Matlab/Simulink/Sim-Power-Systems Model for a PWM AC-to-DC Converter with Line Conditioning Capabilities

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Abstract: Recent developments of the Matlab/Simulink simulation software offer large possibilities for power electronics engineers with the new Sim-Power-Systems toolbox. This paper presents the modeling of a PWM ac-to-dc converter, in order to obtain a toolbox for such types of converters. This toolbox will be used in further simulations to investigate the power line conditioning capability of these converters. It will be presented in detail, step by step, the development of this toolbox and finally the new model will be verified for the case of simple "line-friendly" operation mode.

Keywords: Matlab/Simulink/Sim-Power-Systems toolbox, PWM ac-to-dc converter, line conditioning with ac-to-dc converters.

1. INTRODUCTION

The problems of power factor correction and line harmonic distortions are known and very much discussed nowadays. Large palettes of solutions are proposed which includes static VAR compensators, passive or active filters [1], [2], [3] to improve the quality of the power delivered by the mains.

Previous researches [4], [5], have proven that, besides their main functionality of power conversion, the PWM ac-to-dc converters can overtake also line conditioning tasks. Furthermore, it has been proposed a new control method for these types of power converters in order to provide them with the possibility to support the ac mains [6], [7].

As seen in the mentioned papers, this new and original control method implies some minor modifications in the structure of the control scheme of these converters. Three operation modes of the converter were defined according to the actual status of the mains. These operation modes are respectively simple line conditioning, active line conditioning and complex line conditioning.

The investigation of the steady-state characteristics and of the operating space of these converters, have proven their capability of conditioning the ac line [8]. The operating space, which consists of curves in the three dimensional space, proves the capability of the PWM ac-to-dc converters to operate in simple and active line-conditioning.

However, more simulations with the converter coupled to a distribution network are necessary in order to study the behavior of these types of converters in applications closed to the real applications. Fortunately, the recent apparition of the Sim-Power-Systems toolbox in the Matlab-Simulink software has made possible a more power electronics engineering approach to Matlab-Simulink simulation models.

This paper will present the development of a Matlab-Simulink-SimPowerSystems toolbox for a PWM ac-to-dc converter provided with active line conditioning capabilities. This model will be used in the future simulations and studies of the behavior of these converters when coupled to a real ac distribution network. The simulations presented in this paper will investigate the performances and validity of the toolbox model.

2. BUILD-UP OF THE CONVERTER'S TOOLBOX

Matlab-Simulink models for the PWM ac-to-dc converter provided with active line conditioning capabilities have been made earlier in [6], [7] and [9] in order to investigate the dynamical performances of these converters. However, it is not possible a direct coupling of this model to the ac power distribution network’s Matlab-Simulink-SimPower Systems model. Therefore we need to reconfigure the old model by providing an interface to SimPowerSystems toolbox.

Previous papers like [6], [7] and [9] have presented in detail the operation mode of the PWM ac-to-dc converter provided with active line conditioning capabilities, also indicated in Figure 1.

Previous models of these types of converters have been made entirely in Matlab-Simulink. Therefore an appropriate mathematical model was necessary for both power conversion circuit and control circuit. The following set of equations described the power electronics part of the system:
\[ u(t) = \hat{U} \cdot \sin \omega \cdot t \]
\[ L \cdot \frac{di(t)}{dt} = u(t) - u_c(t) - R_L \cdot i(t) \]
\[ i_{rd}(t) = \frac{u_d(t)}{u_c(t)} \cdot i(t) \]
\[ C \cdot \frac{du_d(t)}{dt} = i_{rd}(t) - i_s \]

where \( u(t) \) and \( i(t) \) are the ac input line instantaneous voltage and respectively current. \( \hat{U} \) is the magnitude of \( u(t) \), \( L \) and \( R_L \) are the inductance and resistance of the ac side inductor, \( u_d(t) \) and \( i_{rd}(t) \) are the dc rectified voltage and current, \( C \) is the output filtering capacitor’s capacitance, \( i_s \) is the current flowing through the dc load and

