Modeling and Simulation of a Multiphase Diode Bridge Rectifier

Davide Tebaldi[1] and Roberto Zanasi[2]

Abstract— In this paper, an analytical approach for modeling a multiphase diode bridge rectifier suitable for control purposes is presented. The model has been implemented in Matlab/Simulink by means of a function performing the AC/DC current conversion and takes into account the main non-idealities of semiconductor diodes, such as the turn-on voltage and the on/off resistances. The developed Matlab function makes the simulation of the multiphase diode bridge rectifier very straightforward and its effectiveness has been tested by comparing the simulation results with those obtained by using the rectifier model provided by the PLECS circuit simulator.

I. INTRODUCTION

When dealing with multiphase power sources, an important component is represented by the diode bridge rectifier, namely a device which is able to perform an AC/DC current conversion. In a typical hybrid architecture in the automotive and agricultural fields, such device plays a fundamental role in performing the conversion from the mechanical energy generated by an ICE (Internal Combustion Engine) into the electric energy to be stored in an energy-storage device, such as a capacitor. In these cases, the rectifier performs the AC/DC conversion on the phase currents of an electric machine working as a generator driven by the ICE.

For the design of power electronics components, several simulation platforms are available allowing to perform very accurate simulations of such devices thanks to a deep parametrization of the involved physical elements themselves. However, the simulations performed with these platforms are usually quite slow and heavy, due to the large number of parameters to be taken into account. For this reason, the models made available by such platforms are not meant for control engineers, who need to make very fast simulations with models which are as simple and as flexible as possible, in order to develop and test different control strategies for the architecture in an effective manner.

An analytical description of the working mechanism of a three-phase diode rectifier is performed in [1]. The typical approach for performing the modeling is through the use of switching functions, see [2], [3], [4], [5] and [6].

The objective of this paper is to provide the reader with an analytical approach for modeling a multiphase diode bridge rectifier which is very well suitable for control purposes, since the model can be connected to a multiphase power source characterized by any number of phases. By referring to a typical application involving an electric machine, the multiphase feature represents quite a significant advantage,

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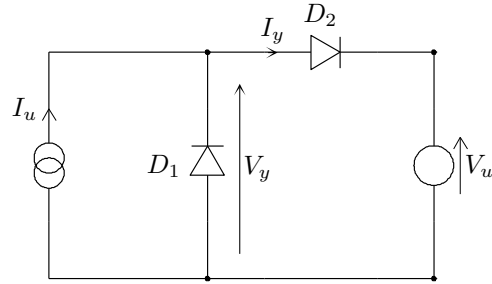
Fig. 1. Electric circuit of the single-phase, half-wave rectifier.

as one could easily switch from a three-phase to a multiphase motor depending on the needs by using the same rectifier model, which automatically adapts itself to the number of phases of the input power source. Using a motor with a larger number of phases brings several advantages during the AC/DC conversion, namely a significant reduction in terms of current and voltage ripples, which in turn reduce the stress placed on the capacitor when filtering, thus extending its life.

In this paper, the presented rectifier model is tested in two different simulative scenarios: the first one shows that the simulation results obtained in Matlab/Simulink by using the presented rectifier model coincide with those obtained by using the rectifier model available from the PLECS circuit simulator, showing the effectiveness of the presented modeling solution. The second simulation shows that the presented rectifier model works effectively also when employed to perform the AC/DC conversion on the output currents of a three-phase generator, modeled by using the Power-Oriented Graphs (POG) modeling technique [7]-[8].

II. DIODE RECTIFIER MODELING

An effective way of modeling the multiphase diode bridge rectifier consists in:

1) Derivation of the single-phase diode rectifier model;
2) Extension of the diode rectifier model to the multiphase case;

This section is focused on step 1): reference is therefore made to the single-phase, semiconductor-based rectifier shown in Fig. 1. Variables I_u, V_u, I_y, V_y are the input current, the input voltage, the current flowing through diode D_2 and the voltage across diode D_1, respectively. The two diodes D_1 and D_2 can be replaced by two equivalent nonlinear resistors $R_1(I_1)$ and $R_2(V_2)$, see Fig. 2. The two nonlinear functions $V_y(I_1)$ and $I_y(V_2)$ are:

