Design of $\Delta\Sigma$ Based PID Controller for Wind Energy Systems

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Abstract—The present study designs a novel $\Delta\Sigma$-based PID controller for controlling the rotor side converter (RSC) of a doubly-fed induction generator (DFIG) based wind energy conversion system (WECS). The proposed controller essentially uses $\Delta\Sigma$ modulators to represent the analogue signals in single-bit which is ideally suited for FPGA or application specific integrated circuit implementation and offers numerous advantages due to its inherent parallel nature. The performance of the controller is compared with various controllers including a conventional PID, Q and Dynamic Fuzzy-Q learning (DFQL) based intelligent controllers. The results of the simulation on WECS consists of 20 wind turbines and 20 DFIGs, illustrate that the $\Delta\Sigma$ based PID controller could perform better compared to conventional PID and Q-learning based controllers.

Index Terms—$\Delta\Sigma$-based PID Controllers, Doubly-Fed Induction Generator, Dynamic Fuzzy-Q Learning

I. INTRODUCTION

Due to various environmental issues, the demand for renewable energy (i.e. solar, wind) has grown considerably during the last decade. Amongst several renewable energy sources, wind power plays a critical role in many countries. The wind generators in modern wind energy conversion system (WECS) often use either the DFIG or the squirrel-cage induction generator; the former being more popular due to various advantages they offer [1], [2].

During the past few years, renewable energy systems (RES) based on DFIG has been a popular research area for many researchers. They have suggested many methods to control and model such systems [2]–[5]. Detailed descriptions about the modelling of Electrical and mechanical dynamics can be found in [7], [10]. In typical DFIG based schemes, there are two ways that a controller can be implemented. It can be implemented in grid side converter (GSC) or in RSC. However, in this study for convenience, only RSC control is considered. RSC control mainly focuses the active power and reactive power components on the rotor side. There are many different types of controllers in the literature that have been designed to improve the performance of the RSC. Namely, fuzzy logic control [11] and sliding-mode control [4]. DFIG modelling using Matlab/Simulink was introduced in [13] and some other literature related to DFIG can be found in [16], [17].

It is worth to note that, most of these controllers are implemented using micro-controllers and digital signal processors which is the standard method of digital implementation. Typically, binary words are optimised for a fixed width in practice, for example 8-bit, 16-bit or 32-bit. There are some critical factors that determine the choice of word size namely the hardware cost, the control algorithm that is being used, the signal-to-noise ratio (SNR) and most importantly dynamic range that is required. These multi-bit implementations require high information rate between control subsystems despite their success in implementation. Hence, it often becomes computationally extensive and requires large routing area and more valuable silicon area on an FPGA.

Recently, an alternative technique has been proposed based on bit-stream ($\Delta\Sigma$ modulators) for selected control applications, primarily due to many advantages [18], [21]. Amongst the many benefits, this method offers, the key benefit is that each signal is represented by a single bit which eases place and route operations for the FPGA systems reducing input/output use to one pin for a particular signal. It will make isolation of systems using optocouplers easy and is a significant advantage. The main goal of the present investigation is to determine whether the bit-stream-based $\Delta\Sigma$ modulator can be used to control a DFIG based WECS. The rest of this paper is organised as follows. Modelling of wind turbines driven by DFIGs are briefly described in Section-II. Section-II briefly describes the modelling of wind turbines driven by DFIGs. In Section-III, the principles of $\Delta\Sigma$ PID are illustrated. The performance of the designed controller in comparison to other controllers is investigated considering a WECS in Section-IV.
with conclusions in Section-V.

II. MODELLING OF WIND ENERGY CONVERSION SYSTEM

Fig.1 illustrates the schematic of a WECS used in this study. The simplified aggregated model is also known as a one-mass system and is described by [22], [23]:

\[
\frac{d\omega_{m,agg}}{dt} = \frac{1}{2H_{m,agg}}(T_{m,agg} - T_{e,agg} - D\omega_{m,agg}) \tag{1}
\]

where, \(\omega_{m,agg}\), \(T_{m,agg}\), \(T_{e,agg}\) and \(D\) denote the rotor speed, the total mechanical torque; the total electrical torque of aggregated DFIG and damping coefficient respectively. The aggregated mechanical torque \(T_{m,agg}\) and power \(P_{m,agg}\) is calculated from [16], [17]:

\[
T_{m,agg} = \frac{P_{m,agg}}{\omega_{m,agg}}, \quad P_{m,agg} = \frac{0.5\rho R^2 C_p(\lambda, \beta)}{P_{rated}} \tag{2}
\]

