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Design of a Yaw Positioning Control System for 100kW Horizontal Axis Wind Turbines Based on On/Off Control with Dead Band and Hysteresis

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Abstract

In order to maximize wind energy conversion a wind turbine should be positioned perpendicular to the wind incoming direction. For a small scale wind turbine this objective can be achieved using a tail mechanism while for a medium or large scale wind turbine it requires an active control mechanism. A medium or large scale wind turbine should also be controlled in a desired position between 0˚ to 90˚ when wind power exceeds capacity of the wind turbine as well as when the wind turbine enters into shut-down mode. The direction of a wind turbine is controlled using a yawing system. In this research a yawing system consisted of a yaw mechanism and an electronic controller for a 100 kW horizontal axis wind turbine has been built. This paper deals with design of a yaw positioning control system to rotate the yaw mechanism following the position reference signal. On/Off control with dead band and hysteresis approach was adopted to build a positioning controller. The positioning controller encapsulates a speed controller as inner loop where maximum rotational speed of the yaw mechanism is 1,15 rpm. From the experimental results it is concluded that the designed yaw positioning controller performs well giving no cyclic instability at 0° vicinity as well as providing no response towards fast wind direction change.

Keywords: horizontal axis wind turbine, yaw, positioning control, on/off control, dead band, hysteresis.

Introduction
In order to maximize wind energy conversion a wind turbine should be positioned perpendicular to the wind incoming direction. For a small scale wind turbine this objective can be achieved using a passive tail mechanism [1]. A large scale wind turbine having two blades may have torque controller and blades pitch controller and not being equipped with active yaw controller [2]. However, to reduce structural dynamic loads, continuous yaw control was proposed based on a periodic LQ method for large turbines with two blades [3]. When an asynchronous cage induction motor is used as the actuator for yawing mechanism, vector control approach can be used to design a yaw controller. Fuzzy-PID synthesis may be used to design a yaw controller as demonstrated in computer simulation work [4].

In this research, a mechanical-electrical control system for a 100 kW horizontal axis wind turbine electrical power generation plant has been designed. This wind turbine has 3 blades without any pitch control mechanism. The mechanical-electrical control system is constructed of a mechanical brake controller, a yaw controller and an electrical torque controller. All these 3 controllers are coordinated by a supervisory controller. This paper described the design of the yaw positioning control system used in the wind turbine. Beside for maximizing wind power conversion, the wind turbine must also be controlled in a desired position between 0˚ to 90˚ when wind power exceeds capacity of the wind turbine as well as when the wind turbine enters into shut-down mode. In this sense, the yaw controller functions as a servo positioning controller.

Historically, in the beginning of its development, servo positioning control was constructed as the outer loop of a speed control system with speed controller in the inner loop [5]. Later development of control method gave advent of a positioning control without speed control loop, as shown by some examples [6]. However, presently there are still many products in the market taking the form of speed control [7][8][9].

In this research, an induction electrical motor equipped with speed control inverter is used as the actuator [7]. Dead band with hysteresis control approach was adopted to build the servo positioning controller [10]. The positioning controller encapsulates a speed controller as inner loop where maximum rotational speed of the yaw mechanism is 1,15 rpm. The yaw controller is realized using a microcontroller Atmega-8 [11]. Before installation in the real wind turbine power plant, the yawing system was tested in the laboratory. This paper reports design method and experimental results to evaluate the performance of the yaw controller.

Yawing System Description
In this research a yawing system for a 100 kW wind turbine electrical power generation plant is built. It is consisted of a slewing bearing, induction electrical motor, motor reduction gear, yawing pinion, motor inverter, nacelle/bed plate, 100 kW 3 phases induction generator and control panel. Figure 1 shows the yawing system set up in the laboratory. The speed of the induction motor is reduced by the gear box, and coupled to the outer gear of the slewing bearing through the pinion. The

outer diameter of the slewing bearing is 100,8 cm and the nominal power capacity of the induction motor is 1,5 kW. The yawing system assembly and the induction generator are fixed on the bed plate representing a nacelle of a wind turbine electrical power generation plant. In turn, the bed plate is fixed to the inner gear of the slewing bearing. Since the outer gear of the slewing bearing is fixed to the tower, as the yawing pinion is rotated by the motor the bed plate assembly rotates around. A wind direction sensor is used to measure wind direction (not shown in the figure 1).