$$V_y(I_1) = V_T \ln\left(\frac{I_1}{I_0} + 1\right), \quad I_y(V_2) = I_0\left(e^{\frac{V_2}{V_T}} - 1\right) \quad (1)$$
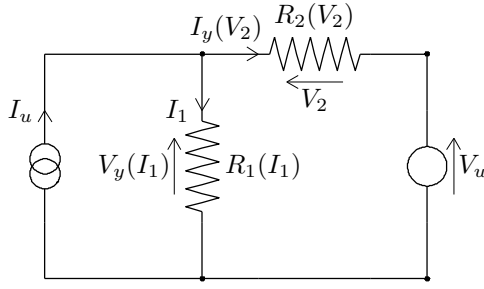
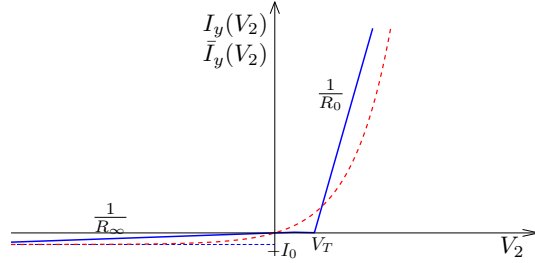Fig. 2. Equivalent electric circuit of the single-phase, half-wave rectifier.

Fig. 4. POG block scheme of the electric circuit shown in Fig. 2.

Fig. 3. Real and simplified input-output characteristics $I_y(V_2)$ and $\bar{I}_y(V_2)$ of diode D_2.

a) Forward biased ($V_2 > V_T$)   b) Reverse biased ($V_2 \leq V_T$)

Fig. 5. Simplified linear models of diode D: forward biased in case a) and reverse biased in case b).

where I_0 is the reverse saturation current flowing through the diode at large reverse bias and V_T is the turn-on voltage of the diode, which is a function of the device temperature and can be assumed to be equal to $0.6\,V$ for a Si PN diode at room temperature. The nonlinear function $I_y(V_2)$ defined in (1) describing the input-output (V_2, I_y) characteristic of diode D_2 is shown in red dashed line in Fig. 3. Note that the nonlinear function $V_y(I_1)$ defined in (1) describing the input-output (V_y, I_1) characteristic of diode D_1 is simply the inverse of function $I_y(V_2)$.

The POG block scheme of the electric circuit reported in Fig. 2 is shown in Fig. 4. The basic properties of the POG modeling technique can be found in [7]. Note that the block scheme shown in Fig. 4 is characterized by the presence of a non linear algebraic loop which cannot be easily solved. To cope with this problem, the nonlinear function $I_y(V_2)$ of diode D_2 can be substituted by the following piecewise linear function:

$$\bar{I}_y(V_2) = \begin{cases} \dfrac{V_T}{R_\infty} + \dfrac{V_2 - V_T}{R_0} & \text{for} \quad V_2 > V_T \\[3mm] \dfrac{V_2}{R_\infty} & \text{for} \quad V_2 \leq V_T \end{cases} \quad (2)$$

where R_∞ is a very high resistance value describing the off resistance of diode D_2 and R_0 is a very low resistance value representing the on resistance of diode D_2. The simplified function $\bar{I}_y(V_2)$ is shown in blue line in Fig. 3. A similar piecewise linear approximation $\bar{V}_y(I_1)$ can also be made for the real nonlinear function $V_y(I_1)$ describing the input-output characteristic of the diode D_1.

The approximated piecewise linear functions in (2) correspond to the two electric bipoles shown in Fig. 5: model a) can be used when the diode is forward biased, that is
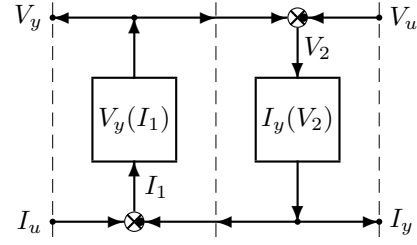
when $V_2 > V_T$, and model b) can be used when the diode is reverse biased, that is when $V_2 \leq V_T$. The forward biased model a) consists of a voltage generator V_T in series with a resistor R_0 representing the on resistance of the diode. The reverse biased model b) consists of a resistor R_∞ describing the off resistance of the diode.

