Passivity-Based Control of Tidal Turbine Based PMSG Using Interconnection and Damping Assignment Approach

Youcef Belkhier[1], Younes Sahri[1], Thiziri Makhlouf[1], Rabindra Nath Shaw[2], Mohit Bajaj[3], and Ankush Ghosh[4](✉)

[1] Laboratoire de Technologie Industrielle et de l'Information (LTII), Faculté de Technologie, Université de Bejaia, Bejaia, Algeria
{younes.sahri,thiziri.makhlouf}@univ-bejaia.dz
[2] Bharath Institute of Higher Education and Research, Chennai, India
[3] Department of Electrical and Electronics Engineering, National Institute of Technology Delhi, Narela, India
mohitbajaj@nitdelhi.ac.in
[4] The Neotia University, West Bengal, India
ankushghosh@ieee.org

Abstract. Marine current conversion systems with permanent magnet synchronous generator (PMSG) have several advantages over the renewable energies and is gradually replacing it in the industry. Non-linear equations describe the dynamics of the PMSG. It is subject to unknown external disturbances (load), and its parameters are variable in time. All these constraints make the control task complex. It requires non-linear controls that compensate for non-linearities, external disturbances, and parametric variations. This paper investigates an interconnection and damping assignment passivity-based control (IDA-PBC) h for the PMSG using the model represented in the dq-frame. Inherent advantages of the IDA-PBC method are that the non-linear properties are not canceled but compensated in a damped way. The proposed PBC is responsible for designing the system's desired dynamic. The efficiency of the suggested technique is investigated numerically using MATLAB/Simulink software.

Keywords: Passivity-based control · Tidal turbine · PMSG · Nonlinear control

1 Introduction

One of the most promising types of renewable energies is the tidal energy due to its high-power density and high potential of electricity generation. The use of PMSG in tidal turbine system has high potential due to its reliability, increased energy, reduced failure and possibility to eliminate the gearbox which lead to low maintenance and enable to the PMSG to be very favorable in wind applications. However, the controller computation for the PMSG is still challenging work, due to unknown modeling error, external disturbances and parameter uncertainties.

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This work provides a novel optimal passivity-based control (PBC). The IDA-PBC technique has the intrinsic advantage of compensating for non-linear features rather than canceling them. The proposed PBC is in charge of creating the system's intended dynamic, whereas the non-linear observer is in charge of reconstructing the recorded signals. In order to compel the PMSG to track speed [3]. The fundamental goal of this research is to synthesis the controller while taking into consideration the whole dynamic of the PMSG and making the system passive. It is accomplished by reorganizing the suggested strategy's energy and incorporating a damping component that treats the non-linear parts in a damped rather than deleted manner.

The present form organizes the present paper, the detailed about the case study is given in Sect. 2, and along the Sect. 3 we describe the suggested controller. Section 4 is devoted to GSC regulation. Section 5 reports the simulation results and their discussions by the application of IDA-PBC algorithm to model illustrated in Sect. 2. This paper has been completed by some conclusions and perspectives stated in Sect. 6.

2 System Design

2.1 Marine Current Turbine Model

The configuration of the investigated conversion system with Matlab/Simulink is presented in Fig. 1. The proposed strategy is applied to the PMSG to regulates the produced power via the generator [4]:

$$P_m = \frac{1}{2}\rho C_p(\beta, \lambda) A v^3 \tag{1}$$

$$T_m = \frac{P_m}{\omega_m} \tag{2}$$

$$C_p(\beta, \lambda) = \frac{1}{2}\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right) e^{-\left(\frac{21}{\lambda_i}\right)} \tag{3}$$

$$\lambda_i^{-1} = (\lambda + 0.08\beta)^{-1} - 0.035\left(1 + \beta^3\right)^{-1} \tag{4}$$

where, v denotes the tidal speed, β denotes the pitch angle, ω_m denotes the generator speed, R denotes the radius of the blades, ρ is fluid's density, C_p represents the power coefficient, A is blades area, and $\lambda = \frac{\omega_m R}{V}$ λ denotes the tip-speed ratio.