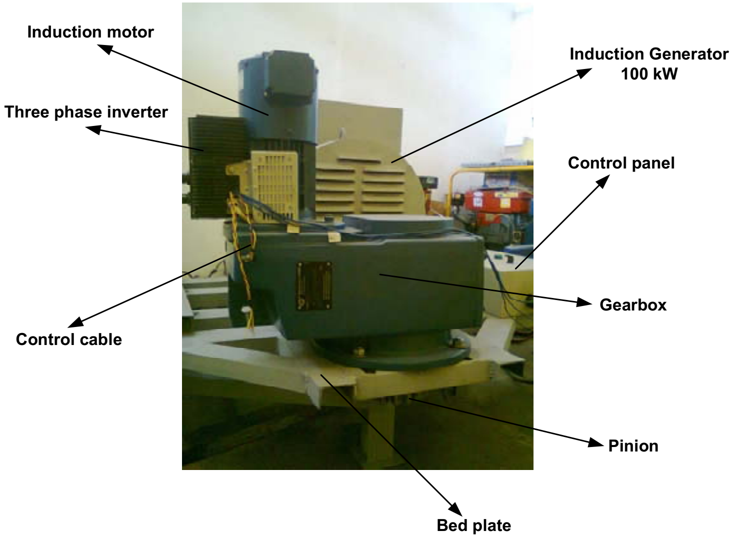


Figure 1: Yawing sistem set up in the laboratory.

In the positioning control of the yawing system, the induction motor and inverter play roles as an actuator which receives control command from an electronic controller. The controller delivers a control command to the actuator through a control command interface chard. The interface receives two control commands those are CW (clock wise) control command and CCW (counter clock wise) control command where each control command status may be “On” or “Off”. When the CW control command is activated (“On”) the yaw mechanism rotates in CW direction. Oppositely, when the CCW control command is activated the yaw mechanism rotates in CCW direction. The rotational speed of the induction motor is fixed to a preset value.

The maximum rotational speed of the pinion is 5,4 rpm. Since the gear ratio between the pinion and the slewing bearing is 21:99, the maximum rotational speed of the yaw mechanism becomes 1,15 rpm.

It is known that the present inverter technology with speed control loop used for induction motors provides settling time of 0,5 second. Therefore, in this paper sampling time of positioning controller is set to 0,5 second. During 0,5 second the yawing mechanism travels $2{,}33 \times 10^{-3}$ rotation. Since number of teeth of the slewing bearing is 99, during the period of one sampling time the slewing bearing passes

0,231 (=2,33. 10^{-3} x 99) number of teeth. This means less than ¼ tooth is passed in one sampling time.

If the degree of precision of the yaw mechanism is set to one tooth of the slewing bearing (which corresponds to 1/99 ≈ 1%, which is precise enough in a control system), it will not result in oscillation instability for the actuator is more precise than the required system output. This principle has been applied for designing a controller of a dc/dc converter used in a power supply of microprocessor [12].

In this paper a wind direction sensor of type NRG #200P is used [13]. Basically this is a potentiometer that produces analog output voltage proportional to the wind direction when it is supplied with a constant DC voltage as voltage reference. It can work with power supply between +1 VDC to +15 VDC and only responds to wind speed higher than 1 m/second. Therefore, wind velocity less than 1 m/s will give no effect to the sensor. Measurement span of the sensor is 0˚ to 360˚ with linearity of 1 %. In this paper a power supply of +5 VDC is used as voltage reference of the wind direction sensor.

In the wind turbine electrical power generation plant described in this paper, the electrical power generated by the induction generator is transmitted from the generator terminal in the nacelle at the top of the tower to the power house on the ground via 3 lines of power cables. Control and communication between instruments in the nacelle and instruments in the power house are conducted through fiber optic. The rotation of the nacelle relative to the tower must be limitted, otherwise the cables will be over twisted and broken. In this research the nacelle rotation is limitted to maximum value of 3 rotation either in clock wise (CW) direction or counter clock wise (CCW) direction. When the nacelle has already experienced 3 times rotation in the same direction the yaw electronic controler will send control command to rotate the yaw mechanism in the opposite direction. In this research, a rotary encoder is used to count the number of rotation of the nacelle.

Design of Yaw Positioning Controller

In this paper a yaw positioning controller is designed having three control modes as follows.

1. Control mode 1 (maximizing mode): tracking towards yaw angle reference value of 0˚.
2. Control mode 2 (minimizing mode): tracking towards yaw angle reference value of 90˚.
3. Control mode 3: Anti twist.
4. Control mode 4: Shutdown

Reference angle 0˚ is devoted to maximize wind energy conversion while the reference angle 90˚ is to minimize wind energy conversion to electrical power. Anti twist control mode is used to avoid the power and control signal cables being over twisted and broken. Shutdown control mode is activated when the yawing angle control system needs to be stopped from operating for the purpose of safety.

