

Modeling and Nonlinear Control of a Wind Turbine System Based on a Permanent Magnet Synchronous Generator Connected to the Three-phase Network

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ABSTRACT

This article presents nonlinear control of wind conversion chain connected to the grid based on a permanent magnet synchronous generator. The control objectives are threefold; i) forcing the generator speed to track a varying reference signal in order to extract the maximum power at different wind speed (MPPT); ii) regulating the rectifier output capacitor voltage; iii) reducing the harmonic and reactive currents injected in the grid. This means that the inverter output current must be sinusoidal and in phase with the AC supply voltage (PFC). To this end, a nonlinear state-feedback control is developed, based on the average nonlinear model of the whole controlled system. This control strategy involves backstepping approach, Lyapunov stability and other tools from theory of linear systems. The proposed state-feedback control strategy is tested by numerical simulation which shows that the developed controller reaches its objectives.

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1. INTRODUCTION

In this work, we have interested wind energy. Till now, there are two types of wind turbines: the wind speed fixed directly connected to the grid by the stator and variable speed wind turbines commissioned by the stator and the rotor by means of electronic power converters [1]. Thanks to the numerous advantages it has compared to other types of electrical machines (robustness, maintenance, price), the permanent magnet synchronous machine is interesting for use as a generator coupled to a wind turbine [2], [3], [4].

In this article, we will look at the study of a complete chain of wind energy conversion shown in Figure 1 which includes a synchronous permanent magnet generator that converts wind energy into an output voltage whose amplitude and frequency vary depending on the wind speed and AC/DC/AC converters which connects of the generator and the network via a LCL filter.

In order, nonlinear or having non-constant parameters systems, conventional control laws may be inadequate because they are not strong especially when the demands on accuracy and other dynamic characteristics of the systems are strict. We must use control laws insensitive to parameter variations, to disturbance and nonlinearities. For this purpose, several tools are available in the literature, such as proportional integral (PI) controllers [5], [6], [7]. this mode of control is insufficient to control of such complex system where the parameters are not stable over time, other research interested by advanced method

like sliding mode [8], [9]. but also, this technique shows a chattering phenomenon which has a negative effect in the mechanical part of the machine, moreover, platitude approach is described in another article [10].

In this article, we present a backstepping to control power converters associated with the generator. The Backstepping approach is a systematic and recursive design methodology for nonlinear feedback control [11]. The control to apply in different parts of the system. The generator-side converter is mainly used to control the generator speed to extract the maximum output power at various wind speeds [12], [13], the network-side converter is mainly used to control the reactive power on the one hand and maintain tension in the DC bus capacitor of the constant value and the make the current output of the inverter in the phase with the grid voltage.

The rest of the paper is organized as follows: the model mathematical of the whole system is presented by the equation of states in Section II; Section III describes in details the proposed control strategy based on backstepping approach for the system studied, while in Section IV gives simulation results demonstrating the good performance of the proposed method in MATLAB/Simulink, then a conclusion at the end of paper.

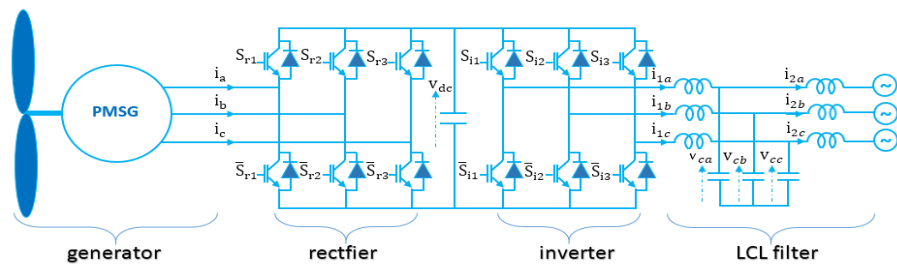


Figure 1. Architecture of the Wind Power System

2. MODELING OF THE WIND SYSTEM

2.1. Generator Modeling

To simplify the system of equations with variable coefficients, a model in the Park reference of this machine will be used. The Park reference is simpler to manipulate because the electrical quantities evolve like continuous magnitudes. One can switch from one to the other marker using transit matrices.