By using the two simplified models shown in Fig. 5, the electric circuit reported in Fig. 1 can always be described by using one of the following three simplified circuits:

A) *Diode D_1 is reverse biased and diode D_2 is forward biased.* This case happens, see Fig. 6, when current I_u satisfies the condition $I_u > I_\gamma$ where I_γ is defined as follows:

$$I_\gamma = \frac{V_u + V_T}{R_\infty}. \quad (3)$$

Note: the expression of I_γ in (3) can be computed by applying the Kirchhoff voltage and current laws to the circuit in Fig. 6 at the very initial moment when D_1 becomes reverse biased and D_2 becomes forward biased, i.e. when current $I_y \approx 0$ is negligible. Diode D_1 is reverse biased and therefore is modeled using the bipole R_∞ in Fig. 5.b. Diode D_2 is forward biased and therefore is modeled using the bipole V_T-R_0 in Fig. 5.a. One can easily verify that the state-space equations of the electric circuit shown in Fig. 6 are the following:

$$\begin{bmatrix} V_y \\ I_y \end{bmatrix} = \begin{bmatrix} \dfrac{R_0 R_\infty}{R_0 + R_\infty} & \dfrac{R_\infty}{R_0 + R_\infty} \\[3mm] \dfrac{R_\infty}{R_0 + R_\infty} & -\dfrac{1}{R_0 + R_\infty} \end{bmatrix} \begin{bmatrix} I_u \\ V_u \end{bmatrix} + \begin{bmatrix} \dfrac{R_\infty}{R_0 + R_\infty} \\[3mm] -\dfrac{1}{R_0 + R_\infty} \end{bmatrix} V_T \quad (4)$$

B) *Diode D_1 is forward biased and diode D_2 is reverse biased.* This case happens, see Fig. 7, when current I_u satisfies the condition $I_u < -I_\gamma$, with I_γ defined in (3). Diode D_1 is forward biased and therefore is modeled using the bipole V_T-R_0 in Fig. 5.a. Diode D_2 is reverse
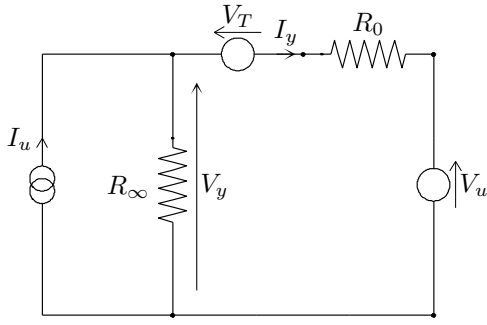
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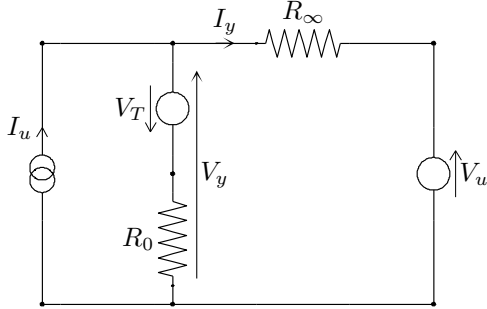Fig. 6. Simplified circuit A) when diode D_1 is reverse biased and diode D_2 is forward biased.

Fig. 7. Simplified circuit B) when diode D_1 is forward biased and diode D_2 is reverse biased.

Fig. 8. Simplified circuit C) when both diodes D_1 and D_2 are reverse biased.

TABLE I
PARAMETERS FOR PLOTS IN FIG. 10 AND 11.

R_∞	Diode off resistance	10 [Ω]
R_0	Diode on resistance	0.1 [Ω]
V_T	Diode turn-on voltage	0.6 [V]
I_u	Input current	$I_u \in [-10; 10]$ [A]
V_u	Input voltage	10 [V]

biased and therefore is modeled using the bipole R_∞ in Fig. 5.b. The state-space equations of the electric circuit shown in Fig. 7 are the following:

$$\begin{bmatrix} V_y \\ I_y \end{bmatrix} = \begin{bmatrix} \frac{R_0 R_\infty}{R_0 + R_\infty} & \frac{R_0}{R_0 + R_\infty} \\ \frac{R_0}{R_0 + R_\infty} & -\frac{1}{R_0 + R_\infty} \end{bmatrix} \begin{bmatrix} I_u \\ V_u \end{bmatrix} + \begin{bmatrix} -\frac{R_\infty}{R_0 + R_\infty} \\ -\frac{1}{R_0 + R_\infty} \end{bmatrix} V_T \quad (5)$$

C) *Both diodes D_1 and D_2 are reverse biased.* This case happens, see Fig. 8, when current I_u satisfies the condition $|I_u| < I_\gamma$, with I_γ defined in (3). Both D_1 and D_2 are reverse biased and therefore they are both modeled using the bipole R_∞ shown in Fig. 5.b. The state-space equations of the electric circuit shown in Fig. 8 are the following:

$$\begin{bmatrix} V_y \\ I_y \end{bmatrix} = \begin{bmatrix} \frac{R_\infty}{2} & \frac{1}{2} \\ \frac{1}{2} & -\frac{1}{2 R_\infty} \end{bmatrix} \begin{bmatrix} I_u \\ V_u \end{bmatrix} \quad (6)$$

Note that this modeling approach is applicable when there are no additional physical elements in between diode D_2 and voltage generator V_u, see Fig. 1.