Since the wind direction sensor is fixed on the top of the nacelle, the sensor output signal y_θ (volt) implies the error (deviation) between the nacelle (turbine) direction θ_n (°) and the wind direction θ_w (°).

$$y_\theta = G_s(\theta_n - \theta_w) \quad (1)$$

where: G_s denotes the gain of the wind direction sensor.

In the maximizing mode, the yaw controller moves the nacelle so that the output signal of the wind direction sensor becomes 0 (Volt). When the direction of the wind varies the yaw positioning controller should be able to make the nacelle direction follows the wind direction. In this sense, the yaw positioning controller must be designed to realize the function of a tracking controller.

In this paper the yaw positioning controller is designed using on/off control having dead band and hysteresis. Figure 2 shows input-output characterisitcs of this control approach. Parameters Δ and h represent dead band value and hysteresis value, respectively. x is the input variable and M is the output value. The input of this controller is the deviation between reference value r and the wind sensor output signal y_θ.

$$x = r - y_\theta \quad (2)$$

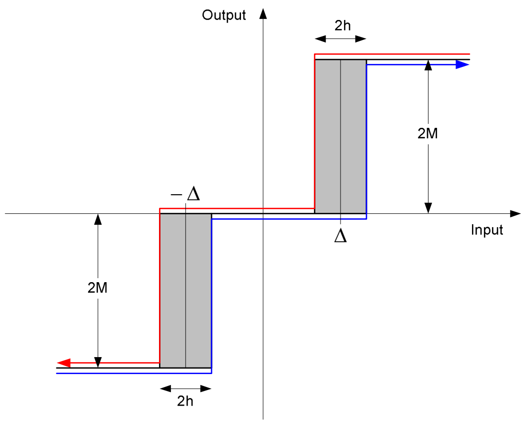


Figure 2: Input output characteristics curve (on/off control with dead band and hysteresis).

The describing function of on/off control with dead band and hysteresis is given by the following equation [10].

$$N = \sqrt{\left(\frac{A_1}{X}\right)^2 + \left(\frac{B_1}{X}\right)^2} \angle \tan^{-1}\left(\frac{A_1}{B_1}\right) \quad (3)$$

where:

$$\frac{A_1}{X} = -\frac{4\alpha\beta}{\pi}\left(\frac{\Delta}{X}\right)^2;$$

$$\frac{B_1}{X} = -\frac{2\beta}{\pi}\frac{\Delta}{X}\left[\sqrt{1-\left(\frac{\Delta}{X}\right)^2(1-\alpha)^2} + \sqrt{1-\left(\frac{\Delta}{X}\right)^2(1+\alpha)^2}\right]$$

$$\alpha = \frac{h}{\Delta};\ \beta = \frac{M}{\Delta}$$

The block diagram of the yaw control system is illustrated in figure 3.

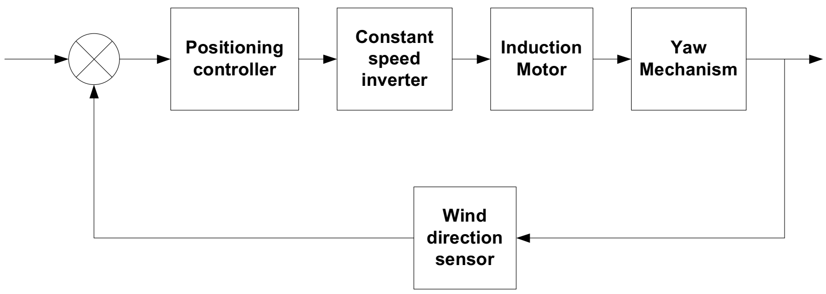
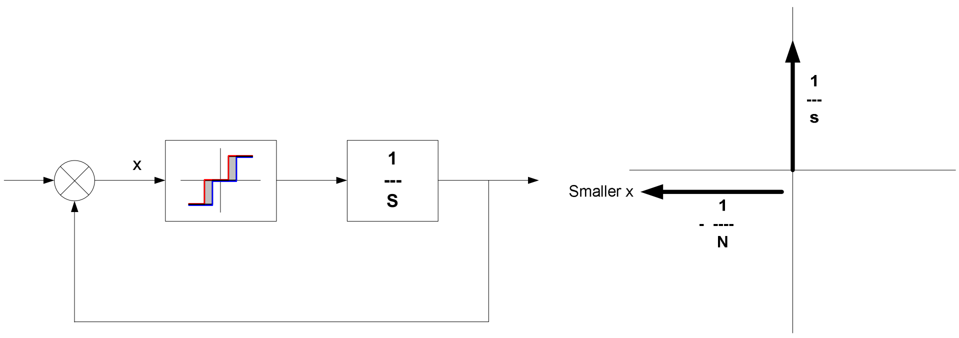


Figure 3: Block diagram of the yaw control system.