2.2 Model of the PMSG

Model of the PMSG is as below [3–5]:

$$v_{dq} = R_{dq}i_{dq} + L_{dq}\dot{i}_{dq} + p\omega_m\Im\left(L_{dq}i_{dq} + \psi_f\right) \tag{5}$$

$$J\dot{\omega}_m = T_m - T_e - f_{fv}\omega_m \tag{6}$$

$$T_e = \frac{3}{2}p\psi_{dq}\Im i_{dq} \tag{7}$$

where $R_{dq} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix}$ denotes the stator resistance matrix, $f_{f\ v}$ represents the coefficient of the viscous friction, $\psi_f = \begin{bmatrix} \varphi_f \\ 0 \end{bmatrix}$ is the flux linkages vector, T_e ffv represents the electromagnetic torque, $L_{dq} = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix}$ denotes the induction matrix of the stator, J represents the total inertia moment, $v_{dq} = \begin{bmatrix} v_d \\ v_q \end{bmatrix}$ denotes voltage stator vector, $i_{dq} = \begin{bmatrix} i_d \\ i_q \end{bmatrix}$ denotes the stator current vector, and ω_m denotes the PMSM speed. φ_f are the flux linkages due to the permanent magnets, p is the number of pole-pairs, and $\Im = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$.

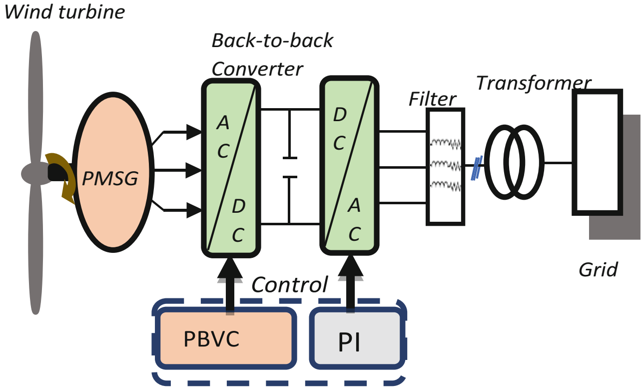

Fig. 1. Tidal conversion system.

3 IDA-PBC Controller Design

As stated in Sect. 1, the behavior of the tidal turbine-based PMSG is a nonlinear mathematical issue, and the conversion system needs an optimal improved energy harvesting to increase operating efficiency. The MSC purpose is to communicate the energy generated by the turbine with as little loss as possible.

3.1 IDA-PBC Theory

As shown below, IDA-PBC was established as a mechanism for controlling physical systems defined by the PCH model [3, 6]:

$$\begin{cases} \dot{x} = \frac{\partial H}{\partial x}(x)[\mathcal{J}(x) - \mathcal{R}(x)] + gu \\ y = g^T(x)\frac{\partial H}{\partial x}(x) \end{cases} \tag{8}$$

where, $H(x) : \Re^n \to \Re^+$ is the total stored energy, $x \in \Re^n$ represent the state vector, $u \in \Re^m$, $m < n$ is the controller action, the product of u and $y \in \Re^m$ has units power, and $\mathcal{J}(x) = -\mathcal{J}^T(x)$, $\mathcal{R} = \mathcal{R}^T(x) \geq 0$ are the matrix of interconnection and dissipation, respectively. The PMSG model (5)–(7) can then expressed in PCH form as: $g = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix}$, $\mathcal{R}(x) = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & 0 \end{bmatrix}$, $x = [x_1 x_2 x_3]^T = D\begin{bmatrix} i_d \\ i_q \\ \omega_m \end{bmatrix}$ is the state vector, $D = diag\{L_d, L_{q,} J_T\}$, $u = \begin{bmatrix} v_d \\ v_q \\ -T_m \end{bmatrix}$ is the input vector which represent the voltage controller vector of the PMSG, $\frac{\partial H}{\partial x}(x) = \left[i_d i_q \omega_m\right]$ is the output vector and $\mathcal{J}(x) = \begin{bmatrix} 0 & 0 & x_2 \\ 0 & 0 & -(x_1 - \phi_f) \\ -x_2 & (x_1 - \phi_f) & 0 \end{bmatrix}$. The controller aim is reduced to find the following equation $u(x)$ [6]:

