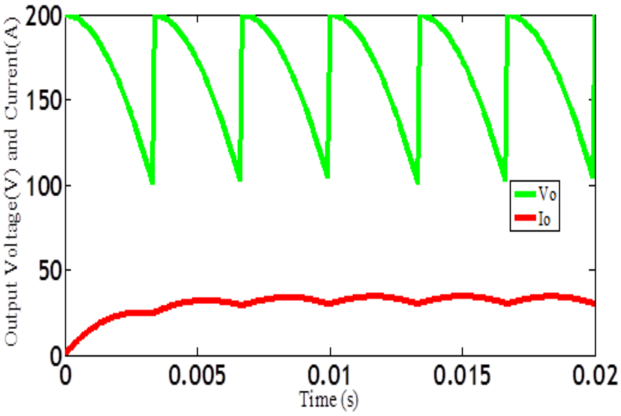

Figure 8: SIMULINK Model Output Voltage (V) and Output Current (A) of the 6 Pulse Rectifier with R=5Ω , L=10 m H, $\alpha = 30°$

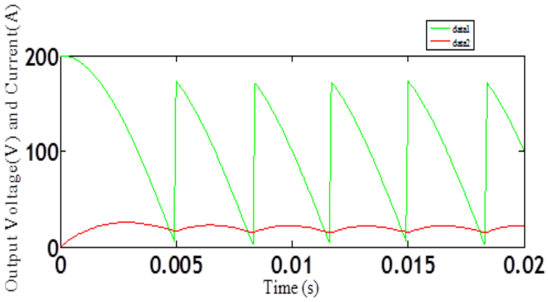

Figure 9: SIMULINK Model Output Voltage (V) and Output Current (A) of the 6 Pulse Rectifier with R=5Ω, L=10 m H, α=60°

4.2 With RLE$_0$ Load

The simulation block of the thyristor rectifier for the discontinuous mode of operation is obtained easily using a limited integrator which does not allow negative output currents. The output voltage is the ideal rectifier output, when the output current is greater than zero. The output voltage is switched to the open load voltageE_0.

Considering the output voltage of the thyristor rectifier across the RLEo load is given by

$$\mathrm{V}_0 = \mathrm{IoR} + \mathrm{L}\frac{\mathrm{dIo}}{\mathrm{dt}} + \mathrm{Eo} \qquad (11)$$

The output current equation becomes

$$\mathrm{Io} = \frac{1}{\mathrm{L}}\int (\mathrm{V}_0 - \mathrm{Eo} - \mathrm{IoR})\mathrm{dt} \qquad (12)$$

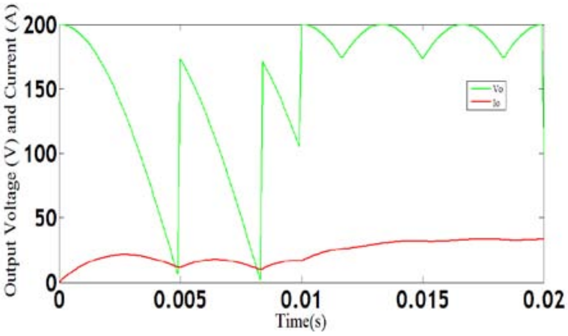

Figure 10: SIMULINK Model Output Voltage (V) and Output Current (A) of the 6 Pulse Rectifier with R=5Ω, L=10 m H, Eo=25, α=60°.

5. Conclusion

The proposed SIMULINK model of the thyristor rectifier is able to simulate almost any p (p>1) phase thyristor rectifier which helps to simulate the open loop systems of the rectifier with high pulse numbers. Here the proposed model does not describe the source or thyristor voltages and currents or abnormal working conditions. This paper gives an approach to establish a general pulse thyristor rectifier dynamic model which is based on the steady state rectifier behavior and corrected to accurately represent its dynamic transients. In this paper we considered only null commutating reactances having instantaneous switching, no conduction loss and zero overlap angles. This dynamic model is very simple, fast and effective simulation method for the output variables of thyristor rectifiers.

References

[1] J. Fernando Silva, *"System simulation of thyristor rectifier"*, Revue Internationale de Genie Electrique, Volume 2-n° 1/1999, pages 7 a 34.
[2] J. Fernando Silva, *"MATLAB/SIMULINK model for thyristor rectifiers"*,
[3] Rashid M.H, *"Power Electronics- Circuits, Devices and Applications Power"*, Prentice-Hall, 3rd Edition, 2003.
[4] Dr. Bhimbra P.S, *"Fundamentals of Power Electronics and Drives"*, Dhanpat Rai and Co (Pvt).

About Author

Vikas. M has obtained his B Tech degree in Electrical and Electronics from Dr. Ambedkar Institute of Technology, Bangalore and currently pursuing his M Tech in power electronics system and controls in Manipal University, Manipal .His area of interest is power converters, power systems and embedded systems. He has published a journal in International Journal of Science and Research ISSN 2319-7064 volume 2 issue 6 June 2013.

Dr. B. K Singh has 28 years of teaching experience and is also a member of recognized professional organizations such as ISTE, IE (I) and SSI. His area of interest includes Distributed generation System. His top research publications are, International Journal of Applied Engineering Research ISSN 0973 – 4562 Volume 4 Number 8 (2009) pp. 1543 – 1556 and Modeling and Performance Analysis of Solid Oxide Fuel call based Distributed Generation System International Energy Journal (RERIC). And also He has published a journal in International Journal of Science and Research ISSN 2319-7064 volume 2 issue 6 June 2013