III. DIODE RECTIFIER: IMPLEMENTATION IN MATLAB

This section addresses the extension of the single-phase diode rectifier model to the multiphase case, namely step 2) introduced at the beginning of Sec. II, and its implementation in Matlab/Simulink by means of the developed function `Rectifier` shown in Fig. 9. This function generates the output power variables V_y and I_y of the diode rectifier as a function of the input power variables I_u and V_u. The
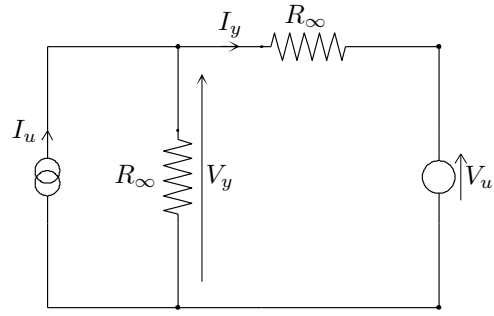
parameters of the diode passed to the `Rectifier` function by means of the `Diode` structure are the following: the on-resistance R_0, the off-resistance R_∞ and the turn-on voltage V_T. It is important to notice that the definition of these parameters is up to the user, making it possible to simulate different types of diodes having different characteristics. The function has a *multiphase* structure, meaning that it can be used with any number of input phases. The dimension of input power variable I_u indicates the number of phases that are employed, and is used to determine the dimension of output power variables I_y and V_y, accordingly. An "if-else" structure is used to identify which model, among the A), B) and C) ones reported in Sec. II, has to be used in order to employ the correct state-space equations. A "for" loop is then used to cycle over the number of phases of the considered system.

The outputs V_y and I_y of function `Rectifier`, when using the parameters reported in Tab. I, are shown in Fig. 10 and Fig. 11. The voltage $V_y(I_u)$ across diode D_1 as a function of current I_u is shown in Fig. 10, and the current $I_y(I_u)$ flowing through diode D_2 as a function of current I_u is shown in Fig. 11. Note that the blue, green and red segments shown in Fig. 10 and Fig. 11 correspond to the A, B and C models described in the previous section, respectively. One can easily verify that the slopes $\alpha_1, \beta_1, \delta_1, \alpha_2, \beta_2, \delta_2$ present in Fig. 10 and Fig. 11 have the following values:

$$\begin{cases} \alpha_1 = \frac{R_0 R_\infty}{R_0 + R_\infty} \simeq R_0 \\ \beta_1 = \frac{R_0 R_\infty}{R_0 + R_\infty} \simeq R_0 \\ \delta_1 = \frac{R_\infty}{2} \end{cases} \qquad \begin{cases} \alpha_2 = \frac{R_\infty}{R_0 + R_\infty} \simeq 1 \\ \beta_2 = \frac{R_0}{R_0 + R_\infty} \simeq \frac{R_0}{R_\infty} \\ \delta_2 = \frac{1}{2} \end{cases}$$

Note that the values reported in Tab. I for resistances R_0 and R_∞ do not represent a real case and have been chosen in order to obtain nice behaviors for the $V_y(I_u)$ and $I_y(I_u)$ functions reported in Fig. 10 and Fig. 11.

```
function [Iy, Vy] = Rectifier(Iu,Vu,Diode)
R_0   = Diode.R0;      % diode on resistance
R_inf = Diode.Rinf;    % diode off resistance
VT    = Diode.VT;      % diode turn-on voltage
%
Iy    = zeros(length(Iu),1);
Vy    = zeros(length(Iu),1);
%
for ii=1:length(Iu)    % cycling over the number of phases
    if Iu(ii)<(-(Vu+VT)/R_inf)      % D1 on D2 off
        Vy(ii)=(Iu(ii)*R_inf+Vu)*R_0/(R_0+R_inf)...
            -VT*R_inf/(R_0+R_inf);
        Iy(ii)=(Iu(ii)*R_0-Vu-VT)/(R_0+R_inf);
    elseif Iu(ii)<((Vu+VT)/R_inf)   % D1 off D2 off
        Vy(ii)=(Iu(ii)*R_inf+Vu)/2;
        Iy(ii)=(Iu(ii)*R_inf-Vu)/(2*R_inf);
    else                            % D1 off D2 on
        Vy(ii)=(Iu(ii)*R_0+Vu+VT)*R_inf/(R_0+R_inf);
        Iy(ii)=(Iu(ii)*R_inf-Vu-VT)/(R_0+R_inf);
    end
end
```

