Dynamic Modeling of Six Pulse Rectifier Using MATLAB

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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 (β). 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 (p > 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 (p > 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 p(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].

Volume 2 Issue 7, July 2013
www.ijsr.net

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2. Ideal voltage source

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 pulse rectifier with the pulse phase control divides the mains phase behavior to the rectifier. Firing the thyristors of a p presents a random delay which endows some minimum rectifier response to small variations of the trigger angle when its current falls below holding level. Furthermore the trigger angle. Once conducting, each thyristor only turns off the mains power supply, with trigger pulses delayed by the behavior. All their thyristors are fired and synchronized with linear. Electronic power converters due to the semiconductor Line commutated rectifiers are discrete and highly non linear.

The sawtooth function can be given by

\[ r(\omega t) = \omega t - \frac{\pi}{2} \]  

That is the sawtooth function \( R(\omega t) \) is given by

\[ R(\omega t) = \alpha - \frac{\pi}{2} + \text{REM}(\alpha + \frac{2\pi}{p}) \]  

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

The sawtooth function \( R(\omega t) \) obeys two boundary conditions;

Case (i). When \( \omega t = \alpha - \frac{\pi}{2} \)

The value of \( R(\omega t) = \alpha - \frac{\pi}{2} \) from figure 1 which means that REM function of equation (1) is zero. That is the sawtooth function \( R(\omega t) \) is at the minimum position waveform.

\[ \therefore \omega t + d_1 = \frac{2k\pi}{p} \]  

Considering \( k=0 \),
And also \( \omega t = \alpha - \frac{\pi}{2} \)

Now the equation (2) becomes

\[ d_1 = -\alpha + \frac{\pi}{p} \]  

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

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

That is the sawtooth function \( R(\omega t) \) is at the maximum position of the waveform.

Considering for odd \( k=1 \),
And also \( \omega t = \alpha + \frac{\pi}{p} \)

Now the equation (2) becomes

\[ \omega t + d_1 = \frac{2k\pi}{p} \]  

\[ \alpha + \frac{\pi}{p} + d_1 = \frac{2\pi}{p} \]  

\[ \therefore d_1 = -\alpha + \frac{\pi}{p} \]  

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

\[ \therefore d_1 = \frac{\pi}{p} - \alpha \]  

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 \( R(\omega t) \) with the mains source voltages that have a phase lag or lead of the value \( \theta \) which is relative to the synchronization phase. The displacement angle \( \theta \) introduces the phase shift in the sawtooth function and consequently in the output voltage of the rectifier. Here the value of \( \theta \) 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 \( d = d_1 + \theta \) .

The new value of the sawtooth function \( R(\omega t) \) is given by

\[ R(\omega t) = \alpha - \frac{\pi}{2} + \text{REM}(\alpha + \theta + \frac{\pi}{p} - \frac{\alpha}{p} \frac{2\pi}{p}) \]  

This sawtooth function \( R(\omega t) \) 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 \( \theta \) 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 6 pulses Rectifier in the figure 2 must contain a ramp function with the repetition frequency \( \frac{2\pi}{p} \) 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
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 \( r(\omega t) \) 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 \( r(\omega t) = 0 \). Therefore the ideal rectifier simulation block must include an additional non linear function to represent the thyristor memory effect.

The above SIMULINK model of 6 pulses 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 \( \text{MAX}\left(\frac{d(V_m \cos(\omega t))}{dt}\right) = \omega V_m \). Now considering that the \( r(\omega t) \) positive time derivatives correspond to the output voltage first order negative derivatives, a positive rising slope of the sawtooth to the output \( \frac{dr(\omega t)}{dt} \) 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 \( 30^\circ \) to \( 90^\circ \). Here the falling slew rate is not limited figure 3 as it corresponds to decreasing trigger angles as for example \( 120^\circ \) to \( 40^\circ \) 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.

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, RLEq 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)
The output current equation becomes
\[ i_o = \frac{1}{L} \int (v_o - i_o R) dt \] (10)
By looking the above equation number (10), we can write the SIMULINK block diagram.

4.2 With RLEo 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 voltage \( E_o \).

Considering the output voltage of the thyristor rectifier across the RLEo load is given by
\[ v_o = i_o R + L \frac{d i_o}{dt} + E_o \] (11)
The output current equation becomes
\[ i_o = \frac{1}{L} \int (V_o - E_o - i_o R) dt \] (12)

5. Conclusion

The proposed SIMULINK model of the thyristor rectifier is able to simulate almost any \( p > 1 \) 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


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