Since the voltages are the input variables, the output quantities (currents) can be expressed as a function of these, the state model of the synchronous machine, expressed in the rotating d-q reference frame linked to the rotor, is the following [14]:

$$\dot{x}_1 = \frac{p\phi_f}{j}x_2 - \frac{f}{j}x_1 - \frac{1}{J}T_l \quad (1)$$

$$\dot{x}_2 = -\frac{R_s}{L_q}x_2 - p\frac{L_d}{L_q}x_1x_3 - p\frac{1}{L_q}\phi_fx_1 + \frac{1}{L_q}v_{dc}u_1 \quad (2)$$

$$\dot{x}_3 = -\frac{R_s}{L_d}x_3 + p\frac{L_d}{L_q}x_1x_2 + \frac{1}{L_d}v_{dc}u_2 \quad (3)$$

where: $x_1 = \bar{\Omega}$; $x_2 = \bar{i}_q$; $x_3 = \bar{i}_d$; x an averaging value over a cutting period of a real signal \bar{x} .

R_s resistance of the stator windings (L_d, L_q) are d and q axis inductances (i_d, i_q) are the dq components of the stator current, ϕ_f amplitude of the flux induced by the permanent magnets of the rotor in the stator phases, p number of pole pairs, j combined inertia of rotor and load, T_l shaft mechanical torque, f combined viscous friction of rotor and load, ω angular velocity of the rotor (v_d, v_q) denote the averaged stator voltage in dq- coordinate, these voltages are expressed in function of the corresponding control action:

$$\begin{bmatrix} v_d & v_q \end{bmatrix}^T = v_{dc} \begin{bmatrix} u_1 & u_2 \end{bmatrix}^T \quad (4)$$

2.2. Modeling the Inverter and Filter Association

After presenting the model of the machine, we will expose the complete drive system where the controlled inverter is associated with the LCL filter connected to the network [15], [16]:

$$\begin{bmatrix} \dot{x}_{4dq} \end{bmatrix} = -\frac{r_2}{L_2} \begin{bmatrix} x_{4dq} \end{bmatrix} + \frac{1}{L_2} \begin{bmatrix} x_{5dq} \end{bmatrix} - \frac{1}{L_2} \begin{bmatrix} v_{gdq} \end{bmatrix} + M_2 x_{4dq} \quad (5)$$

$$\begin{bmatrix} \dot{x}_{5dq} \end{bmatrix} = -\frac{1}{C} \begin{bmatrix} x_{6dq} \end{bmatrix} - \frac{1}{C} \begin{bmatrix} x_{5dq} \end{bmatrix} + C M x_{5dq} \quad (6)$$

$$\begin{bmatrix} \dot{x}_{6dq} \end{bmatrix} = -\frac{r_1}{L_1} \begin{bmatrix} x_{6dq} \end{bmatrix} + \frac{1}{L_1} \begin{bmatrix} u_{dq} \end{bmatrix} - \frac{1}{L_1} \begin{bmatrix} x_{5dq} \end{bmatrix} + M_1 x_{6dq} \quad (7)$$

$$\dot{x}_7 = \frac{1}{C_{dc}} (i_r - i_o) \quad (8)$$

where: $x_4 = \bar{i}_2$; $x_5 = \bar{v}_c$; $x_6 = \bar{i}_1$; $x_7 = \bar{v}_{dc}$; x an averaging value over a cutting period of a real signal \bar{x} .

$$\text{and } M_1 = L_1 M; M_2 = L_2 M; M = \begin{bmatrix} 0 & \omega \\ -\omega & 0 \end{bmatrix}$$

L_1 and L_2 the self-inductances r_1 and r_2 are its parasitic resistances, $(\dot{i}_{1d}, \dot{i}_{1q})$, $(\dot{i}_{2d}, \dot{i}_{2q})$ are the dq-components of the current flowing the inductors L_1 and L_2 respectively. (v_{cd}, v_{cq}) ; (v_{gd}, v_{gq}) , (v_{od}, v_{oq}) are the dq-components of the capacitor and grid voltage and in the output of inverter respectively. The inverter is featured by the fact that the grid d- and q-voltage can be controlled independently. In fact, one has:

$$\begin{bmatrix} v_{od} & v_{oq} \end{bmatrix}^T = v_{dc} \begin{bmatrix} u_d & u_q \end{bmatrix}^T \quad (9)$$

where: u_d , u_q represent the average d- and q-axis of the 3-phase duty ratio system (u_a, u_b, u_c) .

