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SENSORLESS YAW CONTROL FOR WIND TURBINE USING SIMULTANEOUS PERTURBATION STOCHASTIC APPROXIMATION

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ABSTRACT

Wind turbine generation (WTG) system can increase its real power generation through variable-speed control and yaw control. The variable-speed control means that the rotor velocity may be controlled according to the variation of the wind speed for achieving the maximum power point tracking. The yaw control indicates that the horizontal axis wind turbine needs extra devices to orientate the rotors against the wind direction. On the other hand, simultaneous perturbation stochastic approximation (SPSA) algorithm is a highly efficient gradient approximation that relies on two measurements of the objective function. This paper addresses a sensorless yaw control by realization of SPSA for on-line parameter tuning for the PID controller. A DC motor is used as a plant for illustrating the position control performance. The SPSA is realized in a field-programmable gate arrays (FPGA) development board. Experimental results show that realization of SPSA for WTG is very efficient.

KEY WORDS

Yaw Control, Stochastic Optimization, PID Controller, Wind Turbine

1. Introduction

Renewable energy resources (such as wind, solar, geothermal, biomass, tidal, and hydropower) are one type of distribution generations. Among all, the wind power is being paid much attention due to increasing MW capacity of wind-turbine-generation (WTG). There are several problems to the WTG although WTG provides some advantages to the power system: (i) impact upon the power system operation, e.g., protective relay design and power quality, (ii) technologies required to improve the efficiencies of WTG, and (iii) efficient operation considering WTG integrated with traditional generators. This paper concerns the second issue. Especially, the yaw control, which is generally used for large turbines with power capacity exceeding 50kW, is addressed.

Unlike vertical axis wind turbine, the horizontal axis wind turbine needs extra devices, e.g., induction motor, to orientate the rotor against the wind direction. There are few papers concern the active yaw control. Farret implemented the “hill climbing approach” in a microprocessor to achieve the yaw control [1]. Farret et al. proposed again a control strategy based on measurement of the generated power and control rules [2]. Wu proposed a method using a PD controller and a fuzzy logic controller to conduct the yaw control [3]. Ekelund investigated the potential for active attenuation of structural dynamic load oscillation by means of continuous control of the yaw servo in a WTG system [4].

On the other hand, the simultaneous perturbation stochastic approximation (SPSA) algorithm has attracted considerable attention for challenging optimization problems where it is difficult or impossible to directly obtain a gradient of the objective function with respect to the parameters being optimized [5-9]. SPSA is an easily implemented and highly efficient gradient approximation that relies on two measurements of the objective function for implementing the gradient approximation, compared with the standard finite-difference approaches, which require a number of function measurements proportional to the dimension of the gradient vector. Rezayat employed SPSA to iteratively estimate the weights of neural network and as a result to estimate the control values for operation processes [10]. Bhatnagar et al. used SPSA to develop an optimal structured feedback control policy for rate-based flow control of available bit rate service in asynchronous transfer mode networks in the presence of information and propagation delays [11]. Ji and Familoni presented a direct adaptive SPSA control system with a diagonal recurrent neural network (DRNN) [12]. Gerencser et al. used SPSA for the classification, monitoring, and compression of electrocardiogram (ECG) signals recorded from a single patient over a relatively long period of time [13]. Maryak and Spall used SPSA for image restoration. Comparable performance was attained by SPSA w.r.t the standard technique but SPSA can achieve a faster running time [14].

This paper addresses a sensorless yaw control by realization of SPSA for on-line PID gain tuning. A DC motor is used as a plant for illustrating the position control performance in order to achieve the yaw control. The SPSA is realized in a field-programmable gate arrays (FPGA) development board. FPGA provides a need in the design space of digital systems, complementary to the role played by microprocessors [15]. FPGA can be manufactured by standard VLSI fabrication processes. The program of FPGA (also called a personality) is interwoven into the logic structure. FPGAs are considered primarily as glue logic and prototyping devices jumping to product easily.

