1-1-2006

Energy storage system for reduction of mid-line voltage variation of a DFIG wnd turbine connected to a weak grid

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Abstract

Penetration of wind power into electricity system is constantly increasing. Wind resources are usually distant from existing transmission lines. Wind farms are often connected to weak grids far from central generation stations. Maximum wind power extraction causes the more irregular and unpredicted power output of wind turbine, which has same nature as wind speed variation. The voltage in such long line is vulnerable with the consumption and generation imbalance. In a long line, the mid-line voltage is largely affected by the variation and the penetration of the wind fluctuating power. Fluctuating nature of wind power output and long transmission line have led to concern that the voltage disturbances impressed on the weak system may become unacceptable. Fluctuating power and X/R ratio are key contributors for unnecessary voltage fluctuation and variation along the feeder. Control of the wind power fluctuation and variation can prevent the excessive voltage fluctuation and variation in the system. The weak grid with a doubly fed induction generator (DFIG) wind turbine has a higher probability of the voltage variation due to the fluctuations of the wind speed and load demands. To compensate the variation of power and voltage in a weak grid system, an energy storage system can be designed to provide fast controllable responses. In this paper, effect of energy storage system for reduction of voltage variations has been investigated. The investigation has been carried out through modelling of a doubly fed wind turbine and an energy storage system using SimPowerSystems tools of MATLAB. 1.

Keywords

connected, turbine, grid, wnd, weak, dfig, variation, voltage, line, mid, reduction, system, storage, energy

Disciplines

Engineering | Science and Technology Studies

Publication Details

M. Aktarujjaman, K. A. Kashem, M. Negnevitsky & G. Ledwich, "Energy storage system for reduction of mid-line voltage variation of a DFIG wnd turbine connected to a weak grid," in Australasian Universities Power Engineering Conference (AUPEC 2006), 2006,

HydroTurbine Governor Control: Theory, Techniques and Limitations

Hydro-Turbine Governor Control: Theory, Techniques and Limitations

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ABSTRACT

With the entry of Tasmania into the national electricity market, equipment upgrades are required in many parts of the existing power system. This presents an opportunity to embrace new technology, in order to enhance the current efficiency and productivity of the system. One area is that of hydro-turbine speed governors, an integral part of maintaining the frequency of the output. This paper analyses the current standard control algorithm for turbine governors, the PID controller. It illustrates the processes involved, tuning and their limitations. Finally, alternative control systems are discussed.

1. INTRODUCTION

Hydro Tasmania is currently upgrading much of its plant and equipment, mostly due to the wear and tear of existing systems. This is part of an overall upgrade program intended to bring Tasmania's power industry into line with the National Electricity Market Management Company (NEMMCO) standards. One important type of equipment to be upgraded in many power generation facilities is the turbine governor.

The turbine governor is a system that regulates the inlet of water into a turbine, which in turn rotates the generator to produce electricity. In order to maintain a required generated frequency of 50Hz the speed of rotation must be kept constant. The turbine governor receives information on the current rotational speed of the turbine and adjusts the water flow to maintain the speed at the correct level.

Many of the governors currently in use by Hydro Tasmania are of older, purely mechanical design. While effective, these suffer from mechanical wear due to aging. As these units reach the end of their working life, replacement is essential. At the present moment in time, the replacement of choice within Hydro Tasmania is a Proportional-Integral-Derivative (PID) controller adapted to function as the governor for a turbine.

The use of PID controllers is widespread and popular in many modern industries. The popularity of PID controllers stems in part to their wide applicability to a variety of single input single output (SISO) applications. They are also common, making them easy to obtain.

PID controllers are not without their limitations, however. They are unsuitable for complex systems and lack the ability to adjust to change over time. Intelligent systems offer an alternative approach to control hydro-turbines, avoiding the problems associated with PID controllers. Systems such as Fuzzy Logic controllers, Artificial Neural Networks and Adaptive Neuro Fuzzy Inference Systems offer effective control for complex systems, while remaining relatively simple and easy to implement.