3. DESIGN CONTROL

3.1 Control Objectives

In this work, we are interested in ordering a wind energy conversion chain to produce electrical energy and inject it into the grid. To achieve this objective, the backstepping approach associated with the Lyapunov tools is used to guarantee the asymptotic stability of the closed loop system. From a control point of view, this is expressed into the following three objectives: i) Speed control: Force the speed of the generator to follow a reference signal varies. ii) PFC: the current injected into the network must be sinusoidal and in phase with the AC supply voltage. iii) Controlling the voltage v_{dc} of the DC bus voltage to a reference given v_{dcref} . This is usually set to a constant value equal to the nominal voltage of the inverter input.

3.2 Regulator Design for Synchronous Generator

The control strategy adopted uses cascaded loops, two internal loops for controlling the currents of axis d and q and an external loop for controlling the speed of the generator. Usually, the d-axis current must be regulated to zero in order to keep the flux constant in the air gap of the machine [17]. The q-axis current must track a reference signal from the external speed loop [18]. To solve this tracking problem, the following errors are defined:

$$e_1 = x_1^* - x_1 \quad (10)$$

$$e_2 = x_2^* - x_2 \quad (11)$$

$$e_3 = x_3^* - x_3 \quad (12)$$

Using the equations (1-3) we get the dynamics errors following:

$$\dot{e}_1 = x_1^* - \frac{p\phi_f}{j} x_2 - \frac{f}{j} x_1 - \frac{1}{J} T_l \quad (13)$$

$$\dot{e}_2 = x_2^* + \frac{R_s}{L_q} x_2 + p \frac{L_d}{L_q} x_1 x_3 + p \frac{1}{L_q} \phi_f x_1 - \frac{1}{L_q} v_{dc} u_1 \quad (14)$$

$$\dot{e}_3 = x_3^* + \frac{R_s}{L_d} x_3 - p \frac{L_d}{L_q} x_1 x_2 - \frac{1}{L_d} v_{dc} u_2 \quad (15)$$

Speed regulator: Consider the following Lyapunov function candidate $v_1 = \frac{1}{2} e_1^2$ its derivative is given by the following equation:

$$\dot{v}_1 = e_1 \dot{e}_1 = e_1 \left(x_1^* - \frac{p\phi_f}{j} x_2 - \frac{f}{j} x_1 - \frac{1}{J} T_l \right) \quad (16)$$

In order that the derivative of the test is still negative, it must take the derivative of the form $\dot{v}_1 = -c_1 e_1^2$, where $c_1 > 0$; is a positive design parameter introduced by the backstepping method, which must always be positive and non-zero to meet the stability criteria of Lyapunov function. Following the backstepping approach and in order to ensure the tracking speed stability, the virtual control x_2^* is chosen as follow:

$$x_2^* = \frac{j}{p\phi_f} \left(+ \frac{f}{j} x_1 + \frac{1}{J} T_l + x_1^* - c_1 e_1 \right) \quad (17)$$

To ensure the stability and convergence of component x_2 and its x_2^* Reference; we consider the second Lyapunov following function: $v_2 = v_1 + \frac{1}{2} e_2^2$, allowing to deduct the time derivative of the function Lyapunov;

$$\dot{v}_2 = \frac{j}{p\phi_f} e_1 e_2 - c_1 e_1 + e_2 \dot{e}_2 = -c_2 e_2^2 \quad ; c_2 \neq 0 \quad (18)$$

using (24), (30), we will select the law of command u_1 as follows:

$$u_1 = \frac{L_q}{v_{dc}} \left(x_2^* + \frac{R_s}{L_q} x_2 + p \frac{L_d}{L_q} x_1 x_3 + p \frac{1}{L_q} \phi_f x_1 - c_2 e_2 - \frac{i}{p\phi_f} e_1 \right) \quad (19)$$

Id regulator: We will define the 3rd Lyapunov function to ensure the stability of x_3 : $v_3 = \frac{1}{2} e_3^2$

using the 22, 25, 32 the control law is given by:

$$u_2 = \frac{L_d}{v_{dc}} \left(x_3^* + \frac{R_s}{L_d} x_3 - p \frac{L_d}{L_q} x_1 x_2 - c_3 e_3 \right) \quad (20)$$

3.3 PFC and DC Voltage Controller

A regulator will be designed in three steps Fig.2, so that the currents (x_{abc}) injected into the must be sinusoidal and in phase with the system of grid voltage. By applying the backstepping control method, the control law established using equations (5-8) of which u_d, u_q are the actual control inputs.

