EMITTER International Journal of Engineering Technology
Vol. 5, No. 2, December 2017
ISSN: 2443-1168

Capacitive Energy Storage (CES) Optimization For Load Frequency Control in Micro Hydro Power Plant Using Imperialist Competitive Algorithm (ICA)

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Abstract

This paper presents a method for enhancing the frequency performance of micro hydro power plant by adding an additional device called capacitive energy storage (CES). A modification has been made by adding PID controller as additional controller of CES. Furthermore, to obtain the optimal parameter of CES, an optimization approach called imperialist competitive algorithm (ICA) is used as an optimization method. From the simulation results show that by adding CES-PID the frequency performance of the micro hydro power system is enhanced significantly. Moreover, the best performance is performed by a system with CES-PID optimized by ICA indicated by smallest overshoot. The analysis result obtained small overshoot response by using PID-CES controller that is equal to -1.371e-05pu, for system without controller equal to -0.000318 pu. By comparison, several scenarios for control methods are used.

Keywords - Micro Hydro, Frequency, Capacitive Energy Storage, Imperialist Competitive Algorithm (ICA), Overshoot

1. INTRODUCTION

The problem of stability is a major concern in electric power operating systems because, in steady state conditions, the average velocity for all generators must be the same or synchronous. The frequency and voltage generated by the micro-hydro generator are greatly influenced by the rotational speed of the generator, where the rotational speed of the generator is greatly influenced by the load changes. The power supply supplied by micro hydro at night will decrease, especially above 23:00 hours. This will cause the wheels to rotate faster. As a result, the frequency of electricity will increase and if too high will harm consumer electrical equipment.

Therefore, to support micro hydro performance, frequency control is necessary, to keep the frequency between 49 Hz - 51 Hz. Micro-hydro control mechanism is done automatically by adjusting the gate position so that the incoming water flow can be adjusted with the load, or adjust the load power on the system with the generation for the frequency oscillation damping that occurs. Therefore, it takes a technology to optimize the performance of micro-hydro, that is by applying Load Frequency Control (LFC). The LFC mechanism is designed using Capacitive Energy Storage (CES), which has the ability to provide power compensation in order to reduce or even eliminate the frequency oscillations caused by changes in the electrical load of the customer. CES provides energy storage systems that can operate quickly and automatically. To achieve good damping, optimal tuning of CES parameters is required for use in the system. Therefore, this research proposed a method of intelligent based on Imperialist Competitive Algorithm (ICA) to optimize PID-CES parameter.

In previous studies have discussed many frequency control on micro-hydro, such as [1], [2], [3, 4]. Of the several studies, micro-hydro control is still not optimal because it is still based on conventional PID. Recent research has also applied smart methods for controlling frequencies on micro-hydro, such as [5] using fuzzy logic, CES application in control has also been applied in many systems, such as [6] using Cuckoo Search, [7] using Bat Algorithm. For this reason, we propose a new approach in controlling micro-hydro based CES with hybrid PID and ICA intelligent method as a CES-PID tuning method. From the analysis results obtained a good micro hydro performance with a combination of CES and PID in controlling. Cuckoo Algorithm faster in computing, but there are still some shortcomings, including the computation process that must take several times the sample. While in our study using the ICA method, the results obtained only by one count. In addition we would like to propose ICA-based intelligent methods for power system optimization.

The Imperialist Competitive Algorithm (ICA) method is a computational algorithm that is inspired by the royal competition in seizing power from a region. The correlation between ICA and Micro Hydro is CES as a media control represented as power, searched by ICA algorithm. So when the computation process has been completed, the ICA will find the imperialist who wins, in other words, the optimal parameters. The ICA algorithm will work based on Objective Function, which minimizes Integral Time Absolute Error (ITAE). Implementation of ICA has also been widely used because the results are very optimal in doing the computation process, some of these studies [8] for Power System Stabilizer, [9] for pendulum control.