where \(C_p, \lambda, \beta, \rho, P_{rated}\) and \(R\) denote power coefficient, tip-speed-ratio, blade-pitch angle, air density, rated wind turbine capacity and blade radius respectively. Note that \(\beta\) is chosen to be zero in this paper. The values of various parameters in (2) are calculated from [23],

\[
R = \sqrt{\frac{P_{rated}}{0.5\pi C_p(\lambda)\omega_{w,rated}}}, \quad C_p(\lambda, \beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right) + c_5\lambda \tag{3}
\]

where,

\[
\lambda = \frac{\omega_m R}{v_w}, \quad \lambda_i = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}
\]

and \(v_m\) denote wind speed, \(c_1, \ldots, c_6\) are constants. In this study, the values of various parameters of individual wind turbine in (3) are: \(c_1 = 0.5176, c_2 = 116, c_3 = 0.4, c_4 = 0.5, c_5 = 21, c_6 = 0.0068, P_{rated} = 5MW, v_w = 15m/s.\) The aggregated inertia constant of the system \(H_{m,agg}\) in (1) is given by

\[
H_{m,agg} = (H_t + H_g) \times N \tag{4}
\]

where, \(H_t\) and \(H_g\) are the inertia constant of each individual wind turbine and DFIG respectively. In this investigation, we have considered \(H_t = 4, H_g = 0.1H_t\) and the total number of DFIG is denote by \(N\); \(N = 20\).

B. Modelling of DFIG

The following set of equation describe the dynamics of DFIG in in dq-reference frame [24].

\[
\frac{dI_{qs}}{dt} = \frac{\omega_b}{L_s}(-R_1 I_{qs} + \omega_s L_s I_{ds} + \frac{\omega_r}{\omega_s} E_{qs} - \frac{1}{T_{r,\omega_s}} E_{ds}' - v_{qs} + K_{mrr} v_{qr}) \tag{5}
\]

\[
\frac{dI_{ds}}{dt} = \frac{\omega_b}{L_s}(-R_1 I_{ds} - \omega_s L_s I_{qs} + \frac{\omega_r}{\omega_s} E_{ds} + \frac{1}{T_{r,\omega_s}} E_{qs}' - v_{ds} + K_{mrr} v_{dr}) \tag{6}
\]

\[
\frac{dE_{qs}'}{dt} = \omega_b \omega_s \left[R_2 I_{ds} - \frac{E_{qs}'}{T_{r,\omega_s}} + (1 - \frac{\omega_r}{\omega_s}) E_{ds}' - K_{mrr} v_{dr}\right] \tag{7}
\]

\[
\frac{dE_{ds}'}{dt} = \omega_b \omega_s \left[-R_2 I_{qs} - \frac{E_{ds}'}{T_{r,\omega_s}} + (1 - \frac{\omega_r}{\omega_s}) E_{qs}' + K_{mrr} v_{dr}\right] \tag{8}
\]

where, \(\omega_b\) is the electrical base speed; \(\omega_s\) is the synchronous speed; \(I_{qs}\) and \(I_{ds}\) and \(E_{qs}'\) and \(E_{ds}'\) are dq-components of stator currents and internal stator voltage respectively. The values of various other parameters used in this study are: \(L_m = 4, L_{ss} = 1.01, L_{rr} = 1.005, K_{mrr} = \frac{L_m}{L_{ss}}, L_s' = L_{ss} - L_{m} K_{mrr}, R_s = 0.005, R_r = 1.1 R_s, R_2 = K_{mrr} R_r, R_1 = R_s + R_2, T_r = \frac{L_{m}}{R_r}\) and in p.u. [24].

The electrical power generated by the aggregated DFIGs is calculated as:

\[
T_{e,agg} = \left[\frac{E_{qs}'}{\omega_s} I_{qs} + \frac{E_{ds}'}{\omega_s} I_{ds}\right] \times N \tag{9}
\]

\[
Q_{s,agg} = \left[V_s I_{ds} - V_d I_{qs}\right] \times N \tag{10}
\]

where \(\omega_s\) is the synchronous speed.