The rest of the paper is organized as follows. Section 2 provides the background of SPSA. Section 3 describes the development of the SPSA-based PID controller. Simulation and hardware performance are presented in Section 4. Concluding remarks are given in Section 5.

2. Simultaneous Perturbation Stochastic Approximation (SPSA)

Newton's method can be employed to solve a nonlinear equation $f(x)=0$:

$$x_{k+1} = x_k - f'(x_k)^{-1} f(x_k) \tag{1}$$

where "k" is the iteration index. On the other hand, it was found that many optimization problems are formulated by Lagrangian, denoted by L, for solving unknown vector θ. The necessary condition for obtaining the optimality is as follows:

$$\frac{\partial L(\theta)}{\partial \theta} \equiv g(\theta) = 0 \tag{2}$$

In SPSA, the variables are updated by Eq. (3) which is similar to Eq. (1) according to Newton's method.

$$\hat{\theta}_{k+1} = \hat{\theta}_k - a_k \hat{g}_k(\hat{\theta}_k) \tag{3}$$

where

- $\hat{\theta}_{k+1}$ vector of the estimated unknowns in the $(k+1)$-th iteration.
- $\hat{\theta}_k$ vector of the estimated unknowns in the k-th iteration.
- a_k a multiplier for decreasing updating in the k-th iteration.
- $\hat{g}_k$ vector of estimated gradient of L in the k-th iteration.

The variable a_k in Eq. (3) plays the role of $f'(x_k)^{-1}$ in Eq. (1) and is given by

$$a_k = \frac{a}{(A+k)^{\alpha}} \tag{4}$$

When the simultaneous perturbation stochastic process is used in order to avoid local optimums, $g(\theta)$ is approximated by

$$\hat{g}_k = \begin{bmatrix} \dfrac{y_k^{(+)} - y_k^{(-)}}{2c_k \Delta_{k1}} \\ \vdots \\ \dfrac{y_k^{(+)} - y_k^{(-)}}{2c_k \Delta_{kp}} \end{bmatrix} \tag{5}$$

and

$$y_k^{(+)} = L(\hat{\theta}_k + c_k \Delta_k) + \varepsilon_k^{(+)} \tag{6}$$

$$y_k^{(-)} = L(\hat{\theta}_k - c_k \Delta_k) + \varepsilon_k^{(-)} \tag{7}$$

$$c_k = \frac{c}{(k+1)^{\gamma}} \tag{8}$$

where

- a an empirical constant in accordance with the range of θ.
- c an empirical constant in accordance with the range of θ.
- c_k $\{c_k\}$ is a sequence of positive scalars such that c_k approaches zero.
- Δ_k $\Delta_k \in R^p$ is a vector of p mutually independent mean-zero random variables $\{\Delta_{k1}, \Delta_{k2}, ..., \Delta_{kp}\}$.

The symbols $\varepsilon_k^{(+)}$ and $\varepsilon_k^{(-)}$ represent measurement noise terms that satisfy the following:

$$\begin{aligned} &E(\varepsilon_k^{(+)} - \varepsilon_k^{(-)} \mid \Psi_k, \Delta_k) = 0 \quad for \quad \forall k, \\ &\Psi_k \equiv \{\hat{\theta}_0, \hat{\theta}_1, ..., \hat{\theta}_k\} \end{aligned} \tag{9}$$

In this paper, the parameters a, A, α, c and γ are 0.775, 100, 0.602 and 0.01 and 0.101, respectively. These values were suggested in [5-9] and were verified with some mathematical conditions.

For the yaw control problem, the Lagrangian means the real power generation of the WTG.. The elements of vector θ include three gains (Kp, Ki and Kd) of the PID controller. These three gains will be tuned in an on-line environment with varied wind speed and wind direction.

3. The Proposed Method

The yaw control of a WTG is a process of position tracking. In order to save facility cost, sensorless control with hill-climbing approach (HCA) is considered in this paper. The HCA provides an angle reference for the rotor of the DC motor. The gains of a PID controller are then tuned on-line to achieve the position tracking.