2. SYSTEM MODELING

Micro Hydro Power Plant

The application of micro hydro power plant has increased significantly over the last few decade. Generally, micro-hydro is installed in the rural area near the river. The working principle of micro hydro is same with hydro power system in general, the difference is only in the capacity. The mathematical representation of active power generated in micro hydro can be presented in (1).

$$P_{real}[W] = Q[m^3/s].H[m].k[N/kg].\eta_{turbin}.\eta_{gen} \quad (1)$$

In (1), P_{th} and Q are active power generated from the plant and the capacity of the water that flows to the turbine. While H and k corresponded to the position of the water and gravitational constant. Furthermore, $\eta_{turbine}$ and η_{gen} corresponded to the turbine and generator efficiency. For LFC study, modeling micro hydro in block diagram representation is essential. Fig. 1 shows the block diagram of LFC micro hydro power plant [10].

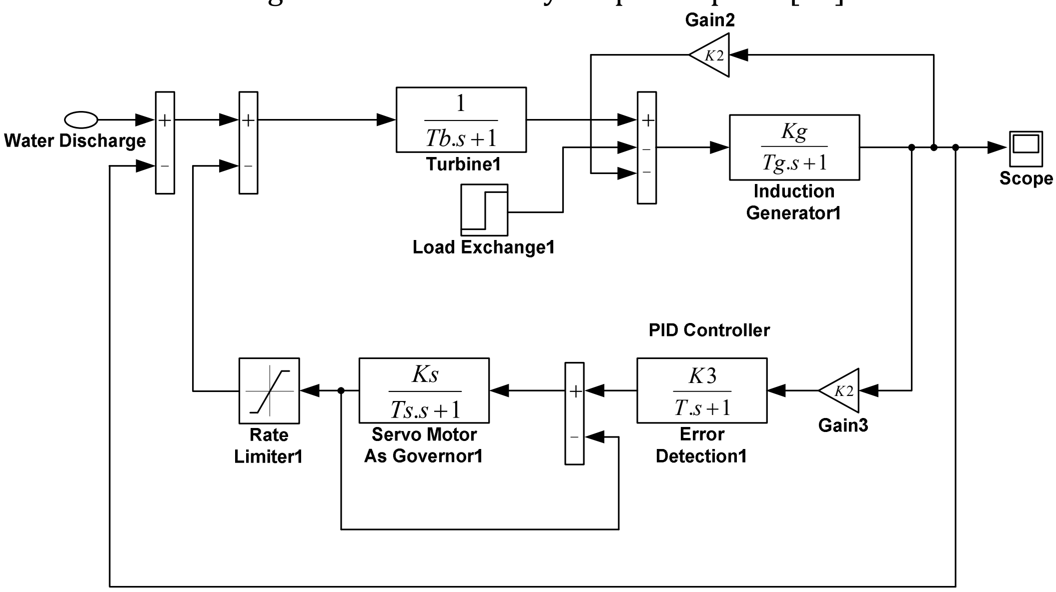

Figure 1. Micro Hydro Block Diagram [6].

From the error detection block, the signal Δω will be forwarded to the servomotor block used by the governor. In this block, there are parameters that are Ks and Ts. As for the output side of the governor, there is a signal that is fed back as an input value to the governor. Also, the output of the governor is passed to a rate limiter which serves to limit the signal at the highest and lowest saturation value that has been determined. From the output of this limiter rate, it is forwarded as input on the water turbine block.

Capacitive Energy Storage (CES)

Capacitive energy storage (CES) is one of the energy storage devices that utilize capacitor to store and release electrical energy in large amount.

CES consists of the storage capacitor, power electronics and the associated controller as shown in Fig 2 [11, 12].

