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USING MVMO FOR OPTIMAL TUNING OF LINEAR QUADRATIC REGULATORS FOR DFIG-WT

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Abstract: The linear quadratic regulator (LQR) controller is used to enhance the low voltage ride through (LVRT) of doubly-fed induction generator based wind turbines (DFIG-WT). A heuristic optimization method, which is MVMO, is used for optimal design of the LQR weighting matrices Q and R. The objective function of the optimization problem is to minimize the peak short-circuit current and the associated time constants. In order to have realistic values the MVMO problem was constrained by the maximum available machine side converter in order to avoid over-modulation during fault periods. Additionally, the minimum threshold of the stator voltage that will lead to disconnection of the DFIG-WT was considered as a constraint. The results show that the new proposed controller enhanced the LVRT.

Keywords: Linear quadratic regulator, Doubly-fed induction machine, wind turbines, MVMO.

1. INTRODUCTION

Wind power is a main source of clean and sustainable electrical energy. It is expected to reach 10% of the global electricity supply by 2020 ("GLOBAL WIND ENERGY OUTLOOK 2012 - GWEC," n.d.). The doubly-fed induction generator based wind turbine (DFIG-WT) represents the highest proportion of wind turbine installations among other Wind Turbine (WT) technologies (Zhou et al., 2009). This attributed to the robustness and easy maintenance of the DFIG-WT. Additionally; it offers major features such as variable speed operation over a typical range of ±30% of the synchronous speed, decoupled control of active and reactive power, and voltage support capabilities. A typical layout and assigned control objectives of a DFIG-WT is shown in (Fig. 1).

There exists various control techniques proposed for DFIG-WT control. In (Maharjan and Kamalasadan, 2014) an online identification and adaptive tuning of PID controller was introduced for sensor-less control of the DFIG-WT, while in (Sa-ngawong and Ngamroo, 2013) an adaptive based optimal fuzzy logic controller was proposed for frequency control of DFIG-WT in standalone power system. In (Soltani et al., 2006)(Djoudi et al., 2014) (Susperregui et al., 2014) a sensorless control based on adaptive sliding-mode control (SMC) and parameter estimation method is proposed for active and reactive power control of DFIG-WT, while a variable structure control based on SMC was proposed in (Bekakra and Attous, 2013a).

The adaptive and variable structure control techniques proposed have a complicated structure which limits their implementation in practical application. This is due to the limitations in converter capacity, the concerns of the algorithm reliability and stability, and the estimations involved for the control parameters. Therefore, a conventional PI-controller is mostly applied for DFIG-WT control. However, due to the nonlinearities inherited in the DFIG-WT the proper tuning of the PI-controller gains is tedious.

The internal model control (IMC) is applied for tuning the PI-controller gains for a field-oriented induction machine in (Harnefors and Nee, 1998) and for DFIG-WT in (Soleimani-Bidgoli et al., 2010). The IMC has the advantage of referring the tuning problem into the adjustment of only one parameter, which is the desired closed-loop bandwidth that can be directly expressed in certain machine parameters. However, the IMC does not consider the error in measurement and nonlinearities as well as the limited capability of the converter. Heuristic optimization methods were also applied for optimal tuning of the PI-controller. Particle swarm optimization (PSO) was applied for optimal tuning for maximum power tracking in (Bekakra and Attous, 2013b), but the results did not yield any remarkable enhancement in the transient performance. The PSO and mean variance mapping optimization (MVMO) were applied

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in (Qiao et al., 2006) and (Chakravarty and Venayagamoorthy, 2011) respectively for enhancing the transient performance and LVRT of the DFIG-WT, but the results were compared to the results of manually tuned PI-controllers, thus limiting the credibility of the results, also the optimization problem was not constrained by the maximum available machine side converter (MSC) voltage.

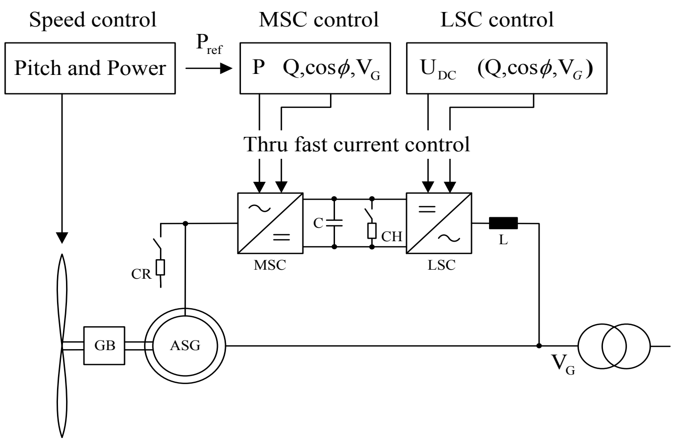

Fig. 1 DFIG-WT system configuration

An alternative control approach for DFIG-WT is the linear quadratic regulator (LQR), which offers optimal tuning of the controller gains in feedback system. The LQR was applied to tune the controller gains of uninterruptible power supply (UPS) inverter system, in a distributed generation (DG) system in (Hasanzadeh et al., 2011) and for three level inverters in (Pou et al., 2005), where the weighting matrices Q and R are chosen based on the desired transient response. In (Barakati, 2008) a genetic algorithm is deployed to optimally chose the diagonal parameters of the weighting matrices Q and R to achieve a desired closed loop Eigen values of DFIG. In this paper the MVMO is applied to optimally design the weighting matrices Q and R in the LQR formulation in order to enhance the LVRT of the DFIG and to avoid over-modulation during fault periods by constraining the MVMO problem by the maximum MSC available voltage. The results are compared to the results from a DFIG-WT of which controller depends on a feed-forward decoupled current control and a feedback PI-controller, of which gains are optimally tuned using the same objective function assigned for LQR.