The investigation is carried out by neglecting the stator transients. The excessive active power of the rotor \(P_r\) is assumed to pass through the GSC to the power grid while the reactive power \(Q_r = 0\). This implies that \(P_{tot} = P_s + P_r\) and \(Q_{tot} = Q_s\). More details about DFIG can be found in [26].
III. DESIGN OF $\Delta \Sigma$ BASED PID CONTROLLER

The design principle of $\Delta \Sigma$-based PID controller is briefly described in the following section. $\Delta \Sigma$ modulator is one of the key components of the $\Delta \Sigma$-based control system. It is consisted of two main components, a $\Delta \Sigma$ encoder ($\mathcal{E}_{\Delta \Sigma}$) and a $\Delta \Sigma$ decoder ($\mathcal{D}_{\Delta \Sigma}$). The schematic of $\mathcal{E}_{\Delta \Sigma}$ and $\mathcal{D}_{\Delta \Sigma}$ is shown in Fig-2. Encoder and decoder are connected through a communication channel. As represented in Fig-2, the thick solid lines show the weighted signal and the dotted line shows the bit-stream (BS) signal. The input signal $\hat{e}$ is encoded into a BS signal $\hat{\delta}$ by $\mathcal{E}_{\Delta \Sigma}$ which consists of one integrator, one two-level quantizer and a multiplexer. The decoder $\mathcal{D}_{\Delta \Sigma}$ which consists of single multiplexer reconstructs the estimated input of $\mathcal{E}_{\Delta \Sigma}$. The conversion of the input of $\mathcal{E}_{\Delta \Sigma}$ is done through error feedback.

![Fig. 2: $\Delta \Sigma$-based encoder/decoder. (a). Encoder (b). Communication Channel (c). Decoder](image)

Note that, the conventional linear controller design technique is based on an approximate linear model of a system. This linear model can be obtained by perturbing the system dynamics around a desired operating point. Therefore, linear controller behaves optimally around linearisation point. In the following, we, therefore, briefly describe the feedback control design of $\Delta \Sigma$ based control design under the assumption that the system is linear. Consider a linear time-invariant (LTI) plant described by,

$$\dot{x} = Ax + Bu$$

$$y = Cx$$

where $x \in \mathbb{R}^n$, $u \in \mathbb{R}^m$ and $y \in \mathbb{R}^p$ denote the states of the linearised plant, the inputs and the output of the linearised plant, respectively. Here, a analogue controller is used to stabilise the system described in (11) asymptotically. The dynamics of the analogue controller is described as,

$$\dot{x}_c = A_c x_c + B_c e$$

$$u = C_c x_c + D_c e$$

where $x_c \in \mathbb{R}^n$ and $e$ denote respectively the states of the controller and the error signals. It is convenient to assume the reference signal to be zero ($r = 0$), without loss of generality, hence $e = -y$. By combining (12) with (11) gives the dynamics of the closed loop system as:

$$\dot{x}_{cl} = A_{cl} x_{cl}$$

where

$$x_{cl} = \begin{bmatrix} x \\ x_c \end{bmatrix}$$

$$A_{cl} = \begin{bmatrix} A - BD_c C & BC_c \\ -B_c C & A_c \end{bmatrix}$$

Assume that the controller (12) has been designed such that, $A_{cl}$ is strictly stable. Note that by inserting the $\Delta \Sigma$ based encoder and decoder in the control system gives the $\Delta \Sigma$ based control system which is shown in Fig-3. Here, $\mathcal{E}_{\Delta \Sigma}$ encodes feedback signals to BS signals at the transmitter. Then those BS signals go through $\mathcal{D}_{\Delta \Sigma}$ to produce $\hat{e}$. Ideally $\hat{e} = \hat{\delta}$.

![Fig. 3: Configuration of $\Delta \Sigma$ based control system.](image)

It is important to consider the problem of incorporating $\mathcal{E}_{\Delta \Sigma}$ and $\mathcal{D}_{\Delta \Sigma}$ with the system described in (13). Note that $Q$ matrix of dimension $p \times p$ and is positive definite. Here, $p$ is the number of $\Delta \Sigma$-Modulators that is being used. The estimated signals which is also the output of $\mathcal{D}_{\Delta \Sigma}$, are defined by,

$$\hat{e} = \text{diag}\{\mathcal{E}_{\Delta \Sigma} \circ \mathcal{D}_{\Delta \Sigma}\} \ast \hat{\delta} = Q \text{sgn}(s)$$

where $s = \hat{\delta} - \hat{\hat{\delta}}$. The states of the feedback system can be defined as,

$$\begin{bmatrix} \hat{x}_d \\ \hat{s} \end{bmatrix} = \begin{bmatrix} A_1 & 0 \\ A_2 & 0 \end{bmatrix} \begin{bmatrix} \hat{x}_{cl} \\ s \end{bmatrix} + \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} \hat{e}$$

with $A_1 \in \mathbb{R}^{(n+v)\times(n+v)}$, $A_2 \in \mathbb{R}^{p\times(n+v)}$, $B_1 \in \mathbb{R}^{(n+v)\times p}$ and $B_2 \in \mathbb{R}^{p\times p}$.