\[ u_d(t) = \begin{cases} 
+ u_d(t) & \text{if } \Delta i(t) \geq \frac{hbw}{2} \\
- u_d(t) & \text{if } \Delta i(t) \leq \frac{hbw}{2}
\end{cases} \]

is the voltage on the ac side of the converter. In equation (2) \( hbw \) represents the hysteresis bandwidth and \( \Delta i(t) \) is the difference between the current given by the active line conditioning unit \( i^*(t) \) and the actual current \( i(t) \) measured at the converter’s ac side.

However, the SimPowerSystems toolbox made it possible to implement the power conversion part with circuit elements. Therefore there is no need for the mathematical model described by equations (1). Section 2.1 of the present paper will describe in detail the building up of the power electronics part with the help of SimPowerSystems blocks.

Unfortunately some mathematical operations like trigonometric operations necessary in the active line conditioning unit can not be done with Sim-PowerSystems blocks. In this case we need the Simulink blocks. The control block is realized therefore with Simulink blocks.

The output dc voltage is measured and in the same time it is converted from SimPowerSystems to Simulink. The filter, needed to smooth the oscillations from the output DC voltage, is a second order band stop filter with the following transfer function:

\[ H(s) = \frac{s^2 + \omega_0^2}{s^2 + B \cdot s + \omega_0^2} \]

where:

\[ f_0 = \frac{\omega_0}{2 \cdot \pi} = 100\text{Hz} \]
\[ f_B = \frac{B}{2 \cdot \pi} = 20\text{Hz} \]

are the central frequency, \( f_0 \) and respectively the bandwidth \( f_B \) of the filter.

After being filtered, the measured dc voltage is compared with the reference voltage \( U_{d^*} \) and the result, \( \Delta u_d \) is applied to a PI voltage controller which gives at its output the value of the active current, \( I_{a^*} \), based on the following equation:

\[ I_{a^*}(t) = K_P \cdot \Delta u_d(t) + K_I \cdot \int \Delta u_d(t) \, dt \]

where \( K_P \) and \( K_I \) are the proportional and respectively integral constants of the controller.
The active current, $I_a^*$, is then applied to the line conditioning block which will provide, based on the conditioning signal, $c(t)$ and the measured ac voltage, $u(t)$, the appropriate signal $i^*(t)$, corresponding to the required line conditioning mode (relations (8)). This block is described in detail in section 2.2.

The signal $i^*(t)$ is compared with the actual current measured on the ac side of the converter, $i(t)$ and the result, $\Delta i(t)$, is applied to the bi-level current controller which will provide the control pulses for the converter’s bridge as described in section 2.2.

The parameters of the simulated converter are given in the table below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated apparent power</td>
<td>250VA</td>
</tr>
<tr>
<td>Converter’s ac-side voltage</td>
<td>48Vrms</td>
</tr>
<tr>
<td>Converter’s rectified voltage</td>
<td>100Vdc</td>
</tr>
<tr>
<td>Converter’s rated current</td>
<td>5.2083Arms</td>
</tr>
<tr>
<td>AC line frequency</td>
<td>50Hz</td>
</tr>
<tr>
<td>PI controller’s proportional constant</td>
<td>0.9</td>
</tr>
<tr>
<td>PI controller’s integrating constant</td>
<td>90</td>
</tr>
<tr>
<td>Hysteresis bandwidth</td>
<td>0.5</td>
</tr>
</tbody>
</table>

In order to interface the old model with the Sim-Power-Systems toolbox, the whole converter model or a part of it must be converted to Sim-Power-Systems blocks. Unfortunately some mathematical operations like trigonometric operations necessary in the active line conditioning unit can not be done with Sim-Power-Systems blocks. In this case we need the Simulink blocks. Therefore the most suitable and also elegant way is to build a new, hybrid structure. As a result, the power electronic part of the converter will be based on Sim-Power-Systems blocks and the control part on Simulink blocks.