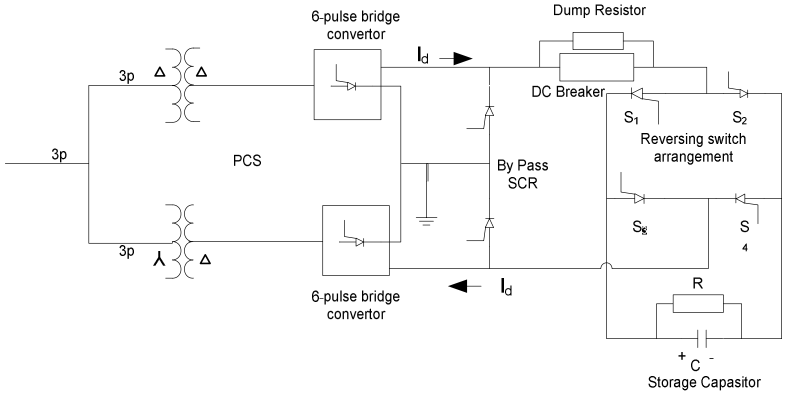

Figure 2. Capacitive Energy Storage [6, 13].

For frequency stability study, CES could be simply modeled as second order differential equation as described in (2), (3). In (2), C and R are corresponded to the capacitance and resistance constant of the storage capacitor, while ΔE_d and ΔI_d related to the capacitor voltage deviation and capacitor current deviation. Moreover, the value of ΔE_{d0} can be described in (4), while (5) and (6) presented the maximum and minimum value of ΔE_{d0}. By considering equations (2)-(6), the block diagram of CES can be modeled as shown in Fig. (3) [11, 12].

$$\Delta E_d = \left[\frac{1}{sC + 1/R} \right] \Delta I_d \tag{2}$$

$$\Delta P_{CES} = (E_{d0} + \Delta E_d).\Delta I_d \tag{3}$$

$$E_{d0} = \frac{[E_{d\max}^2 + E_{d\min}^2]^{1/2}}{2} \tag{4}$$

$$E_{d\min} = 30 E_{d0} \tag{5}$$

$$E_{d\max} = 1.38 E_{d0} \tag{6}$$

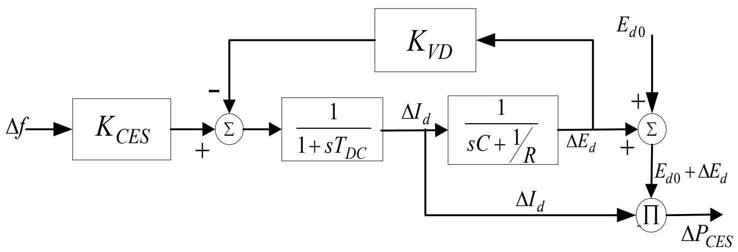

Figure 3. CES Diagram Block [13].

3. DESIGN CES USING IMPERIALIST COMPETITIVE ALGORITHM

Imperialist Competitive Algorithm

Imperialist competitive algorithm (ICA) is an evolutionary algorithm inspired by the imperialist competition. This algorithm was first established in 2007 by Esmail Atashpaz. ICA consist of 8 steps namely initialization, movement, revolution, the exchange between imperialist and colonies, merger empire, calculate the total strength, and imperialist competition [14, 15].

Empire Initialization

In the initialization process, ICA forms an array of variable values to be optimized. In other intelligent algorithms, such as GA, this array is called a chromosome, so in ICA there is a state term. In a state defined as 1 x Nvar array. Some of the best countries will be chosen as imperialists to lead the empire. The rest of the previous population will form colonies owned by the empire. An empire will consist of one imperialist and several colonies. The most powerful imperialist has the largest number of colonies. The ICA country initialization can be presented as (7) [14, 15].

$$country = [P_1, P_2, P_3 ... P_{N_{\mathrm{var}}}] \tag{7}$$

Equation (7) is the variable that will be optimized by ICA. The cost of each country can be calculated by evaluating the position of each country as described in (8) [14, 15].

$$cost = f(country) = f(P_1, P_2, P_3 ... P_{N_{\mathrm{var}}}) \tag{8}$$

The division of the colony should be based on the strength of the imperialists. To divide the colony must be based on the proper imperialist, therefore the imperialist cost must be normalized first using calculation as given in (9) [14, 15].

$$C_n = c_n - \frac{\max}{i}(c_i) \tag{9}$$

In (9), c_n is the cost of the imperialist, and C_n is the normalized cost. Furthermore, the strength of each imperialist can be calculated as given in (10), while the number of initial colonies for n empire can be described in (11) [14, 15].

$$p_n = \left| \frac{C_n}{\sum_{i=1}^{N_{imp}} C_i} \right| \tag{10}$$

$$N.C._n = round\{P_n . N_{col}\} \tag{11}$$

In (12), $N.C._n$ is the initial number of colonies of the nth empire and N_{col} is the number of early colonies. The colony with the n imperialist will soon form the n empire. The empire will further form the initial empire as shown in Figure 4 [14, 15].

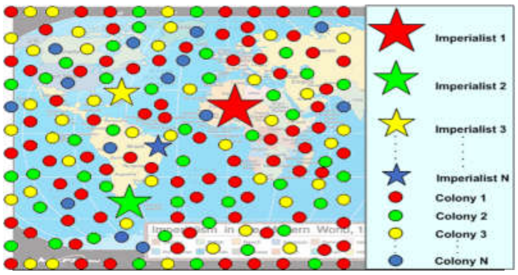

Figure 4. Early Empire [14].

The imperialist will seek to improve his colony by moving all the colonies to him. The movement of this colony is further shown in Fig. 5, if this movement continues continuously it will make all the colonies move to imperialist movement. The mathematical representation of Fig. 5 can be described as given (12) [14].

Figure 5. The movement of the Colony towards the Imperialists in random deviations [14].

$$x \sim U(0, \beta x d) \tag{12}$$

In (12), the value of β is a constant number above 1, thus making the colony progressively move closer to its imperialist from both sides, and d is the distance of colony and imperialism. The movement of the next colony does not directly lead to imperialism. To model, a random number of irregularities is added to the motion in (13) can be used [14, 15].

$$\theta \sim U(-\gamma, \gamma) \tag{13}$$

Where γ is a parameter that governs the deviation from the initial direction. However, the values of β and γ are not arbitrarily chosen, in most implementations, the value of β is about 2 and the value of γ is about π / 4 (rad) to produce a better convergence to the global minimum.

The next step of ICA is a revolution. In ICA terminology, the revolution will cause a country to suddenly change its socio-political characteristics. That is, despite the imperialist assimilation process, the colony randomly shifts its position to move on the social-political axis. Furthermore, when the colony moves toward the imperialists, a colony may have a better cost than its imperialists have. When this happens, then the exchange of positions between each imperialist and the colony will occur. Then the algorithm will continue with the new imperialists. In the movement of colonies and imperialism to the global minimum, some imperialists may move to the same position. If the distance between the two imperialists is less than the threshold distance, then both will soon form a new empire and a new imperialist in the position where the two imperialists meet. S Imperialists have a great influence on the empire's strength, but the strength of the colony also gives little effect. The total cost of an empire is defined as the sum of imperialist cost with the average cost of colonies possessed by imperialists from one empire can be described as given in (14). The value of ξ denotes the contribution influence of the colony [14, 15].

$$T.C._n = \cos t(imperialist_n) + \xi\, mean\{Cost(colonies\, of\, empire_n)\} \tag{14}$$

In (14), *T.C.n* is the total cost of the nth empire with a positive value of less than one, thus causing the total strength of the empire to be more influenced by the imperialists than the colony. All empires seek to have colonies from other empires and rule them. Competition of power will gradually decrease the strength of the weak empire and increase the strength of the stronger. The competition is modeled by taking only a few or one of the weakest colonies possessed by each of the weakest empires among all empires and rendering competition between all the more powerful empires to possess the colonies [8].