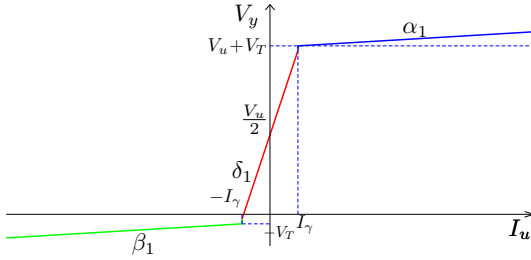Fig. 9. Matlab function `Rectifier` modeling the diode rectifier.

Fig. 10. Output voltage V_y as a function of current I_u.

Fig. 11. Output current I_y as a function of current I_u.

IV. SIMULATION EXAMPLES

A. Example 1: a three-phase rectifier

Let us refer to a three-phase rectifier, where the input power variable I_u and the output power variables I_y and V_y are three-dimensional. The considered system is shown in the Simulink block schemes reported in Fig. 12 and Fig. 13: three independent inductors, described by self inductance matrix $\mathbf{L}_g = \mathrm{diag}(L_i)$, are connected to a three-phase rectifier. Additionally, a capacitor C is used to store the electric energy and the resistor R placed in parallel to capacitor C is used as a load. The Simulink block scheme reported in Fig. 13 shows the inner details of the "Diode Bridges" subsystem present in Fig. 12. The "Rectifier" Matlab block present in Fig. 13 contains the Matlab function `Rectifier` reported in Fig. 9.

The considered system has been simulated in Matlab/Simulink using the parameters and the initial conditions reported in Tab. II. The obtained simulation results are reported in Fig. 14 and Fig. 15. The upper subplot of Fig. 14 shows the time behavior of the three components of the input current vector I_u. The lower subplot of Fig. 14 shows the time behavior of the three components of the output voltage vector V_y. Note that Fig. 14 shows the behavior of the rectifier both when it operates in continuous conduction mode (CCM) and when it operates in discontinuous conduction mode (DCM). The discrimination about the rectifier operating mode has been made as described in [9]. The
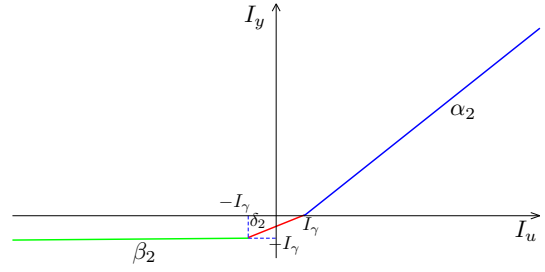
red dashed line in the upper subplot of Fig. 15 shows the time behavior of the voltage V_c across capacitor C. The red dashed line in the lower subplot of Fig. 15 shows the time behavior of the rectified current I_{rect} entering capacitor C. The obtained simulation results show a settling time $T_s \simeq 0.8$ s for the considered system.

The same three-phase rectifier has also been modeled and simulated by means of the PLECS circuit simulator using the same parameters and initial conditions as those reported in Tab. II. The PLECS block scheme of the considered system is shown in Fig. 16. The simulation results obtained using PLECS are very similar to those obtained in Matlab/Simulink. The time behaviors of the voltage V_c and of the rectified current I_{rect} obtained with PLECS are shown in blue line in the upper and lower subplots of Fig. 15, respectively. From this figure, one can easily verify that the difference between the simulation results obtained in Matlab/Simulink and in PLECS is very little: the obtained maximum percentage differences on voltage V_c and on rectified current I_{rect} are about 0.0555% and 1.7338%, respectively. As for the simulation time, the simulation performed with PLECS is slightly faster than the simulation performed with Matlab/Simulink using the developed function in Fig. 9, but still on the same order of magnitude.

The good matching between the simulation results obtained in Matlab/Simulink and in PLECS, together with the similar simulation time, denote the effectiveness of the Matlab function "Rectifier" proposed in the previous section and reported in Fig. 9 for modeling a multiphase diode rectifier in the Matlab/Simulink environment.

B. Example 2: automotive generator with rectifier

Let us consider the automotive physical system shown in the Simulink block scheme of Fig. 17 composed of an ICE, a three-phase synchronous electric motor working as a generator, a three-phase rectifier and a capacitor C. This system has been simulated in Matlab/Simulink using the parameters and the input signals reported in Tab. III and starting from zero initial conditions. The obtained simulation results are reported in Fig. 18, Fig. 19 and Fig. 20.