$$u = \left[g^T g\right]^{-1} g^T \times \left\{\frac{\partial H_d}{\partial x}(x)[\mathcal{J}_d(x) - \mathcal{R}_d(x)] - [\mathcal{J}(x) - \mathcal{R}(x)]\frac{\partial H}{\partial x}(x)\right\} \tag{9}$$

3.2 Controller Design

The proposed strategy's objective is to design the desired Hamiltonian energy function based on PCH theory, which is given as follow [3]:

$$H_d(x) = \frac{1}{2}\left[\frac{1}{L_d}x_1^2 + \frac{1}{L_q}\left(x_2 - x_2^*\right)^2 + \frac{p}{J_T}\left(x_2 - x_2^*\right)^2\right] \tag{10}$$

where, the state vector and the desired state are defined as:

$$x^* = \begin{bmatrix} x_1^* \\ x_2^* \\ x_3^* \end{bmatrix} = \begin{bmatrix} 0 \\ \frac{L_q T_m^*}{p\phi_f} \\ \omega_m^* \end{bmatrix} \tag{11}$$

where, ω_m^*, T_m^* are the desired speed and desired torque which are the tidal turbine speed and torque, respectively in our case. We have $x_1^* = 0$ and we select:

$$\mathcal{R}_d(x) = \begin{bmatrix} r_1 & 0 & 0 \\ 0 & r_2 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$\mathcal{J}_d(x) = \begin{bmatrix} 0 & -J_{12} & J_{13} \\ J_{12} & 0 & -J_{23} \\ -J_{13} & J_{23} & 0 \end{bmatrix}$$

where, the objective is to design the parameters J_{12}, J_{13}, J_{23}, $r_1 > 0$ and $r_2 > 0$ which allows to the controller to guarantee that the speed tracking error is converged. From [6], the controller equation $u(x)$ can be solved with:

$$J_{13} = \frac{pL_d x_3}{J_T},$$

$$J_{13} = -\frac{pL_d x_2^*}{L_q},$$

$$J_{23} = -\frac{pL_q x_1^*}{L_d}$$

Thus, the controller expression become as:

$$v_d = -i_d - pL_d i_q^* \omega_m + i_d^*(R_s - r_1) + \left(i_q - i_q^*\right) pL_d \omega_m^* \tag{12}$$

$$v_q = -r_2 i_q + pL_q i_d^* + (R_s - r_1) i_q^* + \left(p\left(L_d i_d + \phi_f\right) - pL_q i_d^*\right)\omega_m^* \tag{13}$$

4 PI Controller for Grid-Side

To regulate and transmit to electrical energy produced by the PMSG to the grid through the GSC, a classical method is selected which consists on PI strategy. The GSC mathematical model is expressed as follows:

$$\begin{bmatrix} V_{id} \\ V_{iq} \end{bmatrix} = \begin{bmatrix} L_f \dot{i}_{df} - \omega L_f i_{qf} \\ L_f \dot{i}_{qf} - \omega L_f i_{df} \end{bmatrix} + \begin{bmatrix} V_{gd} \\ V_{gq} \end{bmatrix} + R_f \begin{bmatrix} i_{df} \\ i_{qf} \end{bmatrix} \tag{14}$$

$$C\dot{V}_{dc} = i_{dc} + i_{df} \frac{3}{2} \frac{v_{gd}}{V_{dc}} \tag{15}$$

where, V_{gd} and V_{gq} are the grid voltages, i_{df} and i_{qf} are the grid currents, R_f represents the filter resistance V_{id} and V_{iq} denotes the inverter voltages, CC is the DC-link capacitance, L_f is the filter's inductance, i_{dc} is the line current, ω represents the grid angular frequency, and V_{dc} is the DC-link voltage. Finally, the mathematical model of the active and reactive powers is formulated as below [9–14]:

$$\begin{cases} P_g = \frac{3}{2} v_{gd} i_{df} \\ Q_g = \frac{3}{2} v_{gd} i_{qf} \end{cases} \tag{16}$$

5 Simulation Results

The results of the simulations were obtained using MATLAB/Simulink in order to verify the suggested method's performance and dependability. Table 1 lists the parameters that were utilized to simulate the conversion system. From the pole placement method, MSC current PI gains are $K_{\mathrm{gp}} = 100$ and $K_{gi} = 500$. The DC voltage PI gains are $K_{dcp} = 5$ and $K_{dci} = 500$. The parameters $r_1 = 7Rs$ and $r_2 = 10Rs$. The marine current speed dynamic employed for the simulation fluctuation is shown in Fig. 2. The torque is seen in Fig. 3. Once opposed to the DC-link behavior of that in [15], the produced with IDA-PBC is extraordinarily well stabilized around the set point value, as illustrated in Fig. 4, with a rapid convergence and low inaccuracy. Figures 5 and 6 indicate that only active power is provided to the electricity network, whilst reactive power generated is severely limited and well-kept at its rated value, and Fig. 7 illustrates that the control operation accomplishes good sinusoidal grid side permeability with minimal overflow.

Table 1. System parameters

Parameter	Symbol	Value
Grid filter inductance	L_f	0.3 pu
Grid filter resistance	R_f	0.3 pu
Grid voltage	V_g	575 V
DC-link voltage	V_{dc}	1150 V
DC-link capacitor	C	2.6 F
Viscosity friction	J_{fv}	0.01 N.m.s
Total inertia	J	35000 kg. m^2
Flux linkage	ψ	1.48 wb
Pole pairs	p	48
Stator inductance	L_{dq}	0.3 mH
Stator resistance	R_s	0.006 Ω
Water density	ρ	1024 $\mathrm{kg/m}^2$
Tidal turbine radius	R	10 m

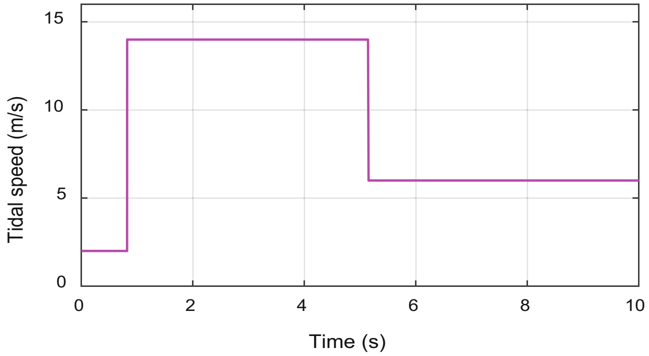

Fig. 2. Tidal speed.

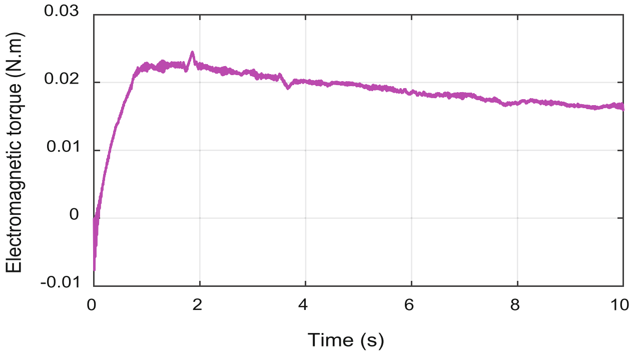

Fig. 3. Electromagnetic torque.

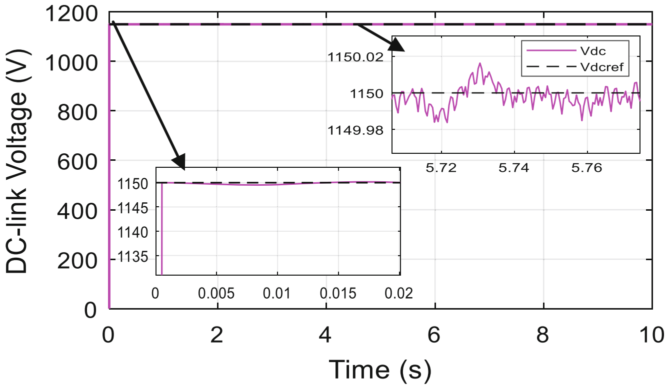

Fig. 4. DC-link voltage.

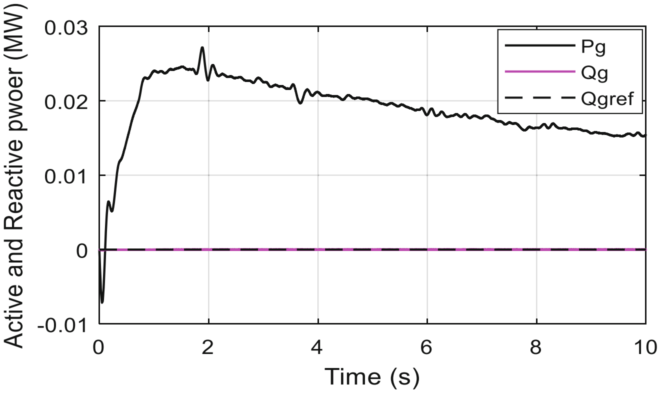

Fig. 5. Active and reactive power.

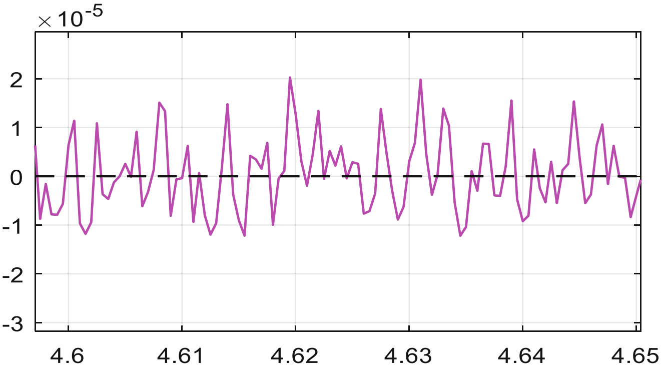

Fig. 6. Zoom of reactive power.

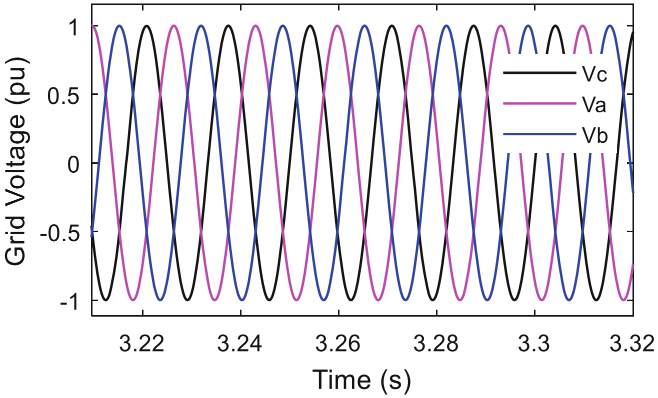

Fig. 7. Grid transfer red voltage

6 Conclusion

In this paper, a new IDA-PBC using the PCH model based on the concept of passivity has been applied to the PMSG. This controller exploits the PCH model of the motor, which highlights three matrices: the interconnection matrix, which represents the internal energy exchange ports between the states of the PMSG, the damping matrix, which represents all the dissipation elements of the system, and the external interconnection matrix which represents the energy exchanges of the PMSG with its external environment. The particular characteristic of the IDA-PBC is the choice of the PCH structure in CL, then the energy function compatible with this model is determined. The paper's proposed technique achieves the paper's aims. The PMSG-based conversion system performs well and efficiently. The structure of the control approach is sensible and easy.

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