2. THEORY OF PID CONTROL

A PID controller uses an algorithm that provides the control signal in a feedback control loop. The name derives from the three functions involved in calculating the corrections.[1]

The Proportional function deals with present values, multiplying the current error by a set value P and subtracting the resultant value from the process's input. This is only applicable in the performance band where P is proportional to the error of the system. The main problem with a purely Proportional controller is that it will over-react to small errors, causing the system to oscillate. While these oscillations will eventually be reduced and eliminated, it is better to avoid them. Also, while a Proportional controller can achieve a steady state, it is almost impossible to avoid a constant error at this state. Ideally, the controller should have no error at the steady state. This is where the Integral stage comes into play.

The Integral stage handles past values, integrating the error over a period of time. This is then multiplied by a constant and subtracted from the process's input. The integral term subtracts part of the *average* error, hence the average difference between the output and the set-point is always being reduced. This helps reduce the oscillations of a Proportional controller, in that the amplitude of the response is adjusted to match the scale of the error (that is, a small error will not generate a large response). The Integral stage also ensures that the stable state error is reduced to zero.

A system that uses P and I terms only will react slowly to changes in the control variable. As the changes will not manifest themselves in the process output, the controller's reaction will be delayed. The Derivative term attempts to overcome this by predicting the future performance of the system. It does this by taking the first derivative over time of the error. This is multiplied by a constant and subtracted from the process's input. This allows the controller to respond to a change in the system much faster than it would otherwise. The larger the derivative term is, the faster the response to a change is.

When all three functions are combined, the controller can reduce error to zero in a stable state and react rapidly to changes in the overall system. To find the values of the constants used in the PID system, the controller must be tuned.

2.1 TUNING METHODS

The basic equation for a PID controller is given as follows [2]:

$$G_c(s) = K_c\left(1 + \frac{1}{T_i s} + T_d s\right) \tag{1}$$

Where $G_c(s)$ is the controller, K_c is the proportional gain, T_i is the integral constant and T_d is the derivative constant. The processes used to find the values of these constants are known as tuning methods.

When designing a controller (of any type) the primary purpose of the controller must be foremost in all considerations. This can include attenuation of load disturbances, sensitivity to measurement noise, robustness to model uncertainty and the ability to follow the set-point. Issues to be considered include the system dynamics, any possible non-linearities, potential disturbances and the process uncertainty [1]. Consequently the first step in any tuning process is to decide the exact requirements in advance of determining any control parameters. The system to be controlled must be understood, the desired operating condition known and any contributing factors taken into account. Once this has been achieved the controller can be designed to meet the required performance criteria and manage the process effectively.

Manual tuning methods typically depend on being able to test the response of a system manually, and then adjust the values of the PID until a satisfactory response has been found. Some methods of calculating approximate values are also used. These values would then be adjusted manually to achieve the required performance.

Most modern industrial facilities use PID tuning software to ensure consistent results. These utilise the same methods in the manual methods, automating the process to reduce the time required and to help improve standardisation.

2.2 FREQUENCY DOMAIN METHOD

This tuning process was put forward by C.K. Sanathanan [3] in 1988. His paper discussed the tuning of PID controllers to act as a governor for a hydroelectric generator, but the principles can be applied to systems that have a similar arrangement. The block diagram for the system is shown in Figure 1 below [3]:

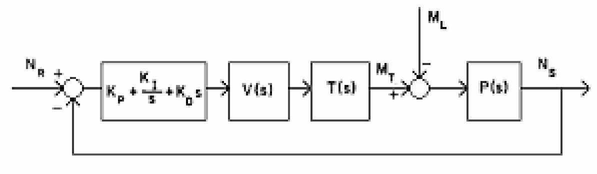

Figure 1: Block Diagram for Control Loop

The first block represents the PID controller. V(s) and T(s) describe individual components of a hydro-generator system (the gate and turbine-penstock respectively) but could just as easily be a single plant. P(s) represents the turbo-generator itself. N_R is the reference speed input (the required speed of the generator in revolutions per minute), M_L is the load placed on the system. N_S is the actual speed of the generator, which is used to determine the error of the system (E).

The first steps in the process [3] involves obtaining detailed transfer functions that describe the operation of the plant (V, T and P). Once these are known a reference model is constructed to represent the system in a theoretical sense. This is shown in Figure 2 [3]:

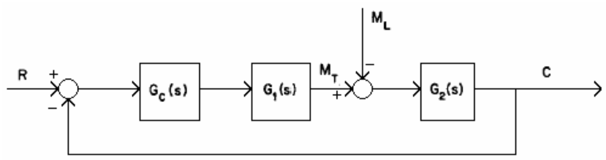

Figure 2: Generalised Model

In this system, $G_C(s)$ represents the controller, $G_1(s)$ combines V(s) and T(s) into a single block and $G_2(s)$ is equal to P(s). The reference model is represented in Figure 3 [3]:

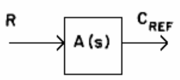

Figure 3: Reference Model

To find $G_C(s)$, the following equation is used [3]:

$$G_C(s) = \frac{A(s)}{[1 - A(s)]G_1(s)G_2(s)} \tag{2}$$

The reference model A(s) is constructed from the known transfer functions for the plant components ($G_1(s)$ and $G_2(s)$), with the poles chosen arbitrarily to fix the performance at a user-specified level. Once A(s) is known, a modified reference model is simulated:

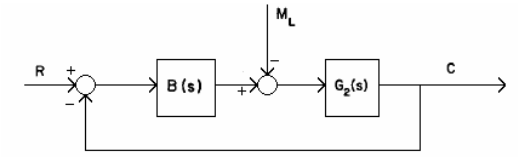

Figure 4: Modified Reference Model

The transfer function of B(s) is found using the following equation [3]:

$$B(s)=\frac{A(s)}{[1-A(s)]G_2(s)} \quad (3)$$

Once an acceptable performance has been achieved using the reference model, the values for the PID controller are obtained using the frequency response of the following [3]:

$$K(s)=sG_C(s)$$
(4)

Once this has been found, the values for the PID controller can be found using the following [3]:

$$\hat{K}(s)=K_I+K_P s+K_D s^2$$
$$\hat{K}(s)\cong K(s) \quad (5)$$

Optimisation between $\hat{K}(s)$ and K(s) is carried out using a means square error reduction process. At this point the PID parameters are known, and can be used to simulate the performance of the plant for verification.

A simulation of a controller tuned using the above method was carried out in Matlab. Models identical to those presented in [3] were created in Simulink and the performance recorded. A set-point of 1500 was used, with a 10% load rejection introduced. For this example, the poles of the reference model were chosen such that each had a damping factor of 0.707 (for a 5% overshoot margin). This led to the PID parameters being chosen as K_I = 0.37, K_P = 2.7 and K_D = 2.916. The reference model was calculated to have the following transfer function [3]:

$$B(s)=\frac{(1-1.986s+0.3605s^2)(1+6.319s)}{s(2.697+0.5553s+0.3473s^2)} \quad (8)$$

The performance of the reference model against that of the final controller is compared in Figure 5 below:

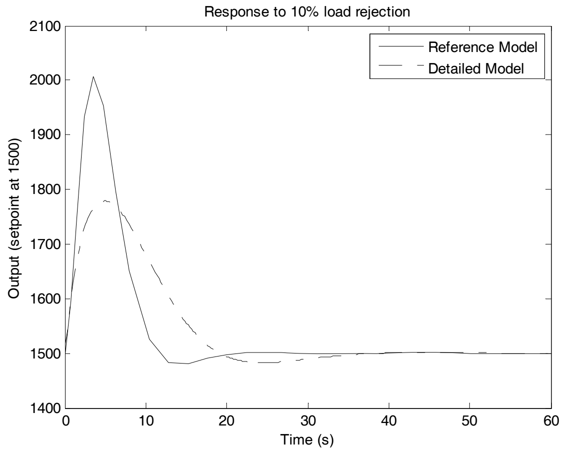

Figure 5: Simulation results for Frequency Domain tuned PID controller

2.3 ROBUST METHOD

This method was put forward in a 2005 paper by Krishnamoorthy Natarajan [4]. The paper proposed a method of tuning PID controllers for hydroturbine speed control that would offer a robust control system. The aim was to develop an effective control system using PID algorithms that would have similar performance to more complicated control systems using high-level functions. The model used was that of a hydroelectric turbine and generator pair connected to an equivalent network to represent the load.

The process itself is described in fairly general terms. The maximum frequency-domain response of the system to a step load disturbance is minimised over all operating points, subject to nominal stability at each operating point. Robust stability at each operating point is enforced by a gain margin of 10dB and a phase margin penalty of 45°.

For a given PID gain, the nominal stability at each operating point is gauged by calculating the closed-loop poles at that point. If any are found in the right-half plane (RHP) of the Laplace domain a penalty function (p) for nominal stability (ns) at an operating point (k) is created, as defined by [4]:

$$p_{ns_k}=L,\text{ if closed-loop poles in RHP}$$
$$p_{ns_k}=0,\text{ if no closed-loop poles in RHP}$$

L is chosen to be larger than any other possible penalty function values to stress the importance of nominal stability at an operating point. The author of the paper chose a value of 1000 for this purpose.

As phase and gain margins are usually inequality constraints, the penalty function for robust stability should be zero (or close to zero) whenever the inequality constraints are satisfied. Conversely, the penalty function should be large when the inequality constraints are not met. The penalty functions for phase margin (pm) and gain margin (gm) at a given operating point are given as [4]:

$$p_{pm_k}(\varphi_k)=k_1[1+\tanh(k_2(\varphi_d-\varphi_k))] \quad (9)$$

$$p_{gm_k}(m_k) = k_3[1 + \tanh(k_4(m_d - m_k))] \tag{10}$$

where φ_k is the estimated phase margin (in radians) at the operating point k, m_k is the estimated gain margin (in dB) at the operating point k, φ_d is the desired phase margin (in radians) and m_d is the desired gain (in dB). k_1 through to k_4 are positive constants chosen at the designer's discretion.

It was stated that the desired phase and gain margins were set at 45° and 10dB respectively for the purposes of the study [4]. The sharpness of the transition region between when the constraints are satisfied and when they are not in the penalty function can be increased by increasing k_2 and k_4, while k_1 and k_3 control the magnitude of the penalty. For the purposes of the study, values of $k_1= k_2= k_3= k_4=50$ were used.

The closed-loop frequency response of the unit frequency deviation (n) to a step load disturbance (d) should be minimised for closed-loop performance. This is denoted as $G_k(j\omega)$ for operating point k. From this, the performance index at the operating point suitable for minimisation to obtain controller gains can be expressed as [4]:

$$F_k = \max_{\omega_\epsilon[\omega_1,\omega_2]} |G_k(j\omega)| + p_{ns_k} + p_{pm_k} + p_{gm_k} \tag{11}$$

Where ω_1 and ω_2 are the minimum and maximum frequencies (in radians per second) of the range over which performance is demanded. This is further modified to suit the purposes of a single PID controller to the following [4]:

$$F = \max_{\substack{\omega_\epsilon[\omega_1,\omega_2] \\ k=1,2\ldots N}} |G_k(j\omega)| + \sum_{k=1}^{N} [p_{ns_k} + p_{pm_k} + p_{gm_k}] \tag{12}$$

Here, N is the number of operating points over which F should be minimised. For the purposes of the paper, the author chose N = 9. The author further notes that the minimisation of both F and F_k is a non-linear operation. The author used the Nelder-Mead simplex search model (cited but not given) to find solutions for his research.

The range of frequencies over which performance is demanded for (12) is given as 0.01 to 100 rad/s. Frequencies below 0.01 rad/s have slow settling times while frequencies above 100 rad/s do not contribute to the performance index as the response is already well attenuated at this point. Frequencies as high as 100 rad/s are included as the penalty functions shown earlier are estimated by numerical interpolation from the relevant transfer functions (obtained from the plant model). As the frequencies at which gain and phase margin occur during the optimisation are not known in advance, a large frequency range is used to avoid any need for extrapolation.

With the values outlined earlier, the author determined the transfer function of the PID controller to be as follows [4]:

$$C(s) = 0.66 + 0.29s + \frac{0.49}{s} \tag{13}$$

This was obtained by making a number of initial estimates of the actual parameters and allowing each case to proceed to convergence using the search model mentioned earlier. The final results of these trials agreed to the first two decimal places, giving the values in (13).

When simulating the performance of the PID controllers tuned using this method, three equivalent networks were considered. These were named N1, N2 and N3. N1 represented a nominal network, with normal loads. The N2 network corresponded to a heavily loaded network with a large capacity, while the N3 network represented a lightly loaded network with low capacity. The nature of each network was specified by the values of the base changer (B) and the mechanical start time of the equivalent system (T_S).

For each network, three operating points were specified. These were T1, T2 and T3. T1 simulated an operating point of 22.5MW. T2 denoted an operating point of 84.3MW and T3 represented an operating point of 113.0MW. These operating points were set using the turbine coefficients. These are shown in Table 1[4].

Operating	dm/dz	dm/dh	dm/db	dm/dw	db/dz	dq/dz	dq/dh	dq/db	dq/dw
Point T1	0.88	0.40	0.00	-0.39	0.00	0.80	0.06	0.00	0.13
Point T2	0.90	1.20	0.50	-0.86	2.30	0.40	0.20	0.30	0.38
Point T3	0.34	1.50	0.52	-0.75	1.00	0.38	0.24	0.69	0.62

Table 1: Turbine Coefficients

The model provided in [4] was recreated in Matlab, and simulations carried out using the values shown in Table 1. The simulation results are shown in Figures 6, 7 and 8

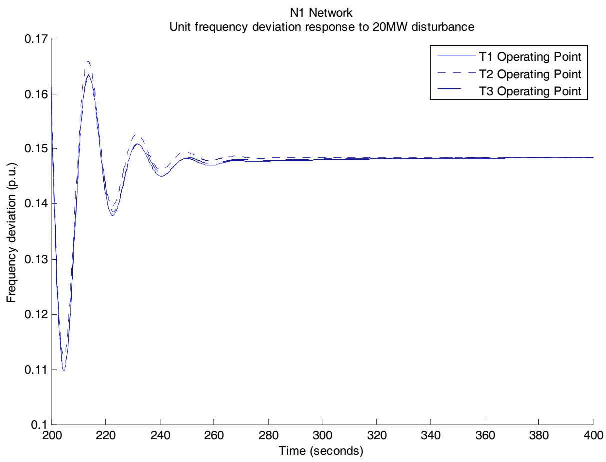

Figure 6: N1 Network Simulation Results

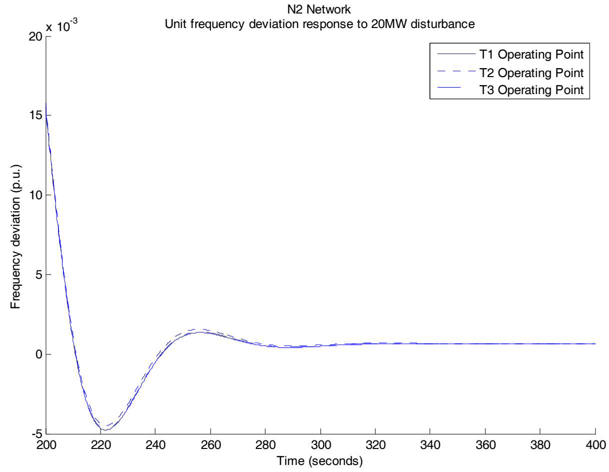

Figure 7: N2 Network Simulation Results

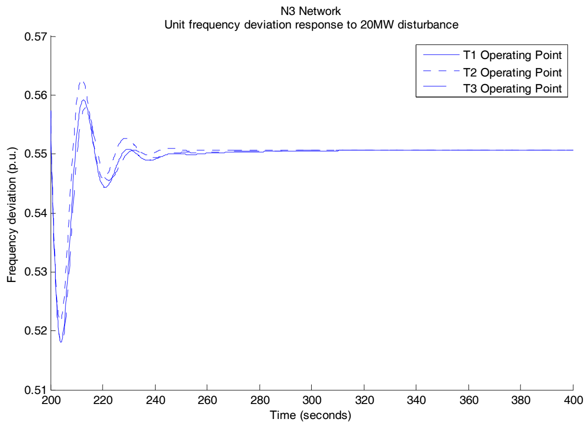

Figure 8: N3 Network Simulation Results

These results match the overall shape of those provided in the original paper. As can be seen, the PID controller achieves a steady state within 2 minutes of a load disturbance. It should be noted that the nature of the model is such that the load disturbance is introduced to the equivalent network, rather to the generator directly.

2.4 LIMITATIONS OF PID CONTROLLERS

While versatile, the PID controller is not without its limitations and problems. In higher order systems, for example, the performance of PID controllers is distinctly lacking when compared to more sophisticated controllers. Normally PID controllers are best suited to no greater than 2nd order systems [1].

A more general problem that can apply to any PID controller is one of "integrator wind-up". This occurs when the actuator that realises the control signal has a response range that is less than that of the controller. In such a case the actuator "saturates" – it is working at its maximum level which is actually less than what was required of it by the controller. The system will effectively be running in an open loop as the response of the controller is no longer directly affected by the output. The error will therefore will continue to be integrated, resulting in a very large integral term (hence the phrase "integrator wind-up"). In such a case the system may oscillate until the error finally reduces to a point where the control signal no longer exceeds the capacity of the actuator, at which point the error will finally be reduced at an acceptable rate. If the actuator saturates at a response level that does not actually decrease the error, the system may become unstable [1, 5].

Another problem associated with actuators is one of mechanical wear of the device. Such a device may develop a "dead-band", especially in a system that repeatedly makes small adjustments in a limited range. This will mean that the control signal will have to include the dead-band, at which point a new dead-band will be established over time due to additional wear [1, 5].

This raises an additional problem associated with PID controllers, which is that they cannot adjust to changes over time. Once a PID controller has been tuned it will remain fixed at that point indefinitely. The system it controls, however, will be constantly (albeit gradually) changing due to age and mechanical wear. If the system as a whole changes then the PID parameters may no longer be as applicable as they had been on the day of installation. Thus any PID controller will see a steady decrease in its effectiveness over time (without maintenance or human intervention), which will eventually reach a stage where it can no longer control the system [1, 5].

Finally, there is a problem with the tuning process itself. Most tuning methods for PID controllers are not 100% accurate for all cases; it is standard practice to use the calculated values as a starting point and adjust the PID controller to better suit the overall system once it has been installed. Even software based "auto-tuning" PID controllers do this to a degree, albeit in an automated process. This makes the process of installing PID controllers a potential problem for a site that requires standardisation across several separate but duplicate systems [1, 5].

3. INTELLIGENT SYSTEMS

Intelligent systems emulate an aspect (or aspects) of human intelligence [6]. This can include the ability to learn and human decision making processes. By using human approaches to problems, intelligent systems can be used in a wide variety of roles. This includes being used as a controller, a task at which intelligent systems have proven themselves able. Three types of intelligent system are particularly suitable for control systems, namely Fuzzy Logic, Artificial Neural Networks (ANN) and Adaptive Neuro Fuzzy Inference Systems (ANFIS).

3.1 FUZZY LOGIC

Fuzzy Logic is a system that represents human decision making processes in a mathematical form. Humans are inherently imprecise by nature, using descriptors such as "fast" or "slow" for turbine speed. Fuzzy logic represents such terms in a numerical fashion, using fuzzy "sets". This approach avoids the crisp nature of conventional Boolean logic, which can cause step impulses when transitioning between states. The use of human descriptors also allows for the easy implementation of expert rules [6].