The upper subplot of Fig. 18 shows the three phase currents $\mathbf{I}_g$ provided as output by the electric generator, which are also the input I_u of the Matlab function `Rectifier`. The lower subplot of Fig. 18 shows the three input voltages $\mathbf{V}_g$ of the electric generator, which are also the output V_y
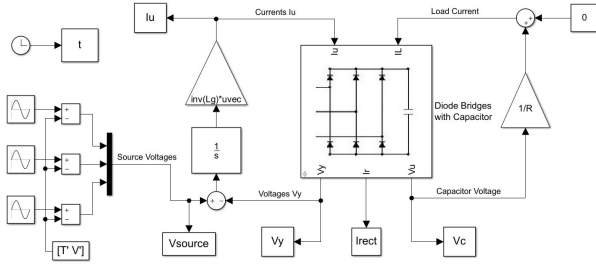
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Fig. 12. Simulink block scheme of the considered system: three independent inductors, a three-phase rectifier and a load resistor R.
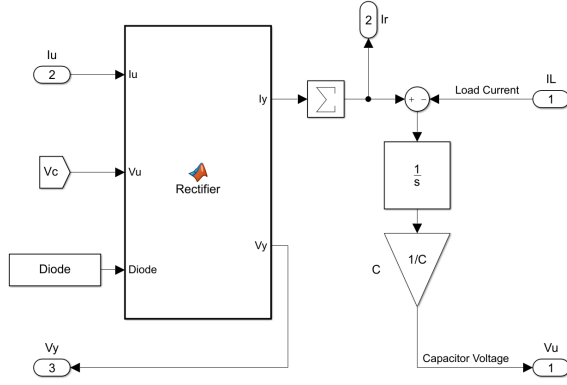

Fig. 13. Simulink block scheme of the "Diode Bridges" subsystem in Fig. 12.

TABLE II
PARAMETERS USED FOR THE SIMULATION OF SYSTEM IN FIG. 12.

V_{pk}	Max source voltages value	100 [V]
f_{in}	Source voltages frequency	25 [Hz]
L_i	Phase inductors ($i \in \{1, 2, 3\}$)	8.2 [mH]
C	Smoothing capacitance	0.2 [F]
R	Load Resistor	10 [Ω]
V_{c0}	Initial capacitor voltage	50 [V]
$\mathbf{I}_0$	Initial inductor currents	[0 0 0] [A]
V_T	Diode turn-on voltage	0.6 [V]
R_{inf}	Diode off resistance	10 [kΩ]
R_0	Diode on resistance	0.1 [mΩ]

TABLE III
PARAMETERS USED FOR THE SIMULATION OF THE SYSTEM IN FIG. 17.

| m	Number of generator phases	3
p	Number of polar expansions	1
N_c	Number of coils for each phase	30
L_i	i-th self-inductance cnfficient	0.01 [H]
M_0	ij-th mutual inductance coefficient	0.008 [H]
R_{si}	i-th stator phase resistance	1 [Ω]
J_g	Rotor inertia momentum	0.48 [kg m^2]
b_g	Rotor linear friction coefficient	0.08 [$\frac{\text{Nm s}}{\text{rad}}$]
Φ_r	Maximum value of the rotor flux	0.2 [W]
K_p	ICE speed regulator gain	1000
T_{max}	Maximum torque the ICE can provide	1000 [Nm]
C	Smoothing capacitance	0.1 [F]
W_{des}	Desired generator speed	200 [rpm]
V_T	Diode turn-on voltage	0.6 [V]
R_{inf}	Diode off resistance	10 [kΩ]
R_0	Diode on resistance	0.1 [mΩ]
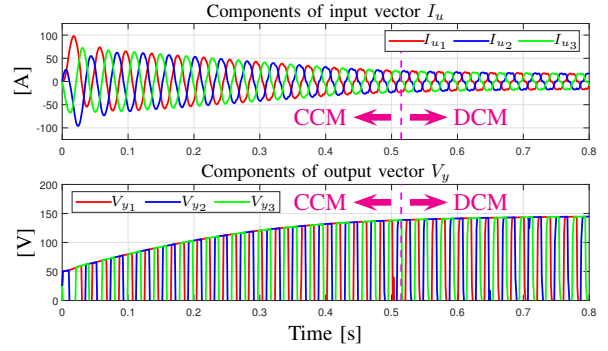
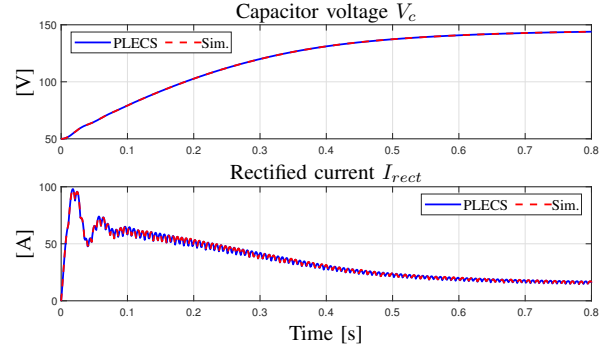Fig. 14. Currents I_{u_i} and voltages V_{y_i}, $i \in \{1, 2, 3\}$.