The induction motor is controlled by the inverter which consitutes a speed control. Therefore, the plant to be controlled by the positioning controller can be expressed as an integrator as illustrated in figure 4 (a) whose the Nyquist diagram is illustrated in figure 4(b).

From the Nyquist stability criterion it is known that if the position of $-\frac{1}{N}$ is not covered by the position of $G(j\omega)$ then the system is stable and a limit cycle instability will not occur in the steady state [10]. Thus, the on/off control with dead band and hysteresis will not produce any oscilation.



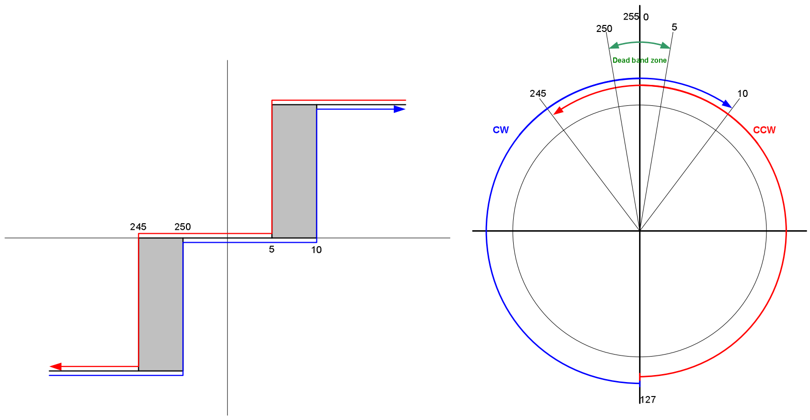
(a)Integrator expression (b)Nyquist diagram

Figure 4: Illustration of the control system block diagram and its Nyquist diagram.

When the yaw angle deviates from 0˚ wind energy conversion will reduce by factor of $cos^3\theta$ [14]. It is known that yaw angle deviation of 10˚ results in a small acceptable value of power reduction [15]. From calculation it is obtained that 10˚

yaw angle deviation reduces power by 4,5%. Yaw angle deviation of 10˚ corresponds to 2,78% rotation of the yaw mechanism.

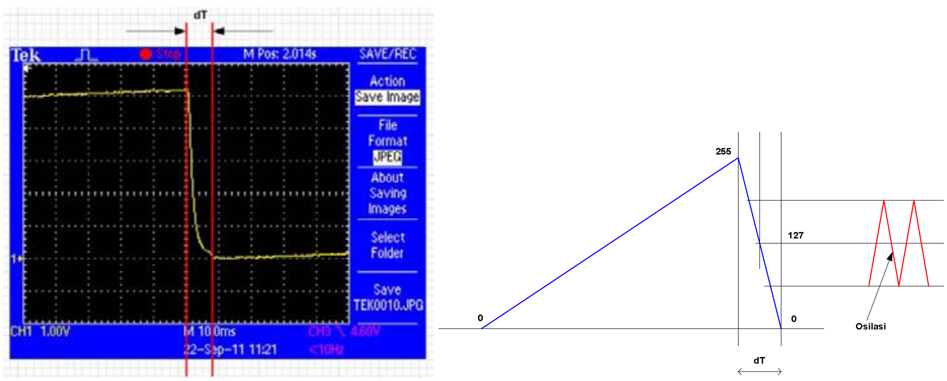
From this derivation, in this paper the dead band value is set around 10˚ as shown in figure 5(a). The proposed control method is illustrated by a circle diagram in figure 5(b). The controller parameter values are set as follows: Δ=0,185 rad., h = 0,062 rad., M = 0,015 rad./second.



(a)On/off control with dead band. (b)The circle expression

Figure 5: Illustration of the proposed control method.

Wind direction may vary fast. Moreover, miss information from the wind direction sensor output may occur when yaw angle moves from 360˚ to 0˚ and vice versa. Figure 6 shows the wind direction sensor output transition from 5V (360˚) to 0V (0˚) which experiences gradual change. The output needs 80 ms to completely change from 5V to 0V. This will stimulate oscillation around 0˚ when a tracking positioning controller is not designed properly. In this paper the yaw electronic controller is design not to respond any fast change of wind direction.



(a)Experimental result (b)Oscillation around 0˚

Figure 6: Wind direction sensor output and illustration of oscillation around 0˚.

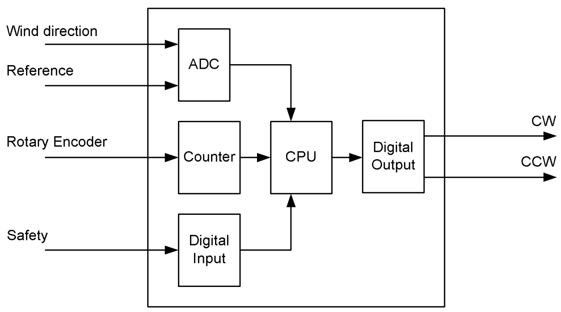
From the above controller design description, it is summarized that in this paper a yaw positioning tracking controller is designed according to the following approaches:

When the yaw angle resides outside the predetermined dead band zone then the positioning controller rotates the actuator to make the yaw angle moves to the reference angle.

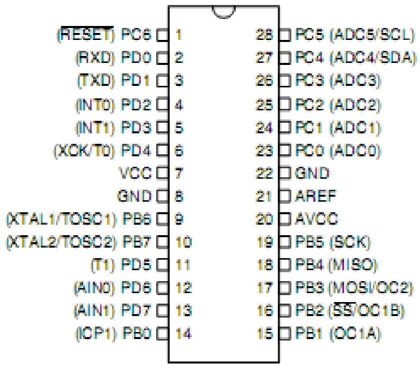
When the yaw angle resides inside the predetermined dead band zone the positioning controller stops the actuator.

The positioning controller only responds to slow change of the wind direction. The controller does not respond to sudden change of direction as well as deviation around 0˚.

Figure 7(a) shows the block diagram of the yaw positioning controller developed in this paper. The controller is realized using a microcontroller (Atmega 8) having pin assignment shown in figure 7(b).



(a)Block diagram of the yaw controller



(b)Pin assignment of Atmega 8 [11].

Figure 7: Realization of the yaw positioning electronic controller.

The yaw electronic controller will be located in the nacelle at the top of the tower. It receives reference signal from the supervisory controller located in the power house on the ground. A convention of communication protocol between the supervisory controller and the yaw controller must be establised. Table 1 shows one example of such communication protocol. When the supervisory controller experiences malfunction (fault) it delivers 0 (V) by default which is intepreted as "Shutdown reference signal" by the yaw controller. To avoid miss information due to noise, in table 1 the difference between the maximum reference value and the minimum reference value lays around 1,2 (V) to 1,25 (V).

Figure 8 shows the flow chart of the control algorithm used in this paper. This algorithm was coded in the microcontroller to realize the designed yaw positioning controller.

Table 1: Communication between the supervisory controller and the yaw controller.

Reference signal	Nominal reference value (V)	Voltage range accepted by the microcontroller (V)
Shutdown	0,63	0,00 – 1,25
Anti twist	1,88	1,30 – 2,50
Angle reference 0°	3,12	2,55 – 3,75
Angle reference 90°	4,38	3,80 – 5,00

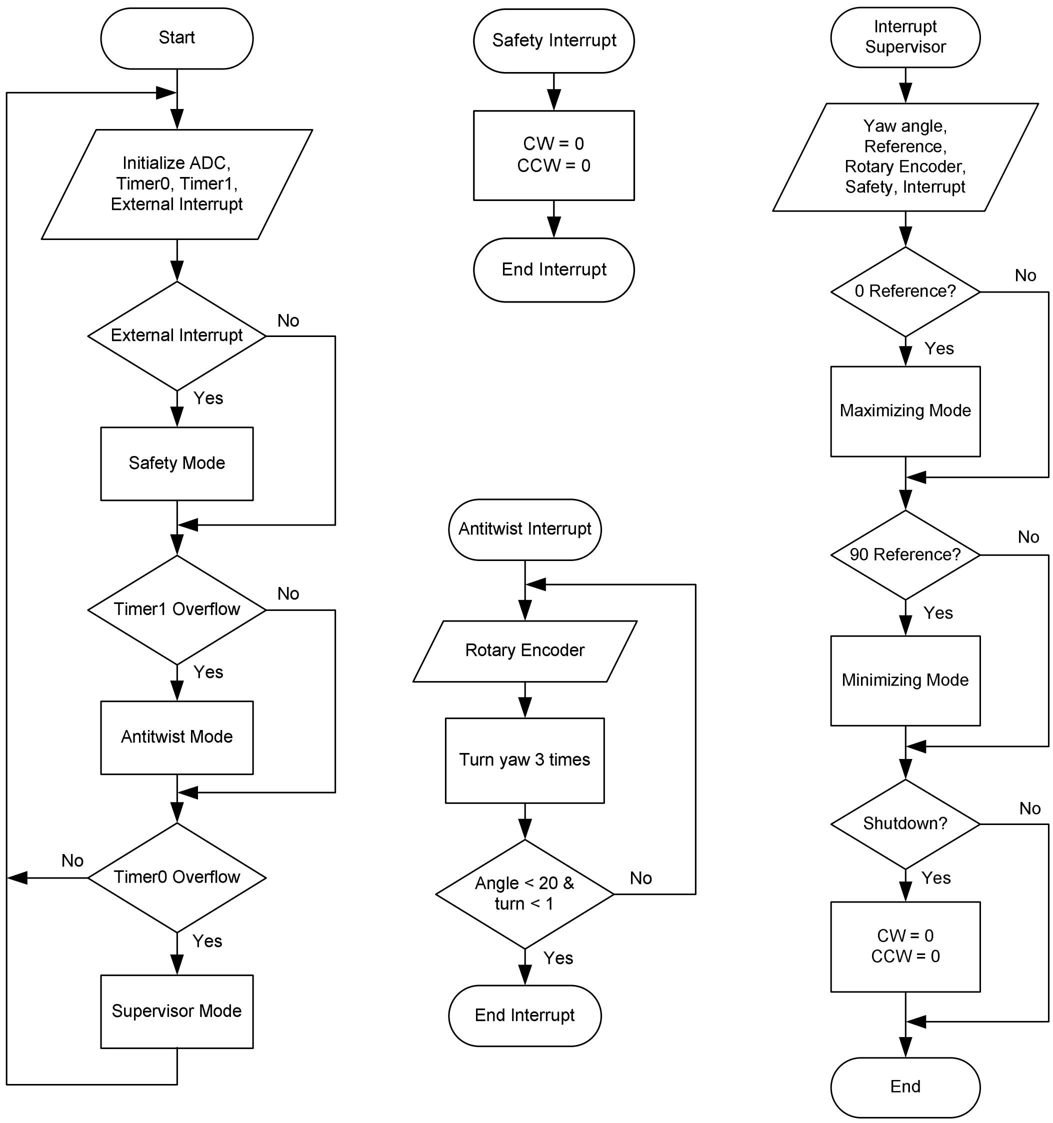
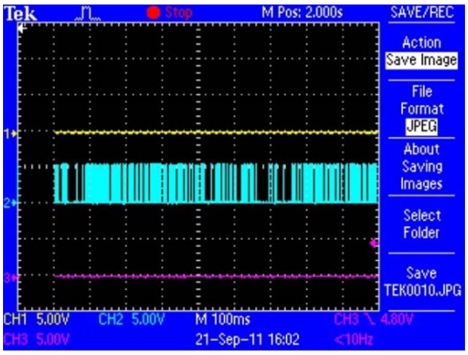


Figure 8. Flow chart of the control algorithm proposed in this paper.

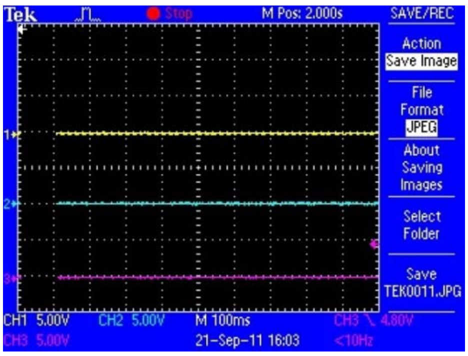
Experimental Results

An instrumentation set up was used for experiment. This set up is constructed by the yaw electronic controller, a driver circuit, a power supply and an osciloscope. The control command produced by the yaw controller is amplified by the driver circuit and then it is delivered to the interface card fixed in the inverter. The power supply provides electrical power to both the yaw controller and the driver circuit. The osciloscopes monitor 3 signals those are CW control command, CCW control command and yaw angle signal. Both CW control command and CCW control command work at TTL level (0 (V) and 5 (V)). 0 (V) represents the control command being passive and 5 (V) represents the control command being active. During experiment the rotational speed of the yaw mechanism is set to ¼ maximum speed which equals to 0,28 rpm.

Figure 9 shows the experimental results when the yaw angle is around 0°. Figure 9(a) shows the result when the sampling time of the controller is set 20 micro second while figure 9(b) shows experimental result when the sampling time of the controller is set 0,5 second. The blue line indicates CW control command, the red line indicates CCW control command and the yellow line indicates yaw angle signal. It is obvious that the controller having the faster sampling time produces oscillation around 0°, while the controller having the slower sampling time provides better performance without any oscillation around 0°.



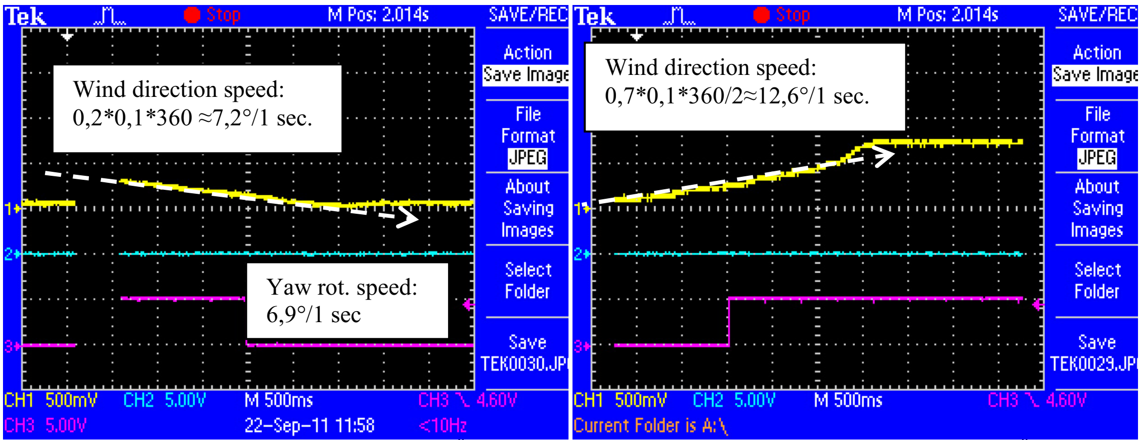
(a)Controller with sampling time 20 micro sec



(b)Controller with sampling time 0,5 sec.

Figure 9: Sampling time effect on the performance around 0^0.

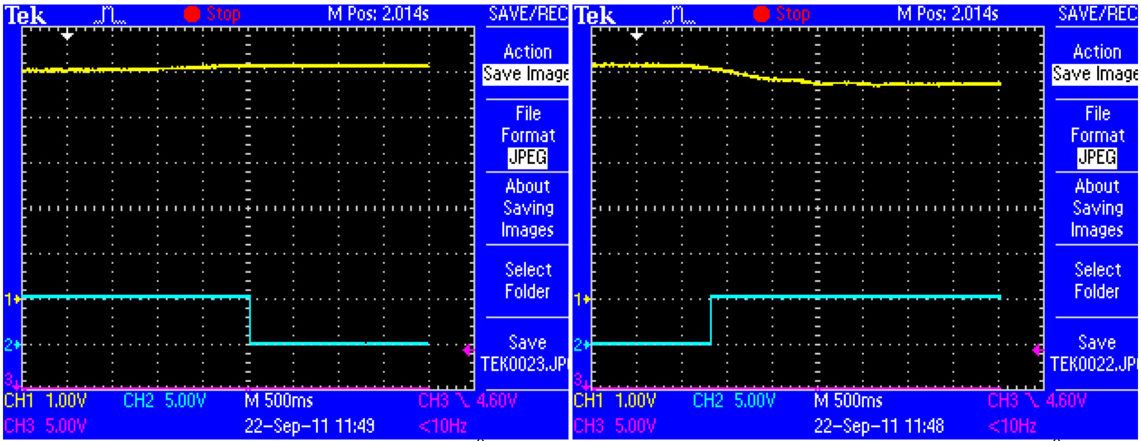
Performance of the controller with 0,5 second sampling time was then further evaluated. Figure 10 demonstrates experimental results when the yaw mechanism rotates following the wind direction trajectory which moves in the CCW direction from 180^0 . The yellow line, red line and blue line denote the yaw angle, CCW control command and CW control command respectively. The horizontal axis denotes time series with resolution of 0,5 second/division which implies that every one horizontal division of activated control command yields $3{,}45^0$ rotational angle of the yaw mechanism. Note that the vertical axis of the yellow line has the resolution of 0,5 V/division which corresponds to 36^0/division. Figure 10(a) shows the result when the yaw mechanism moves towards 0^0, while figure 10(b) shows the result when the yaw mechanism moves apart from 0^0. It can be seen that the controller drives the yaw mechanism towards 0^0 by sending “On” CCW control command until the yaw angle crosses the dead band zone line (10^0) where suddenly the CCW control command turns to “Off”. The control command keeps “Off” even the yaw angle further moves to completly 0^0. However, when the yaw angle moves leaving 0^0 towards 180^0, the CCW control command turns to “On” just at the time when the yaw angle crosses outside of the dead band zone line (10^0). The CCW control command maintains “On” until the yaw angle crosses again the dead band zone line as shown in figure 10 (a). When the yaw angle is positive against the wind direction (0^0) the CCW control command is activated while the CW control command is deactivated.



(a).The yaw angle moves towards 0^0 (b).The yaw angle moves leaving 0^0

Figure 10: The yaw mechanism rotates in the CCW direction at 0^0 vicinity.

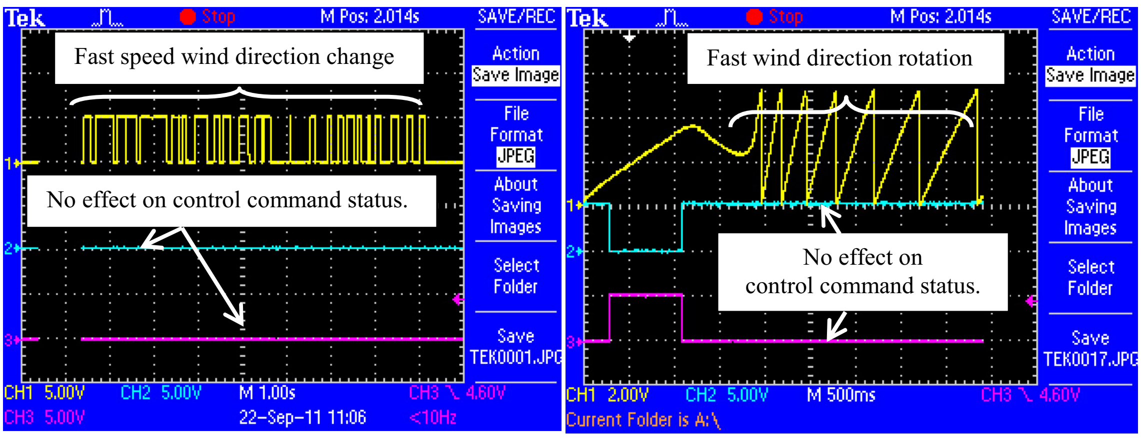
Figure 11 demonstrates experimental results when the yaw mechanism rotates following the wind direction trajectory which moves in the CW direction from 180^0 . The yellow line and the blue line denote the yaw angle and CW control command respectively. The horizontal axis denotes time series with resolution of 0,5 second/division. Note that the vertical axis of the yellow line has the resolution of 1 V/division which corresponds to 72^0/division. Figure 11(a) shows the result when the yaw mechanism moves towards 360^0, while figure 11(b) shows the result when the yaw mechanism moves apart from 360^0. It can be seen that the controller drives the yaw mechanism towards 360^0 by sending “On” CW control command until the yaw angle crosses the dead band zone line (350^0) where suddenly the CW control command turns to “Off”. However, when the yaw angle moves leaving 360^0 towards 180^0, the CW control command turns to “On” just at the time when the yaw angle crosses outside of the dead band zone line (10^0). The CW control command maintains “On” until the yaw angle crosses again the dead band zone line as shown in figure 11(a). When the yaw angle is negative relative to the wind direction (0^0) the CW control command is activated.



(a).The yaw angle moves toward 360^0 (b).The yaw angle moves leaving 360^0

Figure 11: The yaw mechanism rotates in the CW direction at 360^0 vicinity.

Figure 12 shows experimental results when wind direction speed is very fast. Figure 12(a) demonstrates the results when the wind direction changes back and forth between CW and CCW direction around 0˚. Figure 12(b) shows the results when wind direction rotates in the same direction slowly in the beginning but getting faster after 1,25 second.



(a).Wind direction changes very fast (b)Wind direction rotates very fast

Figure 12: Wind direction moves very fast.

It is obvious that neither CW control command nor CCW control command responds to such fast speed wind direction change as well as to such fast wind direction rotation.

Conclusion

From the experimental results the following conclusion can be drawn.

The designed yaw positioning controller with sampling time of 0,5 second provides satisfactory performance at 0˚ vicinity without any cyclic instability.

The designed yaw positioning controller makes the yaw mechanism not respond to either fast change of wind direction or fast wind direction rotation.

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