By choosing $[x_{4dq} x_{5dq} x_{6dq}]^T$ as state variables. We begin by defining the, tracking errors:

$$[e_{4dq}] = [x_{4dq}^*] - [x_{4dq}] ; [e_{5dq}] = [x_{5dq}^*] - [x_{5dq}] ; [e_{6dq}] = [x_{6dq}^*] - [x_{6dq}] \quad (21)$$

where $[x_{4dq}^*], [x_{5dq}^*], [x_{6dq}^*]$ is the reference signals (assumed bounded and sufficiently differentiable).

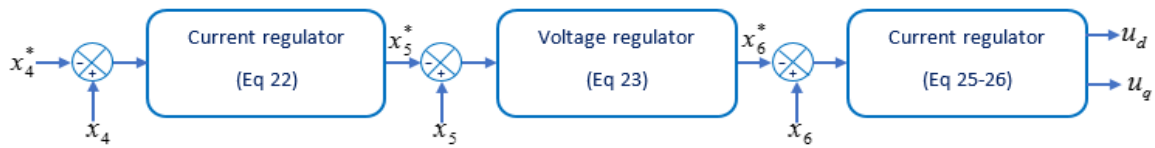


Figure 2. Block Diagram Grid-side Converter Control System

After choosing the two functions of Lyapunov and following the method of backstepping we define the two virtual commands

$$[x_{5dq}^*] = L_2 x_{4dq}^* - r_2 [x_{4dq}] - [v_{gdq}] + M_2 L_2 x_{4dq} - c_4 e_4 \quad (22)$$

$$[x_{6dq}^*] = C [x_{5dq}^*] + [x_{4dq}] - C M [x_{5dq}] - [c_{5dq}] [e_{5dq}] - \frac{1}{C} [e_{4dq}] \quad (23)$$

Where the design parameters quantity $[c_{4dq}]$ and $[c_{5dq}]$ is a symmetric positive definite matrix, are given by:

$$[c_{4dq}] = \begin{bmatrix} c_{4d} & 0 \\ 0 & c_{4q} \end{bmatrix} ; [c_{5dq}] = \begin{bmatrix} c_{5d} & 0 \\ 0 & c_{5q} \end{bmatrix} \quad (24)$$

3.4. Stabilization of Subsystem (18)

The third design step consists in choosing the actual control signals, u_d and u_q , so that all errors $[e_{4dq}]$, $[e_{5dq}]$ converge to zero. To this end, we should make how these errors depend on the actual control signals (u_d, u_q). We start focusing on $[e_{6dq}]$;

Using (7-23) following the backstepping approach, the control law for the system is given by:

$$u_d = -\frac{1}{v_{dc}} \left[r_1 x_{6d} - L_1 \omega x_{6q} + L_1 \dot{x}_{6d}^* - \frac{1}{L_1} e_{5d} - c_6 e_{6d} \right] \quad (25)$$

$$u_q = -\frac{1}{v_{dc}} \left[r_1 x_{6q} + L_1 \omega x_{6d} + L_1 \dot{x}_{6q}^* - \frac{1}{L_1} e_{5q} - c_6 e_{6q} \right] \quad (26)$$

4. SIMULATION AND DISCUSSION

The global control system described by Figure 3 is simulated using the Matlab/Simulink (V. R2015a), operating under Windows. The controlled part is a wind system including the synchronous generator and the association AC/DC/AC power converters via LCL filter. The involved elements have the

following characteristics: $c_1 = 140s^{-1}$; $c_2 = 9e^3 s^{-1}$; $c_3 = 220s^{-1}$; $c_4 = 9e2s^{-1}$; $c_5 = 9e^3 s^{-1}$, $c_6 = 9e^3 s^{-1}$

PMSG: $R_s = 0.425\Omega$; $L_d = L_q = 0.0084H$; $j = 0.02 \text{ Kg.m.m}$; $\phi_f = 0.433wb$; $p = 4$,