Fig. 15. Voltage V_c and current I_{rect}: PLECS vs Matlab/Simulink.

of the Matlab function `Rectifier`. The red dashed line in Fig. 19 shows the generator resistive torque T_g, the blue line in Fig. 19 shows the motive torque T_{ice} provided by the ICE to the generator in order to take it to the desired speed target W_{des}. The upper and lower subplots of Fig. 20 show the voltage V_c across capacitor C and the rectified current I_{rect} entering the capacitor, respectively.

The obtained simulation results show that, at the beginning of the simulation, voltage V_c across capacitor C is sufficiently low and thus all the three phase currents $\mathbf{I}_g$ are different from zero, i.e. all the three branches of the diode rectifier are in conduction denoting its operation in CCM. As the simulation goes by and the capacitor gets charged, voltage V_c increases until it reaches a point where only the difference between the highest phase voltage and the lowest phase voltage is greater than $V_c + 2V_T$, meaning that the third phase current must be equal to zero as the corresponding branch of the diode rectifier is not in conduction, therefore the rectifier starts working in DCM.
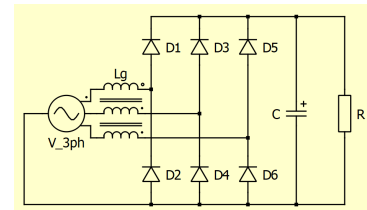

Fig. 16. PLECS block scheme of the considered system: three independent inductors, a three-phase rectifier, a capacitor C and a load resistor R.
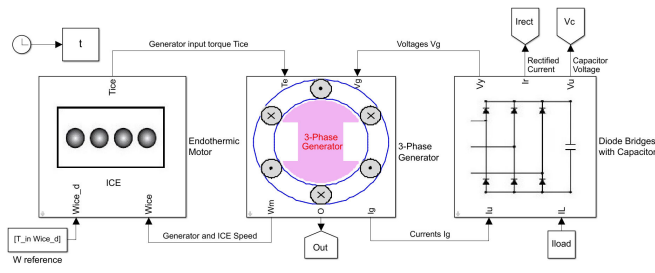
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Fig. 17. Simulink implementation of the system composed of: ICE - Three-Phase Synchronous Generator - Rectifier - Capacitor.
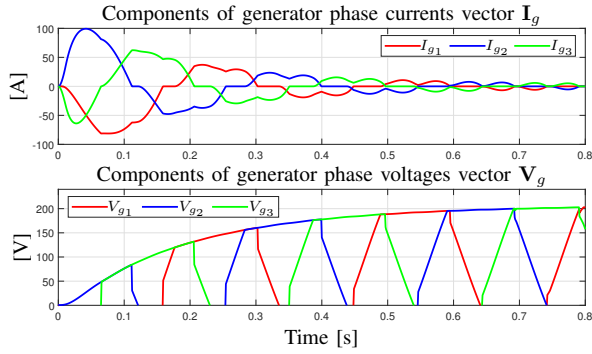

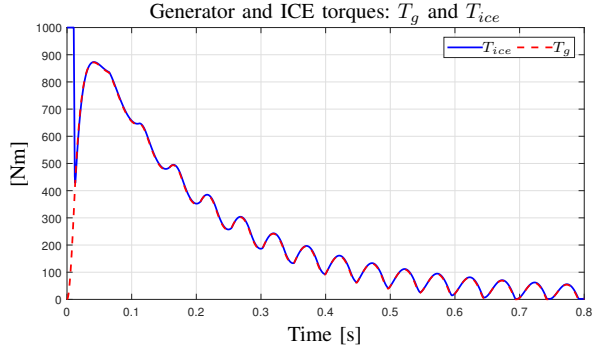Fig. 18. Currents I_{g_i} and voltages V_{g_i}, $i \in \{1, 2, 3\}$.