2. LQR Basics

A linear time invariant (LTI) system has a specific formula given by:

$$\dot{x} = Ax + Bu, \quad y = Cx + Du \quad (1)$$

where, $x \in \mathbb{R}^n$ is the system state, $u \in \mathbb{R}^m$ and $y \in \mathbb{R}^k$ are the system input and output respectively.

The optimal LQR problem is to find an allowable control vector $u(t) = -Kx(t)$ that transfers the state to the desired region of the state space and for which the performance index is minimized (Franklin et al., 2014). This optimality is achieved by minimizing a cost function given by:

$$J_{LQR} = \int_0^{\infty} \left[x(t)' Q x(t) + u(t)' R u(t) \right] dt \quad (2)$$

where Q is $n \times n$ positive semi definite matrix and R is $m \times m$ positive definite matrix.

The LQR cannot be applied to a tracking problem (Hasanzadeh et al., 2011). Therefore, an integrator is added to the system for reference tracking and to guarantee zero steady-state error (Barakati, 2008) as shown in (Fig. 2).

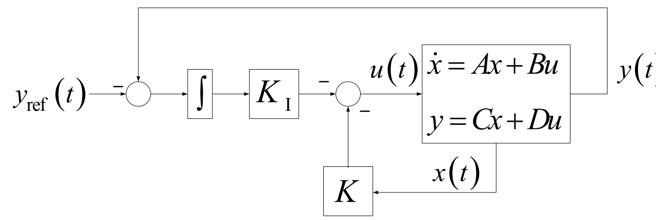

Fig. 2 closed-loop augmented feedback system

3. DFIG Dynamic Model and LQR control

Assuming a uniform air gap and neglecting magnetic saturation, the DFIG space vector model is given by(El-Naggar and Erlich, 2015):

$$\begin{aligned} \underline{v}_S^{\angle 0} &= -r_S \underline{i}_S^{\angle 0} - s\underline{\psi}_S^{\angle 0} \\ \underline{v}_R^{\angle 0} &= -r_R \underline{i}_R^{\angle 0} - \left(s - j\omega_R\right)\underline{\psi}_R^{\angle 0} \\ \underline{\psi}_S^{\angle 0} &= l_S \underline{i}_S^{\angle 0} + l_M \underline{i}_R^{\angle 0} \\ \underline{\psi}_R^{\angle 0} &= l_R \underline{i}_R^{\angle 0} + l_M \underline{i}_S^{\angle 0} \end{aligned} \quad (3)$$

Rearranging (3) for LQR control considering the rotor and stator currents and the integrator output, as the system states, the rotor current as the output and the MSC voltage as the system input yields the following state space:

$$\begin{aligned} \begin{bmatrix} \dot{\underline{i}}_S^{\angle 0} \\ \dot{\underline{i}}_R^{\angle 0} \\ \dot{\underline{v}}_C^{\angle 0} \end{bmatrix} &= \hat{A} \begin{bmatrix} \underline{i}_S^{\angle 0} \\ \underline{i}_R^{\angle 0} \\ \underline{v}_C^{\angle 0} \end{bmatrix} + \hat{B}_R \left[\underline{v}_R^{\angle 0} \right] + \hat{B}_S \left[\underline{v}_S^{\angle 0} \right] + \begin{bmatrix} 0 \\ 0 \\ -I \end{bmatrix} \left[\underline{i}_{R,Ref}^{\angle 0} \right] \\ \left[\underline{i}_R^{\angle 0} \right] &= \begin{bmatrix} C & 0 \end{bmatrix} \begin{bmatrix} \underline{i}_S^{\angle 0} \\ \underline{i}_R^{\angle 0} \\ \underline{v}_C^{\angle 0} \end{bmatrix} \end{aligned} \quad (4)$$

where,

$$\hat{A} = \begin{bmatrix} A & 0 \\ C & 0 \end{bmatrix}, \hat{B}_R = -\frac{1}{\sigma l_S l_R} \begin{bmatrix} -l_M \\ l_S \\ 0 \end{bmatrix}, \hat{B}_S = -\frac{1}{\sigma l_S l_R} \begin{bmatrix} l_R \\ -l_M \\ 0 \end{bmatrix}$$

$$A = -\frac{1}{\sigma l_S l_R} \begin{bmatrix} l_R & -l_M \\ -l_M & l_S \end{bmatrix} \left(\begin{bmatrix} r_S & 0 \\ 0 & r_R \end{bmatrix} - \begin{bmatrix} 0 & 0 \\ 0 & j\omega_R \end{bmatrix} \begin{bmatrix} l_S & l_M \\ l_M & l_R \end{bmatrix} \right) \quad (5)$$

$$C = \begin{bmatrix} 0 & 1 \end{bmatrix}, \; I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \dot{\underline{v}}_C^{\angle 0} = \underline{i}_R^{\angle 0} - \underline{i}_{R,Ref}^{\angle 0}$$

The optimal state-feedback LQR controller for the problem in (4) requires the determination of a matrix gains given by: