Intelligent Control Approach for Fluid Power Transmission of a Wind Turbine System

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Abstract. Fluid power transmission has caught the eye in recent times, in the field of wind turbine technology. The turbine rotor blades tend to yield an aerodynamic torque, which is transformed into a high pressure fluid through a pump. This fluid is utilized to generate speed and torque yet again at the distant end of the circuit. The paramount objective of this research is to obtain a virtually operating dynamic model of a hydraulic powered transmission in a wind turbine, in order to understand its dynamic behaviour and also, to obtain knowledge about the influence of the prime parameters on the wind turbine. To accomplish this task, a virtual hydraulic powered wind turbine system is designed with a power rating of 23KW. The process is virtually simulated on the AUTOMATION STUDIO software (version 6.2). The intelligent control strategy used in the present work is based on fuzzy logic that uses human intelligence for a particular desired outcome. The effectiveness of the recommended controller is contrasted with that of a conventional PID controller in the following paper.

Keywords: Wind Turbine, Automation Studio, Conventional Controller, Fuzzy Logic Controller

1. Introduction

Wind turbines technology is the most adequate and ecologically-friendly form of energy. They work on the simple principle of energy transformation, where the kinetic energy of the wind is converted into mechanical form of energy initially. This is followed by, conversion to electrical energy by means of a generator. Since wind energy being a pollution free form of energy, maintaining the entire set up proves to be very costly. In order to evade the high cost of maintenance, the turbine system is run at constant speeds. The disadvantage of this process is that, maximal wind speed energy isn’t captured by the turbine, as the wind speed keeps fluctuating, hence reducing the overall efficiency of the system. The presence of a continuous variable transmission (CVT) can provide an apt solution to this problem [1,2]. Amongst the many CVT used in the industries, Fluid/Hydrostatic transmission is the most ecologically sound and cost effective form of transmission. Applying befitting control strategies, fluid power transmission can be used in mid-range turbines. This can also cut down on the maintenance cost [3,4].
This paper elucidates the mathematical modeling of a fluid power transmission system. This model is developed in accordance to several equations of fluid power transmission circuit components such as; a hydraulic motor coupled with a generator, several hydraulic safety elements and several other flow based control components. The major focus of this paper is to attain continuous power generation under all working conditions [5]. Development of a controller circuit mainly focuses on obtaining the best form of quality control. The appropriate working conditions can be obtained from simple PI (proportional + integral) controller, or maybe PID (proportional + integral + derivative). There are certain possibilities of non-linearity arising in the model development due to the uncertainty of the wind turbine. Simple controllers like PI and PID can only work smoothly if the process parameters are defined very well. High amount of non-linearity in the model development can lead to their ineffectiveness in the control process. In such a scenario utilizing the fuzzy control concepts, could be more functional [6]. A simple fuzzy based controller, involving a classical approach allows conclusions that could be either true or false. Usually this involves categorizing various ranges or sub-ranges of a continuous variable. This categorization into several ranges usually helps in controlling the concerned parameters. Fuzzy logic is very useful, since it helps in the mapping of mathematical input values into membership functions. The reverse is also possible [7, 8].

The paper will deal majorly with the following control objectives:-

(i) Modeling of hydrostatic transmission system for wind turbine and simulation of the Hydraulic Circuit.

(ii) Approximation of data acquired from “Automation Studio 6.2” into transfer function model for Motor speed by utilizing the tool box system identification tool box accessible in MATLAB.

(iii) Design of Proportional plus Integral plus Derivative Controller and fuzzy logic based Control systems for controlling the Motor speed of the turbine

(iv) Comparison of effectiveness of both control systems.

2. Development of a Hydraulic Power Transmission Model

2.1 Conventional Wind Turbine Basics

A typical wind turbine system can be seen in Fig. 1. The system comprises of turbine blades (a tower onto which the blades are connected), a nacelle, which is connected to a hydraulic pump. At this stage, the kinematic energy of the wind turbine is transformed into pressure energy by the pump. This fluid which is pressurized facilitates the rotary movement of the hydraulic pump through pressurized lines owing to the difference in volumetric displacement between the motor and the hydraulic pump. This pressure energy is then converted to electric energy as the hydraulic motor is coupled to a generator. As the Air flows over the turbine blades, it causes the shaft of the turbine to rotate. After the generator there is a transformer and a power converter enabling to convert the frequency and the voltage level in such a way that the power will be supplied eventually into the power grid. The safe and effective operation of the wind turbine is provided by the controller [9].

To describe model of this system, the subsequent set of governing equations are used:

The \( P_{\text{wind}} \) is the raw power obtained from the wind:-

\[
P_{\text{wind}} = \frac{1}{2} \rho A U^3
\]  

(1)

Where \( \rho \) indicates the air intensity at the blades, \( A \) is the swept area of the blades of the wind turbine and \( U \) is the wind speed.

Now the power that is available at the rotor can be depicted by the following equation:-

\[
P_{\text{rotor}} = P_{\text{wind}} C_p(\lambda, \beta)
\]  

(2)

Where \( \lambda \) – tip speed ratio, \( \beta \) - pitch angle, \( C_p \) - power coefficient

Finally, the torque asserted at the rotor can be indicated as follows:-

\[
\tau_{\text{rotor}} = \frac{1}{2} \rho A H \frac{C_p}{\lambda}(\lambda, \beta)U^2
\]  

(3)
2.2 Fluid power Transmission Circuit Design

The modelling of fluid power transmission system using AUTOMATIONSTUDIO comprises of a variable displacement bi-directional pump/motor connected to a wind turbine (Fig.2). It converts mechanical energy obtained from the turbine into pressure of the oil, which is then transmitted through pipes to the hydraulic motors. The pressure of the oil is converted in to rotation of hydraulic motor which in turn will be connected to the generator to produce electrical energy.

 Certain equations and input parameters need to be considered for the functioning of the model. Several input parameters are obtained from making basic calculations using virtual blade calculator software [10]. The initial conditions required for the software include, the tip speed ratio (TSR) which is assumed as 7, the number of blades as 3, blade efficiency is considered at about 40%, and finally blade radius is considered to be 1 m. These parameters are required to obtain the input blade torque values. When input wind speed of 15m/sec is considered, alongside the above mentioned input parameters, an output torque (input blade torque) of 370Nm is obtained, for an output speed of 586 RPM.
The flow of the pump can be obtained from the following equation:-
\[ Q_p = D_p \omega_p - k_{l.p} P_p \]
where, \( D_p \) stands for displacement of the pump, \( k_{l.p} \) here is for the pump leakage coefficient and \( P_p \) stands for differential pressure of the pump which is shown below as
\[ P_p = P_t - P_q \]
where, \( P_t \) and \( P_q \) are the gauge pressures obtained along the two terminals.

The coefficient of leakage, of the variable displacement bi-directional pump is shown as
\[ k_{l.p} = \frac{k_{H.P.p}}{\rho v} \]
where, \( \rho \) is the density of the fluid (SHELL TELLUS S-32) which is 872 kg/m\(^3\), \( v \) stands for kinematic viscosity of the fluid which is 32 cst and \( k_{H.P} \) stands for Hagen-Poiseuille coefficient and can be seen below as
\[ k_{H.P.p} = \frac{D_p \omega_{nom.p}(1-\eta_{vol.p}) v_{nom.p}}{P_{nom.p}} \]
where \( \omega_{nom.p} \) stands for the pump’s nominal angular speed, \( v_{nom} \) stands for the nominal fluid kinematic viscosity, \( P_{nom.p} \) stands for the pump pressure nominally and \( \eta_{vol.p} \) is the pump efficiency in volumetric terms. Finally, the shaft torque in relation with the pump is given by
\[ T_p = \frac{D_p \rho}{\eta_{mech.p}} \]
where \( \eta_{mech.p} \) is the efficiency of the pump in mechanical terms is given as follows:-
\[ \eta_{mech.p} = \frac{\eta_{total.p}}{\eta_{vol.p}} \]
Likewise, an equation used for displacement \( D_m \) with regards to the motor flow is 0.112l/rev, leakage coefficient \( k_{l.m} \) and differential pressure \( P_m \) can also be shown as:-
\[ Q_m = D_m \omega_m - k_{l.m} P_m \]
\[ P_p = P_a - P_b \]
\( k_{l.m} \) is the density \( \rho \) of the fluid, viscosity \( v \) in kinematic terms and Hagen-Poiseuille coefficient \( k_{H.P.m} \) is given by
\[ k_{H.P.m} = \frac{D_m \omega_{nom.m}(1-\eta_{vol.m}) v_{nom.m}}{P_{nom.m}} \]
Where \( \omega_{nom.m} \) is the motor angular speed nominally, \( v_{nom} \) is the nominal viscosity of the fluid in kinematic terms, \( P_{nom.m} \) is the pressure motor nominally and \( \eta_{vol.m} \) is the efficiency of the motor, in volumetric terms. Finally, the shaft torque driving the motor is given by
\[ T_m = D_m \rho \eta_{mech.m} \]
Where \( \eta_{mech.m} \) is the efficiency of the motor in mechanical terms is shown by:-
\[ \eta_{mech.m} = \frac{\eta_{total.m}}{\eta_{vol.m}} \]
An equation regarding the compressibility of the bulk modulus, volume \( V \) of the fluid in total, pressure \( P \) of the system and flow rate \( Q \) is specified as:-
\[ Q_c = \left( \frac{V}{\beta} \right) \left( \frac{dP}{dt} \right) \]
And
\[ Q_c = Q_p - Q_m \]
Hence,
\[ \left( \frac{dP}{dt} \right) = \left( Q_p - Q_m \right) \left( \frac{\beta}{V} \right) \]
The torque generated from the motor in total is calculated as
\[ T = \frac{PD}{2\pi} \]
Where $D$ is volumetric displacement and $P$ is pressure.

The data regarding angular speed and motor pressure is obtained by simulating the circuit in AUTOMATION STUDIO 6.2 software. The data regarding motor pressure is utilized to obtain the motor torque.

3. Auto Regressive Modelling
Auto Regressive Models with Exogenous input may utilize time-domain and frequency-domain input-output data to describe continuous-time and discrete-time transfer functions, process models, and state-space models. This model contributes many identification techniques such as maximum likelihood, prediction-error minimization (PEM), and subspace system identification [11]. This ARX model performs grey-box system identification to estimate specifications of an user-defined model. This model can utilize the already identified model for system response prediction and plant modelling in Simulink.

In the present work, an ARX model has been obtained relating Motor Speed (Output) and Pump Speed (Input) and the model fits up to 99.79%.

The below mentioned steps are essential for modelling of the ARX model:
1. The apt values for the framework of the wind turbine obtained approximately by the ARX model from the recorded input and output data.
2. The order and gain for the ARX model are depicted by $[K T_{p1} T_{p2}]$ notations. Here $K$ is the gain; $T_{p1}$ and $T_{p2}$ are process time constants.

An ARX model has been developed using input and output data collected for the data sets of wind turbine and the model response is shown in Fig.3. Here samples below are taken over a time period of 32.8995 secs.

$$G_{p1}(s) = \frac{2.0009}{(59.7791s + 1)(0.0000016751s + 1)}$$ (20)

![Figure 3. Measured and Simulated Output for Motor Speed](image)

4. Designing and Comparing Various Conventional Controller Strategies with Fuzzy Logic Controller
The analysis and designing of a fluid power transmitting system needs the selection of the best type of controller. The previously obtained process transfer function for motor speed needs to be transformed into block diagrams based on its open loop response (Fig.3). The block diagrams are imported onto Simulink, for obtaining an apt controller for the fluid transmission system. A proportional plus Integral controller (PI), Proportional plus Integral plus Derivative (PID) controllers are designed because of their simplicity. This isn’t always the case, as some processes might be highly non-linear in nature, hence making it a lot harder to control the process. To counter such a scenario, a fuzzy logic controller can be used and detailed description of FLC is given in ref 12.
The objective is to define the rules, and the membership function necessary to fulfill the proposed function or model of the dynamic system, using TSK (Takagi-Sugeno-Kang) fuzzy structure. The same procedure used in TSK case can also be applied to Mamdani fuzzy structures. In the Simulation, a TSK fuzzy structure along with tuning of scaling gains are used with respect to 3x3 rule base, as defined in Table 1. So the rule table remains fixed, and the scaling gains are varied to obtain the desired response. The resulting scaling gains used for error, change in error and controller output are 3, 70 and 0.4 respectively.

Table 1 Fuzzy Rule Table for Triangular Membership Function

| e(K) | NN | ZZ | PP |
|------|----|----|----|
| Δ e(K) | NN | NN | ZZ |
| NN | NN | ZZ | PP |
| ZZ | NN | ZZ | PP |
| PP | ZZ | PP | PP |

Where NN stands for Negative, ZZ-Zero and PP-positive of rule based system. For optimizing fuzzy logic control of a generator requires a controller that can track wind speed in order to obtain maximum power from the wind turbine without being affected by the variable winds. For a certain value of wind speed, the function of the fuzzy controller FLC is to obtain the speed of a generator in steps until the system settles down at the maximum output power operating point.

5. Simulation Results and Discussion

In the present study an attempt has been made to analyse the closed loop characteristics of Wind turbine for controlling Wind Speed. The effectiveness of Fuzzy Logic controller as shown in Fig.5 over Conventional controller shown in Fig.4 are analysed with different set point changes and with different simulation times. Figures 6, 7, 8, 9, 10 & 11 depict the corresponding closed loop responses of Wind Turbine for different controller designs. Tables 2, 3 and 4 give the time domain and error statistics of a Wind turbine for various controller settings.

![Figure 4 Simulink block diagram of wind turbine system with Conventional Controller](image)

The following tabulated parameters provide important data pertaining to the motor angular speed as per its respective Simulink block diagram. Where RS- repeating sequence, Kp - proportional gain, Ki - integral gain, Kd - derivative gain, tp -peak time, ts - settling time, %Mp for percentage peak overshoot, ISE - integral squared error and finally IAE - integral absolute error.
Figure 5  Simulink block diagram of wind turbine system with Fuzzy based Controller

Figure 6  Simulation Analysis of Motor Speed under different Controllers (Simulation Time=1000Secs)

Figure 7  Simulation Analysis of Motor Speed under Conventional Controller(PID) and Fuzzy based Controller (Simulation Time=1000Secs)
### Table 2. Performance Analysis of Wind Turbine for Different Motor Speeds  
(Simulation Time = 1000 Secs)

| RS | $K_p$ | $k_i$ | $k_d$ | $T_p$ (sec) | $T_s$ (sec) | %Mp | ISE     | IAE     |
|----|-------|-------|-------|-------------|-------------|------|---------|---------|
| PI | 1 4 2 | 0.487 | 0.053 | -           | 48          | 125  | 0.15    | 3.25E+05| 4664    |
| PID| 1 4 2 | 2     | 0.05  | 0.1      | -           | 65   | -       | 9.66E+04| 1972    |
| FLC| 1 4 2 | -     | -     | -        | 18          | 20   | 0.125   | 2.38E+04| 411.7   |

![Graph](image.png)

**Figure 8** Simulation Analysis of Motor Speed under different Controllers (Simulation Time=2000Secs)

![Graph](image.png)

**Figure 9** Simulation Analysis of Motor Speed under Conventional and Fuzzy based Controllers (Simulation Time=2000Secs)
Table 3. Performance Analysis of Wind Turbine for Different Motor Speeds
(Simulation Time = 2000 Secs)

| Controller | RS | $K_p$ | $K_i$ | $K_d$ | $T_p$ (sec) | $T_s$ (sec) | %$M_p$ | ISE         | IAE         |
|------------|----|-------|-------|-------|-------------|-------------|--------|-------------|-------------|
| PI         | 1 4 2 | 0.487 | 0.053 | -     | 48          | 125         | 0.15   | 3.25E+05    | 4664        |
| PID        | 1 4 2 | 2     | 0.05  | 0.1   | -           | 70          | -      | 1.45e+05    | 3453        |
| FLC        | 1 4 2 | -     | -     | -     | 20          | 22.5        | 0.135  | 3.46E+04    | 723.8       |

Figure 10. Simulation Analysis of Motor Speed under Different Controllers
(Simulation Time=3000Secs)

Figure 11. Simulation Analysis of Motor Speed under Conventional and Fuzzy based Controllers(Simulation Time=3000Secs)
Table 4 Performance Analysis of Wind Turbine for Different Motor Speeds
(Simulation Time = 3000Secs)

|   | RS |  |  |  |  |  |  |  |
|---|----|----|----|----|----|----|----|
|   | PI  |  |  |  |  |  |  |  |
|   | 1 4 8 6 | 0.487 | 0.053 | - | 125 | 140 | 0.0875 | 1.55E+06 | 1.78E+04 |
|   | PID |  |  |  |  |  |  |  |
|   | 1 4 8 6 | 2 | 0.05 | 0.1 | - | 125 | - | 6.31E+05 | 9502 |
|   | FLC |  |  |  |  |  |  |  |
|   | 1 4 8 6 | - | - | - | - | 28.125 | 30 | 0.0625 | 1.48E+05 | 1864 |

The simulation studies, as shown above were carried out for different motor speeds with different controller settings. By observing the above simulation analysis Integral Square Error (ISE) and Integral Absolute Error (IAE) are very much reduced and requirements of good controller designs are satisfied with fuzzy logic controller design by proper tuning of scaling gains in the error, change in error and output scaling gain. Also the settling time for fuzzy controller is very much reduced when compared to other controller.

6. Conclusion

Hydraulic transmission system for wind turbine has been modelled and different process control strategies have been implemented through simulation to maximize power. The performance of fuzzy logic controller is better than the simple conventional methods such as PI and PID. Fuzzy controller is implemented to continuously and rigorously adapt the rotational speed of the synchronous generator to the wind speed such that maximum aerodynamic efficiency is achieved.

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