3.2 ARTIFICIAL NEURAL NETWORKS

An ANN emulates the ability of the human brain to learn. ANNs imitate the human brain to a limited extent by using artificial neurons, which behave approximately like organic neurons do. Signals passed between neurons are subject to a multiplier known as a weight. Neurons will "fire", that is generate a signal, when the inputs it receives satisfy a preset condition. By adjusting the weights within a network of neurons according to the current error, an ANN can "learn", as the weights will be adjusted to a point where the error is zero. In this way an ANN can be trained to complete a task without the need for external human tuning. Additionally, an ANN can self-adjust over time by retraining with operational data. Hence an ANN can change over time as the system it is involved in changes [6].

3.2.1 EXAMPLE OF ANN CONTROL

In the following example, a hydro-governor was simulated in Matlab. The model for this system was obtained from a paper by Wozniak [7]. This represented the turbine with a simple negative feedback loop, the system being represented with the following transfer function [7]:

$$G = \frac{-2P\left(s + \frac{I}{P}\right)(s-1)}{s(s+k)(s+2)} \qquad (14)$$

A predictive controller was used, in which an ANN is used to replicate the behaviour of the system. This ANN is then used to predict the response of the plant to a given input, and an appropriate control signal for a given system input is determined. The chart in Figure 9 illustrates the performance of the controller.

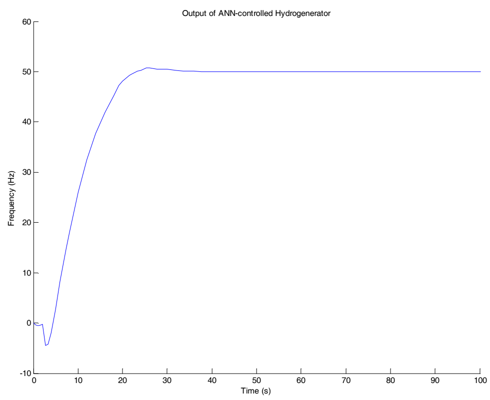

Figure 9: Output Frequency of ANN-controlled Hydro-Generator

3.3 POTENTIAL APPLICATIONS OF INTELLIGENT SYSTEMS IN GENERATOR CONTROL

The use of intelligent systems in control systems has great potential. One application that has seen some development is to use an intelligent system to tune the parameters of a conventional control system such as a PI controller [8, 9]. This has many advantages, as the intelligent system can tune the controller rapidly without the need for human intervention. Ideal results arise when the tuning system is used continuously, so that the controller's parameters are constantly adjusted to compensate for changes within plant parameters. This approach, unfortunately, maybe incompatible with NEMMCO standards, which require a controller's responses to a set of pre-determined inputs be constant over time.

Another approach to using intelligent systems in control systems is to use the intelligent system to form the controller itself. This avoids a level of complexity – instead of tuning an existing controller, the intelligent system is the controller itself. An ANN used in this way would be capable of self-tuning itself to suit the plant it is to control. A fuzzy logic system would have the advantage of smoother responses than can be derived from a more conventional approach. The ANFIS system mentioned earlier combines the best of both worlds, implementing a Fuzzy Logic system with an ANN. This provides a system that can use fuzzy logic and learn.

To develop a controller utilising intelligent systems, data from existing hydroelectric turbines is required. This includes, but is not limited to, Penstock Pressure, Guide Vane Position, Machine Power Output, Speed, System Frequency, Circuit Breaker position, Stop command, Start command, system setpoint and the previous error.

4. CONCLUSION

The fundamental basics of PID controllers have been illustrated, with two tuning methods outlined to demonstrate the process of adapting these devices to a system. As can be seen, such methods are time consuming when performed manually, and at best give an approximate set of parameters for the PID system that should be "fine tuned" in the field.

It has also been high-lighted that PID controllers are not without their limitations. They are inadequate for controlling complex systems, they lack the ability to adapt to changes within the controlled system over time, they can be rendered unstable by inadequate equipment and they are difficult to standardise.

Intelligent systems offer a way of either automatically tuning PID controllers without the need for manual fine-tuning, or to act as the control system itself.

ACKNOWLEDGEMENTS

This research has been funded by the Australian Research Council under ARC Discovery Grant K0014733, "Australian Research Council - Hydro-Turbine Governor Control Utilising Intelligent Systems".

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