3.1 Hill-climbing Approach

The wind turbine is said to have a yaw angle error θ_r when its shaft is in a direction θ_s different from that of the estimated maximum wind intensity θ_w (obtained by HCA). Eq. (10) expresses the relation between the generated power P_g and θ_r. Let $P_{\max}$ be the maximum available power corresponding to the maximum power coefficient.

$$P_g = P_{\max} \times \cos\theta_r = P_{\max} \times \cos(\theta_w - \theta_s) \quad (10)$$

The steps for tracking θ_w can be summarized as follows:

Step 1: Set a positive error ΔP_{ref} .

Step 2: Acquire voltage and current from the WTG.

Step 3: Calculate P_g with information from Step 2.

Step 4: Let $P_{new} = P_g$. Retain P_g obtained in the last iteration as P_{old} .

Step 5: Compute ΔP_{error} , defined as $|P_{new} - P_{old}|$.

Step 6: If $\Delta P_{error} < \Delta P_{ref}$, go to Step 1; otherwise go to Step 7.

Step 7: If $P_{new} > P_{old}$, increase θ_s continuously and go to Step 1.

Step 7: If $P_{new} < P_{old}$, decrease θ_s continuously and go to Step 1.

In this paper, ΔP_{ref} is set to be $P_{old} / 500$.

3.2 On-line PID Gain Tuning using SPSA with DSP Builder

The Altera-Stratix II EP1S25F780C5 chip is employed to develop a FPGA chip in this paper. An ancillary tool, called DSP Builder, is provided for the IC design simulation from Altera. Traditionally, the FPGA design can be implemented by hardware description languages, e.g., Verilog or VHDL. Then these codes were compiled into an IC circuit with logic gates. DSP Builder provides a function similar to Simulink (MDL format) that links individual function blocks to achieve a special control purpose. Of course, the Simulink blocks cannot be applied directly to DSP Builder blocks. Hence, the DSP Builder blocks for the on-line PID parameter tuning using SPSA cover existing blocks provided by Altera and new blocks established by the designers. Because the hardware should be achieved, the A/D and D/A interfaces should be included in this stage. There are five main modules developed for the system as described below.

(i) Initialization module: Off-line resultant Kp, Ki and Kd will be set as initial conditions and these gains will be updated on-line.

(ii) Perturbation module: Small perturbations will be provoked for evaluating Eqs. (6) and (7).

(iii) Lagrangian module: The objective, absolute value of the accumulated error between the actual response and the expected response, will be calculated.

(iv) Random module: This module outputs Δ_k.

(v) PID controller module: This module includes a floating-point division.

Figure 1 illustrates the digital PID controller module using z-transform:

$$k_p + \frac{k_i}{1 - z^{-1}} + k_d (1 - z^{-1}) \quad (11)$$

As shown in Figure 2, the central block entitled as “divider” performs the function of the floating-point division, which is not provided in the DSP Builder. In general, the digital division in the IC design considers only “integer division with remainder.”

When running the DSP Builder simulator, an on-line-like gain tuning can be examined through the “oscilloscope” function and the performance of the controller can be evaluated.

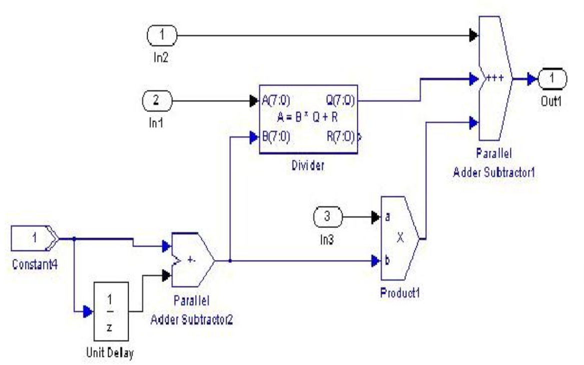

Figure 1 Digital PID Controller Module in DSP Builder

3.3 On-line PID Gain Tuning using SPSA with FPGA

To verify the performance of the designed SPSA-based PID controller, the designed hardware should be compiled into the VHDL. In essence, the hardware compilation includes four steps: (i) converting MDL format (obtained from DSP Builder) to the VHDL (HDL format), (ii) synthesizing the logic simulator to perform timing analysis, (iii) fitting (placement and routing), and (iv) programming the DSP board. More specifically, Steps (ii) and (iii) are achieved by Quartus II. Quartus II produces automatically an IC circuit according to the user’s module design, e.g., five modules described in the preceding subsection, by circuit gate placement and routing. Step (iv) “downloads” the final circuit to the chip.