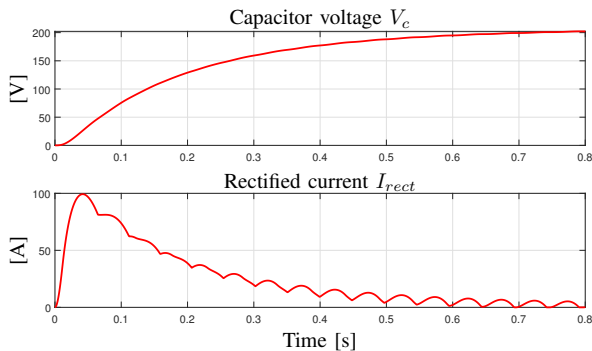Fig. 19. Generator resistive torque T_g and ICE torque T_{ice}.

Fig. 20. Voltage V_c (i.e. V_u of the rectifier) and current $I_{rect} = \sum_{i=1}^{3} I_{y_i}$.

Finally, from Fig. 19 and Fig. 20, one can appreciate the relation of direct proportionality between the generator resistive torque T_g and the rectified current I_{rect}.

V. CONCLUSIONS

In this paper, the modeling of a multiphase diode rectifier has been addressed. The presented model allows to easily simulate a multiphase diode rectifier, that is a device able to work with any number of phases depending on the input circuit connected to it, and accounting for the diode main non-idealities as well. The presented model has been implemented in Matlab/Simulink by means of a Matlab function named Rectifier. Two simulation examples have been presented in this paper. The first example takes into account a three-phase diode rectifier: the system has been modeled and simulated using both the Matlab/Simulink environment and the PLECS circuit simulator. The good matching between the two simulation results denotes the effectiveness of the proposed diode rectifier model. The second simulation example shows how the proposed multiphase rectifier model can be easily and directly inserted in a system composed of an ICE, a generator, a rectifier and a capacitor, that is a typical recharge structure which is often used in automotive hybrid architectures.

REFERENCES

[1] A. Di Gerlando, G. M. Foglia, M. F. Iacchetti, and R. Perini, "Comprehensive steady-state analytical model of a three-phase diode rectifier connected to a constant DC voltage source", IET Power Electronics, vol. 6, no. 9, pp. 1927-1938, Nov. 2013.

[2] G. D. Marques, "A Simple and Accurate System Simulation of Three-Phase Diode Rectifiers", Proceedings of IEEE 24th Annual Conference of the Industrial Electronics Society (IECON), Aachen, Germany, 1998.

[3] O. Ojo and O. Omozusi, "Modeling and Analysis of an Interior Permanent-Magnet DC-DC Converter Generator System", Proceedings of IEEE 28th Annual Power Electronics Specialists Conference (PESC), Saint Louis, MO, USA, 1997.

[4] A. Scacchioli, G. Rizzoni, M. A. Salman, W. Li, S. Onori, and X. Zhang, "Model-based Diagnosis of an Automotive Electric Power Generation and Storage System", IEEE Trans. Syst. Man Cybern. Syst., vol. 44, no. 1, pp. 72-85, Jan. 2014.

[5] M. Kesler, E. Ozdemir, M. C. Kisacikoglu, and L. M. Tolbert, "Power Converter-Based Three-Phase Nonlinear Load Emulator for a Hardware Testbed System, IEEE Trans. Power Electron., vol. 29, no. 11, pp. 5806-5812, Nov. 2014.

[6] A. Di Gerlando, G. Foglia, M. Iacchetti, and R. Perini, "Analytical Model and Implementation by Equations of Three-Phase Diode Bridge Rectifiers Operation", Proceedings of XIX International Conference on Electrical Machines (ICEM), Rome, Italy, 2010.

[7] R. Zanasi, "The Power-Oriented Graphs Technique: system modeling and basic properties", Proceedings of IEEE Vehicle Power and Propulsion Conference (VPPC), Lille, France, 2010.

[8] M. Fei, R. Zanasi, and F. Grossi, "Modeling of Multi-phase Permanent Magnet Synchronous Motors under Open-phase Fault Condition", Proceedings of IEEE International Conference on Control and Automation (ICCA), Santiago, Chile, 2011.

[9] V. Caliskan, D. J. Perreault, T. M. Jahns, and J. G. Kassakian "Analysis of Three-Phase Rectifiers With Constant-Voltage Loads", IEEE Trans. Circuits Syst., vol. 50, no. 9, pp. 1220-1226, Sept. 2003.