### 2.1. The power electronic part

The most important part of the conversion system consists in the power electronics. Because this is a single phase converter we need a simple H-bridge containing four quasi-ideal switches having each in parallel a diode, as shown in figure 2.

Because this model was designed for telecommunication applications a converter having on the ac side an input voltage of 48V RMS and an output rectified 100V DC was necessary. As a result the model...
needs also a line transformer from 230 VRMS to 48VRMS. The transformer is also a quasi-ideal having neglected the self inductance and an infinite coupling inductance. The primary and secondary resistances are given in p.u. calculated with the following relations:

\[
R(p.u.) = \frac{R}{R_{base}} \quad (6)
\]

\[
R_{base} = \frac{U_{base}^2}{P_{n}} = \frac{230^2}{250} = 211.6
\]

The ac side line-inductor and the DC side capacitor were calculated previously, [9] and are given in the table below:

Table 2. The AC side line inductor and the DC side capacitor.

<table>
<thead>
<tr>
<th>DC side capacitor</th>
<th>AC line side inductor’s inductance</th>
<th>AC line side inductor’s resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1650μF</td>
<td>1.76mH</td>
<td>0.331Ω</td>
</tr>
</tbody>
</table>

Figure 3 presents the Matlab/Simulink/Sim-Power-Systems model of the PWM ac-to-dc converter provided with active line conditioning capabilities. It can be noticed, besides the power electronics, the electronic control block, which will be presented in detail in the next section.

2.2. The control part

The model of the control block in Matlab/Simulink is presented in figure 4. Voltage and current measurement units make the conversion between the Sim-Power-Systems model of the power electronics part and the Matlab/Simulink model of the control block.

In the followings, the control block of the converter will be described in detail, taking into account the modifications needed to interface this block with the SimPowerSystems part of the converter.

In the old model, the synchronization signals were built-up with a separate sine wave generator, having the amplitude equal to 1 and the phase same as the phase of the input voltage. This new model is more close to the real one as it measures the input instantaneous voltage and divides it with its computed magnitude to obtain a unity sine wave with phase and frequency equal to the phase and frequency of the ac line, Figure 5.

From the measured sine wave, the synchronization block computes the cosine of the signal, both sine and cosine signals being needed for the line conditioning blocks and calculated with the following relations:

\[
\sin(\omega \cdot t) = \frac{u(t)}{U} \quad (7)
\]

\[
\cos(\omega \cdot t) = \pm \sqrt{1 - \sin^2(\omega \cdot t)}
\]

According to the here proposed control strategy, a so-called conditional signal, c, is needed to inform the converter about the actual state of the ac line. Based on the information contained in this signal, the line conditioning block will decide in which of the simple, active capacitive or active inductive operation modes to, will operate the converter.

On the dc side, the dc voltage is measured and filtered with the help of a band-pass filter, FOB [9]. Then it is compared with the reference voltage, \( U_d^* \), which in this case is 100V. The result of this comparison represents the input of a PI voltage controller which will output the active current’s value \( I_A^* \). This current is limited to the nominal peak value of
the converter’s current in order to limit the apparent power of the converter to its rated-value one.

The line conditioning unit remains unmodified with respect to the old model [6], [7]. The main function of this block is to decide based on the conditioning signal and all other inputs which of the three mentioned operation modes is necessary to be implemented. This block will output the reference current as follows:

\[
\begin{align*}
I_c(t) &= I_{\text{MAX}}^* \cos \phi(t), & \text{for } c = 0 & \text{simple line conditioning} \\
I_c(t) &= I_{\text{MAX}}^* \sin(\omega t + \phi), & \text{for } c = +1 & \text{active capacitive line conditioning} \\
I_c(t) &= I_{\text{MAX}}^* \sin(\omega t - \phi), & \text{for } c = -1 & \text{active inductive line conditioning}
\end{align*}
\]

where \(I_{\text{MAX}}^*\) is the amplitude of the reference current of the converter, \(I_{\text{MAX}}^*\) is the active current’s value given by the PI controller and:

\[
\begin{align*}
\cos \phi(t) &= \frac{I_c(t)}{I_{\text{MAX}}} \\
\sin \phi(t) &= \pm \sqrt{1 - \cos^2 \phi(t)}
\end{align*}
\]  

The following figure, [6], [7], presents the block diagram of the line conditioning unit.