Figure 2 illustrates the final hardware structure of the on-line PID controller for the studied experiment in this paper. The TA-7257 driver is a 7-pin IC that is able to drive a motor in 4 modes: brake, counter-clockwise, clockwise and stop. The drive voltage from TA-7257 is 0-8 V. On the other hand, the Linear Variable Differential Transformer (LVDT) is a linear motion-to-voltage converter. The resolution for the LVDT is 1μm and the precision in full scale is 0.01-0.05%. One may use other sensors with more precision. Because the FPGA and SPSA were addressed in this paper, the inexpensive LVDT was used for testing.

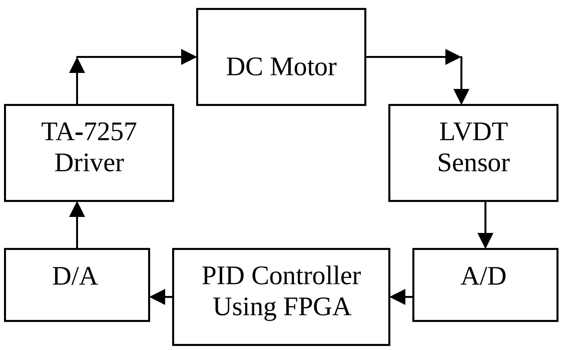

Figure 2 Hardware Structure of On-line PID Controller Using SPSA Realized by FPGA

4. Simulation and Experimental Results

Simulations related to three scenarios using the DSP Builder were conducted first. Then tail vane of an Air-X (300W WTG) was cut out in order to be used for experiment in this paper.

4.1 Simulation Results

The performance of the SPSA-based PID controller was verified by the DSP Builder in this subsection. Because the DSP Builder can simulate the on-line scenario, performance of the PID controller can be examined using the DSP Builder. Three scenarios were studied in the following subsections.

4.1.1 Varied Wind Direction and Fixed Wind Speed

The first scenario is "*Varied Wind Direction and Fixed Wind Speed.*" The wind direction starts at 20 degree and increases at 2.5 and 5 seconds to 40 and 50 degrees, respectively. Then it decreases at 7.5 seconds to 40 degrees. Figure 3 illustrates θ_w and all θ_s's obtained by (i) no PID gains, (ii) fixed PID gains, and (iii) on-line tuned PID gains. It can be found that the θ_s obtained by the SPSA-based PID gains almost coincides with θ_w.

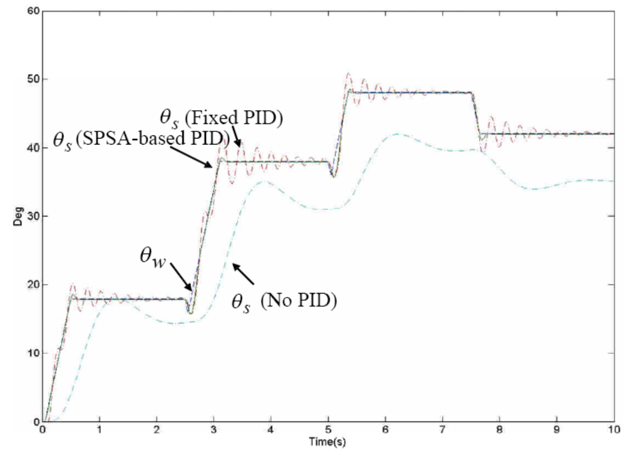

Figure 3 Different θ_s Responses w.r.t θ_w for Scenario 1

4.1.2 Fixed Wind Direction and Varied Wind Speed

The second scenario is "*Fixed Wind Direction and Varied Wind Speed.*" It is expected that HCA can work perfectly without being significantly effected by varied wind speeds. In this scenario, the wind speed increases at 1.5 and 4 seconds. After increasing θ_w to approximate 7 degrees at 1.6 seconds, θ_w starts to decrease because the wind direction does not change. Similarly, θ_w increases to 7 degrees at 4.1 seconds and then decreases. Figure 4 illustrates the θ_w and all θ_s's obtained by different controls. Again, it can be found that the θ_s obtained by the SPSA-based PID gains almost coincides with θ_w.