Network and filter: $v_n = 220V / 50Hz$; $L_1 = L_2 = 5e^{-3}H$; $r_1 = r_2 = 50e^{-3}\Omega$;

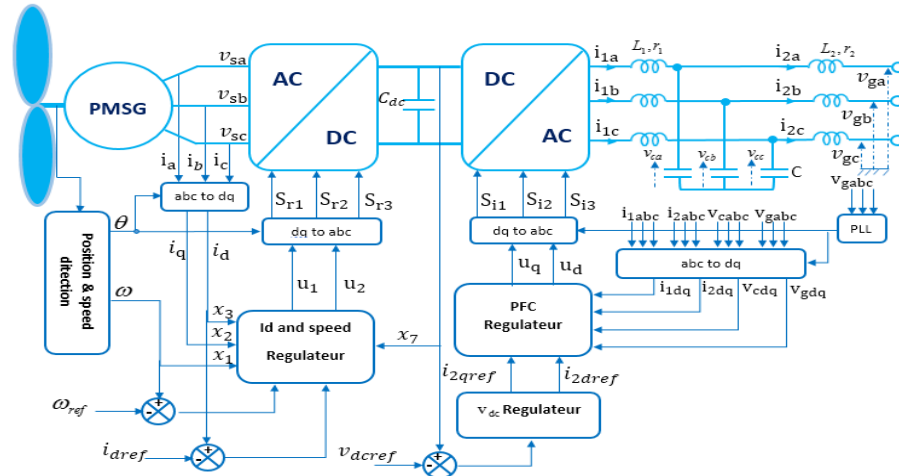


Figure 3. The General Structure Control Device of System

The performance of the regulator is evaluated by varying over time, the speed (Figure 4) and the setpoint of the DC voltage (Figure 8). The reference for the direct component of the stator current i_{sd} set to 0 (Figure 5).

Figures 4 and 5 respectively, shows the machine speed Ω and the d-component of the stator current i_d . The rotational speed of the generator ω does not change a lot of value, even we varied the reference in the 0.2 second it remains practically equal to the reference value Ω_{ref} and the value of the current i_{sd} perfectly converge to their respective reference and takes the value 0 initially fixed. Also, clearly notice in the transient regime the speed of the system with the regulator.

Figures 6 and 7 respectively, shows the q-component of the stator current i_q and the electromagnetic torque. The curve of the current i_{sq} tends to a constant value is of the same shape as that of the couple; it is deduced that the electromagnetic torque is directly proportional to the current i_{sq} presented in the Figure 7. Figures 8 and 9 respectively, shows represent the curve of the DC bus voltage v_{dc} for a reference v_{dc_ref} and the current i_2 inject into the network with the supply voltage.

In the Figure 8 the value of DC-link remains stable at a constant value to give as reference. Also, the current remains all time sinusoidal and in phase with the network voltage complying with the PFC requirement demonstrate by Figure 9 et 10. In the second 0.25 we have varied the reference of the voltage v_{dc} , it is noted that the voltage of the DC bus is enslaved quickly to its new reference, which shows the robustness of our regulator. The Figure 11, show the reactive power injected into the three - phase network (equal to zero) and the electrical power P produced by the machine transferred to the grid by the three-phase inverter.

From the simulation results obtained, for the wind energy system connected to the three-phase network, it can be noted from the first view, that the regulator based on the backstepping approach has a better performance than other regulator, such as directed flow control (FOC) [19], Linearization [20], Direct Torque Control (DTC) [21] and Sliding Mode approach [9], [22], especially in dynamic regime, when the controlled part is subjected to perturbations and variations of system parameters (our case), the algorithms of the classical [23] control using proportional, integral and derivative controllers remain incapable of control such nonlinear system. For so-called sophisticated control laws, there is a major problem which is the necessity of using a mechanical sensor (speed, load torque). This imposes an additional cost and increases the complexity of assemblies. For sliding-mode control, there are technological and physical limitations, such as switching delays or small-time constants at the actuator, which is why a Chatterring phenomenon appears on the sliding surface, this one characterizes by strong oscillations around the surface of commutation;

Where we can observe in all the figures presented in our simulations based on backstepping approach that the response time is very short so that the signals restored to the maximum values, so this rapid correction is of the speed or currents or voltages translated the continuation of our system and assured the performance of our regulator in the injection part the power to the network it is observed that our regulator respects the characteristics of our grid that it is the frequency or the phase, on the one hand, of on the other hand, the power injected into the network, we note that the reactive power tends towards a zero value and the active power reacts with the speed variation of the generator when the speed reaches the maximum the power is totally transmitted to the network.