From (15) we can see that feedback signals are switched signals. However, the system described in (16) becomes a differential equation with a discontinuous right hand side. According to [27], [28], (16) can be can be analyzed using equivalent control method. Detailed analysis of the stability conditions and convergence analysis of $\Delta \Sigma$(BS) based controllers shown in Fig-4 can be found in [12] and in [6], [8], [9], [14], [15], [19], [20], [25], [29], [30].

Fig.4 shows the schematic diagram of $\Delta \Sigma$-based PID controller. Here, $[K_{Lp},K_{U_p}]$, $[K_{L_i},K_{U_i}]$, $[K_{L_d},K_{U_d}]$, and $N_d$ denote respectively the lower and upper bounds of the proportional gains, the integral gains, the differentiator gains,
and the filter coefficient of the differentiator. Following measures are taken to lower hardware consumption. To replace the multiplier with a shift register $N_d$ can be selected in a way such that $N_d R = 2^{-n}$, where $R \in \mathbb{N}_0$. The output of the $\Delta \Sigma$-based PID controller is given by,

$$
\hat{u}(t) = K_p + \frac{K_d h}{\rho} + \frac{K_d N_d}{\rho + N_d h} \quad (18)
$$

IV. SIMULATION RESULTS

In this study we have compared the performance of the $\Delta \Sigma$-based PID controller with the classical PID controller as well as two intelligent controllers based on Q-learning and DFQL. All these controllers are designed considering the WES as shown in Fig.1. System considered in this study consists of 20 wind turbines and 20 DFIGs which are coupled together. The capacities of DFIGs are rated at 5MW. Controllers are designed to control the rotor voltage of DFIGs which can be ensured when the rotor speed is stable.

The general configuration of controlling the WES are shown in Fig. 5. $P_{e,ref}$ and $Q_{s,ref}$ which are the reference values of the real power and reactive power ($Q_{s,ref}$) in Fig.5 are given by [24].

$$
P_{e,ref} = K_{opt} \omega_r^2 \times N, \quad Q_{s,ref} = 0 \quad (19)
$$

where $K_{opt} = 0.5787$.

The outputs of the various controllers are dq-components of rotor volatge $V_{qr}$ and $V_{dr}$. The design of the $\Delta \Sigma$-based PID follows similar procedure discussed in section-III and in [12]. The the sampling frequency ($f_s$) and quantization levels ($q$) of the $\Delta \Sigma$ PID is chosen such that overall system is stable. Note that, $f_s = 1kHz$ and $q = 0.1$.

An occurrence of a fault is simulated by changing the restance of the transmission line $X_e$. $X_e$ is changed from 5 to 0.5 at $t = 5s$. The variations in rotor speed, real power $P_e$ and reactive power $Q_s$ of the faulted system when various controllers are used is shown in Fig.6, Fig.7 and Fig.8 respectively. Note that variations are shown in p.u. It is evident from Fig.6 that the rotor speed of DFIG stabilises after a few seconds in $\Delta \Sigma$ based PID; whereas other controllers take over 50 secs.

However, as it can be seen in Fig.7 and Fig.8 that the variations of real power $P_e$ and reactive power $Q_s$ of $\Delta \Sigma$ based PID and conventional PID is almost similar. But, the performance of Q-learning and DFQL controllers are poor when compared with $\Delta \Sigma$ based PID and conventional PID. This is probably due to the longer learning time of Q-learning and DFQL controllers.

V. CONCLUSIONS

A $\Delta \Sigma$-based PID controller is designed for DFIG based wind energy system which is represented by an aggregated model. The performance of $\Delta \Sigma$ based PID controller is compared with three other controllers namely conventional PID, Q-learning and DFQL respectively. The results of the simulations on WECS consisting of 20 wind turbines and 20 DFIGs which are coupled together, show that $\Delta \Sigma$ based PID controller performs better than all the other three controllers, and variation of real power $P_e$ and reactive power $Q_s$ of $\Delta \Sigma$ based PID and conventional PID is almost similar. It is noted that $\Delta \Sigma$ based PID controller could find the optimal control action required to stabilise the system, faster than other controllers. Future work could be done considering the application of the $\Delta \Sigma$-based PID controller in large-scale WECS to improve the performance of the system behaviour.

REFERENCES

Fig. 6: Variations in Rotor Speed.

Fig. 7: Variations in real power $P_e$. 
Reactive Power

(a) Conventional PID controller.

(b) $\Delta\Sigma$ based PID controller.

(c) Q-Learning controller.

(d) DFQL controller.

Fig. 8: Variations in reactive power $Q_r$.