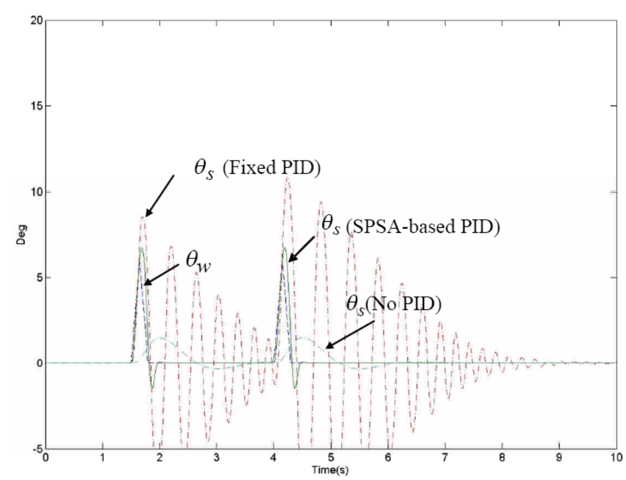

Figure 4 Different θ_s Responses w.r.t θ_w for Scenario 2

4.1.3 Varied Wind Direction and Varied Wind Speed

The third scenario is "*Varied Wind Direction and Varied Wind Speed.*" Because the performance of SPSA-based approach is superior to those of the fixed and no PID gains, this subsection discusses more detailed performance attained by the proposed method.

The wind direction was changed at 2.5, 5 (both increase) and 7.5 (decrease) seconds. The wind speed increases at 1.5 and 3.5 seconds and decreases at 6.5 second. Figure 5 illustrates the θ_s responses and θ_w for Scenario 3. The expected and actual kW (%) were also shown. Again, it can be found that the θ_s obtained by the SPSA-based PID gains almost coincides with θ_w.

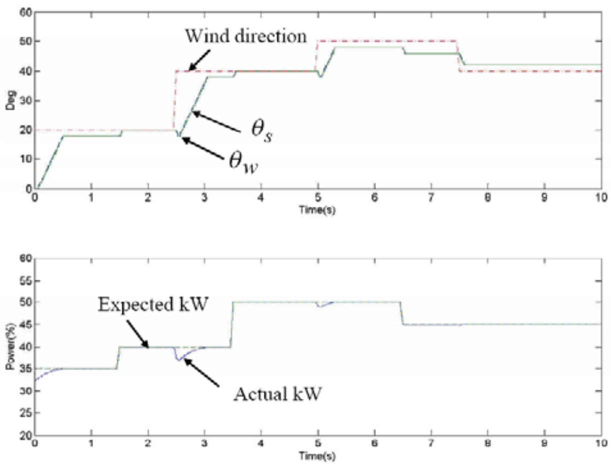

Figure 5 θ_s, θ_w, expected and actual kW (%) for Scenario 3.

4.2 Experiment Results

The mathematical model of the DC motor was embedded in the DSP Builder in Subsection 4.1. For hardware realization, the voltage and current signals measured by PC817 and LA-55P (Hall device) from the Air-X WTG will be fed into the Altera-Stratix II EP1S25F780C5 development board. The interfaces of the voltage/current were parts of the VHDL code. Figure 6 illustrates the realization of the SPSA-based PID controller for the yaw control of the WTG system.

The wind speed was varied within 8 ~8.5 m/s initially. The wind direction was changed at 4.5 seconds from 0 to 70 degrees, resulting in θ_w increasing. The wind speed at 6.5 seconds increases, too. Figures 7 and 8 show the system response for this experiment. Essentially, the θ_s obtained by the on-line tuned PID gains almost coincides with θ_w.