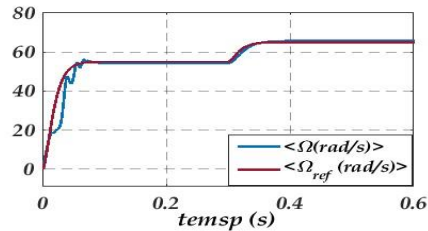


Figure 4. Rotor Speed (Rad/s) and its Reference

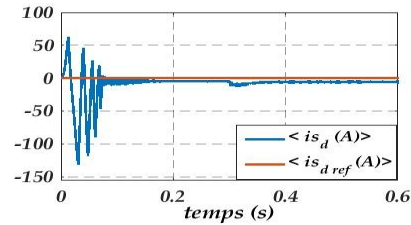
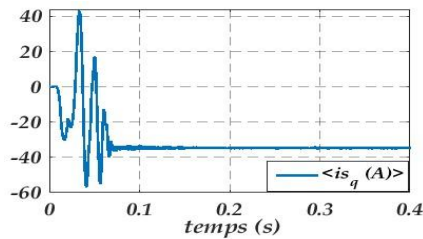
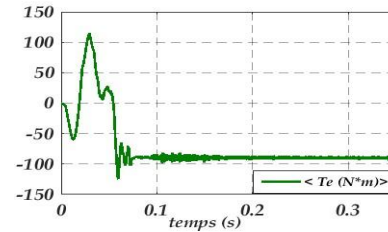
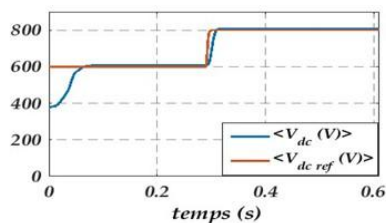
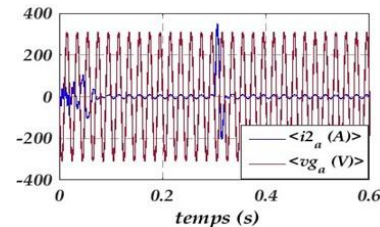
Figure 5. D'axis Stator Current i_d and its ReferenceFigure 6. Q'axis Stator Current i_q Figure 7. Electromagnetic Torque T_e Figure 8. DC-link Voltage v_{dc} 

Figure 9. Unitary Power Factor (P F C)

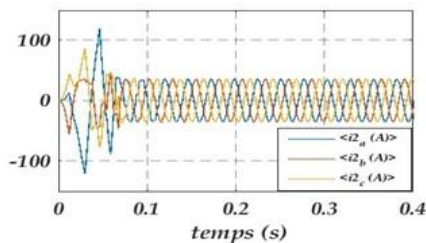
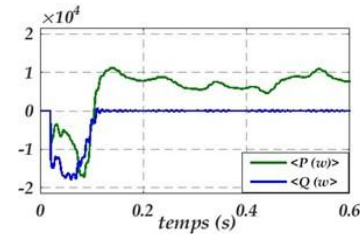
Figure 10. Output Current i_{2abc} 

Figure 11. Active and Reactive Power

5. CONCLUSION

In this paper, we have considered the problem of controlling the wind turbine synchronous generator connected to the power network through power electronic AC/DC/AC converters connected to the grid via LCL filter. The system dynamics have been described by the averaged 6th order nonlinear state-space model (1-3),(5-8). Based on such a model, the Lyapunov stability and averaging theory are used to design nonlinear controller defined by equations (19,20,27,28). the later guarantees quite interesting average performances; It is formally established that the control objectives are actually achieved in average with a quite satisfactory accuracy. Speed following his reference perfectly, the tracking quality is quite satisfactory as the response time is small after the change the wind speed, the current injected into the network remains sinusoidal all the time and in phase with the voltage of the network complying with the requirement PFC., the continuous bus DC-link follows a constant reference value. The formal results are confirmed by several simulations.

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