To start the competition, first, the probability of possession of each empire is based on its total strength. Normalization of total cost and proprietary probability from empire to n are then sequentially formulated as given in (15) and (16) [14, 15].

$$N.T.C._n = T.C._n - \max\{T.C._i\} \tag{15}$$

$$p_{p_n} = \left| \frac{N.T.C._n}{\sum_{i=1}^{N_{imp}} N.T.C._i} \right| \tag{16}$$

The weakest Empire will collapse in power competition and the colony of the empire will be distributed to the other empires. An empire will collapse and be eliminated if the empire loses all its colonies [14, 15].

Design CES using ICA

Figure 6 shows the flowchart of ICA method used in this study. The objective function used to test the stability of the system is to minimize Integral Time Absolute Error (ITAE) as given in (17) [16-19].

$$ITAE = \int_0^t t\left|\Delta\omega(t)\right| dt \tag{17}$$

The parameters that will be optimized by ICA are Kces, Tdc, Kp, Ki, and Kd. Table 1 shows the parameter of ICA on this paper, while Table 2 illustrates the test system parameters (LFC micro-hydro). Furthermore, the upper and lower limit of each parameter is shown in Table 3.

Table 1. ICA Parameter

Parameters	Values
Countries Values	50
InitialImperialists	5
Decades	50
RevolutionRate	0.3
AssimilationCoefficient	2
AssimilationAngleCoefficient	0.5
Zeta	0.02
Damp Ratio	0.99
Uniting Threshold	0.02

Source : [8]

Table 2. Micro Hydro Parameters

Parameters	Values
Tb	1
Kg	1
Tg	13,333
K1	5
K2	8,52
K3	0.004
T	0,02
Ts	0,1
Ks	2,5
Sg	40
pf	0,8
Vg	400/231
ω	1500
fg	50

Source : [6, 20]

Table 3. Ces-PID Parameters Limits

Parameter	Limits	
	Lower limit	**Upper limit**
Kces	0	100
Tdc	0	1
Kp	0	50
Ki	0	1
Kd	0	1

Source : [6]

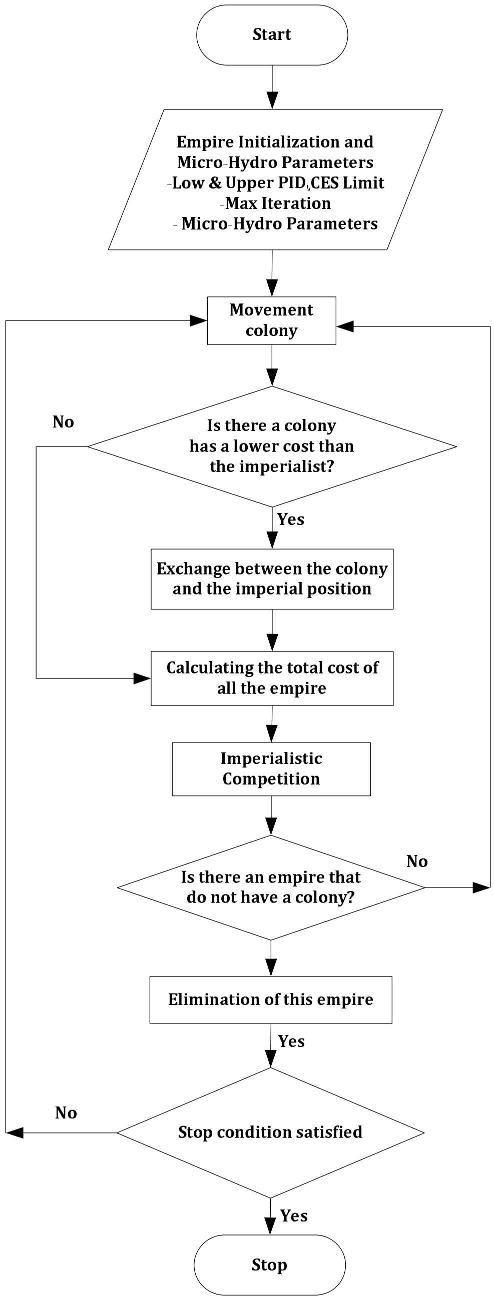

Figure 6. CES-PID tuning flow diagram using ICA [8]

ICA find the fitness function (minimum ITAE) after 40 iterations and the minimum value of ITAE is 0.0000000001674 as shown in Fig. 7. Furthermore, Table 4 shows the optimized parameter of CES-PID.