The switches are controlled by a logical signal of type 0 – 1. The control signals for the switches are built-up in the bi-level hysteresis control unit. The hysteresis bandwidth can be set externally. The bi-level hysteresis control unit’s internal structure is presented in figure 7.

The hysteresis control unit builds up the control signal using the following Matlab script:

```matlab
function bc=histcontr2(deltai,hbw,ucprev)
if deltai>=hbw/2
  bc=1;
elseif deltai<=-hbw/2
  bc=0;
else
  bc=ucprev;
end
```

where \(hbw\) represents the hysteresis bandwidth. From the control signal it is derived also a signal by a logical NOT operator.

2.3. The final toolbox

Now that both power part and controller are ready, the converter’s model can be grouped in a subsystem. In order to make the parameterization easier, a mask was made for the obtained converter model. The final toolbox which will be used in simulations is presented in figure 8.
3. INVESTIGATION OF THE DESIGNED CONVERTER TOOLBOX

In this paper, only the examination in simple line conditioning (line-friendly) operation mode will be presented. Therefore, the conditioning signal input will be a constant 0. Because of the switching elements, the traditional solvers like ode2 can not be used. Only stiff solvers are applicable like ode23tb or ode15s.

In the followings, it will be presented and discussed the simulation results for the line-friendly operation mode of the converter. A 0.5s simulation time was considered with variable step size and ode15s solver.

Figure 9a presents the ac line current on the primary-side of the line transformer. Having a 250VA rated apparent power transformer with 230V RMS on the primary-side and taking into account that the converter works at half of its rated apparent power, it will result an rms current of 543.478mA RMS. On the secondary-side (figure 9b) we have a voltage of 48V RMS which will result in an rms current on the secondary of 2.604A RMS.

On the dc side, the voltage will appear modulated with a sine wave having 100Hz (figure 9c). This is why we need a band-stop filter tuned to this frequency.

After being filtered (figure 9d), this voltage will be compared with the reference voltage (in this case 100V), and then applied to the PI voltage controller. This controller gives the active current which will be limited to the converter’s peak rated current (figure 9e). Based on this active current, the synchronization signals and the line conditioning signal, the conditioning unit will give the reference current (figure 9f).

From this reference current, the bi-level hysteresis current controller will form the control signals which will control the switches of the H-bridge. Because the converter works in simple line conditioning mode (line-friendly operation), as expected, the power factor of the converter is unity (figure 9g). In other words, the converter acts like an active resistance from the point of view of the ac public mains. Most of the converters nowadays present this kind of operation mode.

4. CONCLUSIONS

In this paper it has been presented the design of a Matlab/Simulink/Sim-Power-Systems toolbox for a PWM ac-to-dc converter provided with active line conditioning capabilities. It has been shown that the new Sim-Power-Systems toolbox offers the possibility of a more close to power electronics engineering approach to simulations.

It has been described in detail, step by step the building-up of a combined Matlab Simulink and SimPowerSystems model of a toolbox for PWM ac-to-dc converter provided with active line conditioning capabilities. Simulations made in order to verify the model have proven its operation and validity. However, only simple line conditioning (line friendly) operation mode has been considered in this paper.

This toolbox will be applied in future simulations, more complex ones, which will be made to investigate the performances of these types of converters when connected to a power distribution network model.

REFERENCES


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Fig. 9. Simulation results.
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