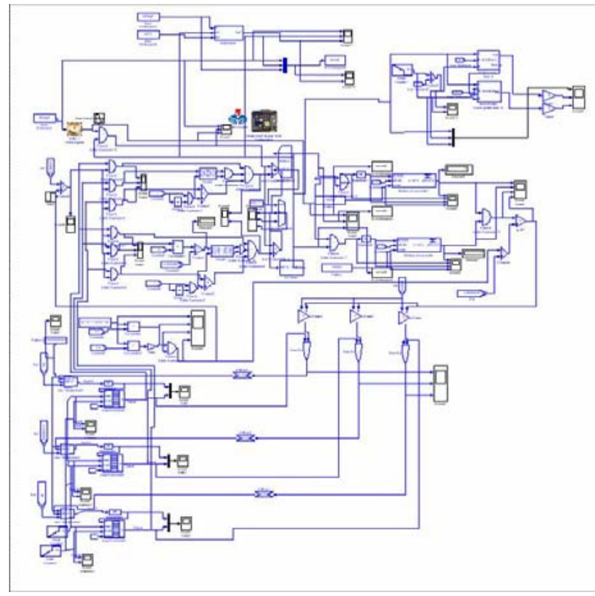

Figure 6 Realization of SPSA-based PID Controller

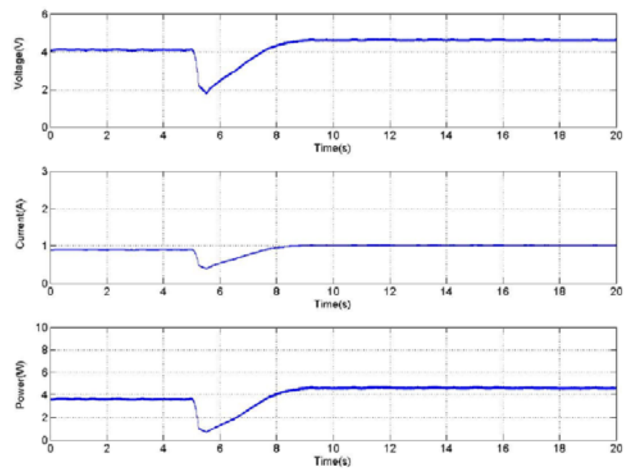

Figure 7 Voltage, current and Power Response obtained by on-line measurement

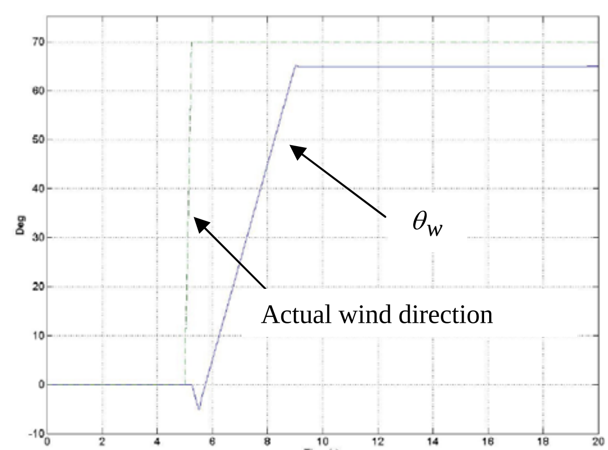

Figure 8 Actual Wind Direction and θ_w.

5. Conclusion

In this paper, the yaw control of a WTG by realization of simultaneous perturbation stochastic approximation (SPSA) for on-line PID gain tuning is presented. The SPSA takes advantages of highly efficient gradient approximation that relies on two measurements of the objective function, i.e., kW generation. The features of SPSA can be easily implemented using FPGAs that are developed for designing the IC logic circuit. There are five modules developed for SPSA in the FPGA chip. The DC motor is used as a plant for position control. Both DSP Builder simulation and experimental results show that the SPSA algorithm is very efficient for on-line PID gain tuning for the yaw control of a WTG system.

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