Table 4. Results of CES-PID Optimization with ICA

Parameter	Best Solution
Kces	89.6555
Tdc	0.0430
Kp	39.2752
Ki	0.9189
Kd	0.0492

Source: Result Analysis

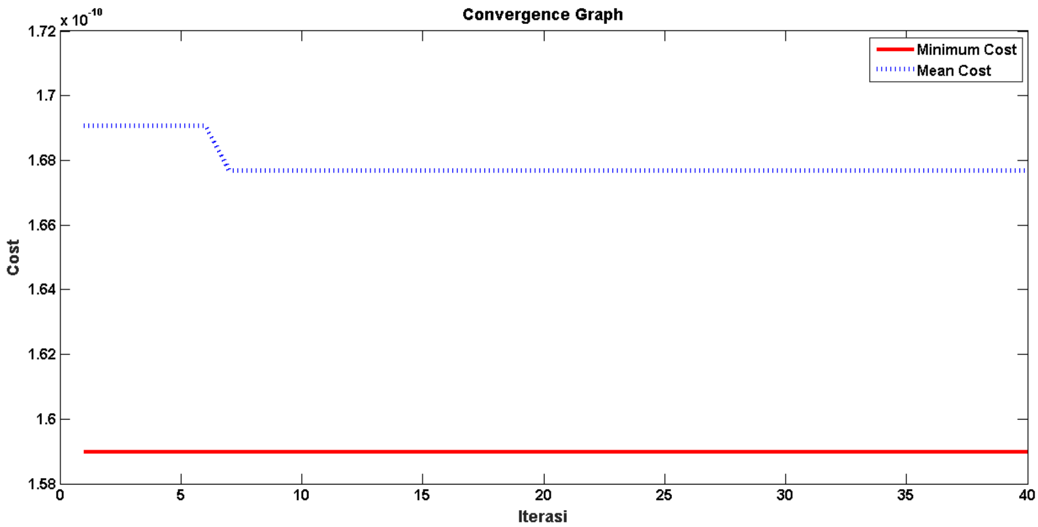

Figure 7. Convergence graph of ICA

Figs 8-11 shows the micro hydro power plant design used in this study. Figure 8 shows the Micro hydro model design with PID controller, Figure 9 shows the micro-hydro model design with PID-CES controller. For systems without control, the modeling is almost identical to the previous modeling. In the system without additional control, micro-hydro control is done by the governor. An experiment without a controller means that the frequency control of a micro hydro power plant is performed only by the governor and error detector to provide feedback from the generator output to the water turbine. While with the additional PID controller, directly fed back from the generator output to the inductor generator input itself, not tied to the water turbine. The CES controller gives the output of PES. Pces is a stored power, then processed to be inserted on the input side of the generator. The position of the CES controller placement is the same as replacing the PID in the previous diagram. However, when combined two controllers, a simple PID controller will be included in the CES block diagram. Figure 10 shows the CES model design and Figure 11 shows overall system design.

Hydro Power modeling begins with a water discharge to rotate the water turbine. Then, the Water turbine block which has parameter Tw. The water energy that turns the turbine is converted into a mechanical power that becomes one of the input values for the generator. From the error detection block, the signal will be forwarded to the servomotor block used by the governor. In this block, there are parameters Ks and Ts. As for the output side of the governor, the signal is fed back as an input value to the governor. Also, the output of the governor is passed to a rate limiter which serves to limit the signal at the highest and lowest saturation value that has been determined. From the output of this limiter rate, it is forwarded as input on the water turbine block. In addition to predefined parameters, there is an input value to the generator coming from the load frequency change. The input signal due to load changes is a very decisive part of how the frequency setting system is running. The value of this signal depends on the power load used by the customer.

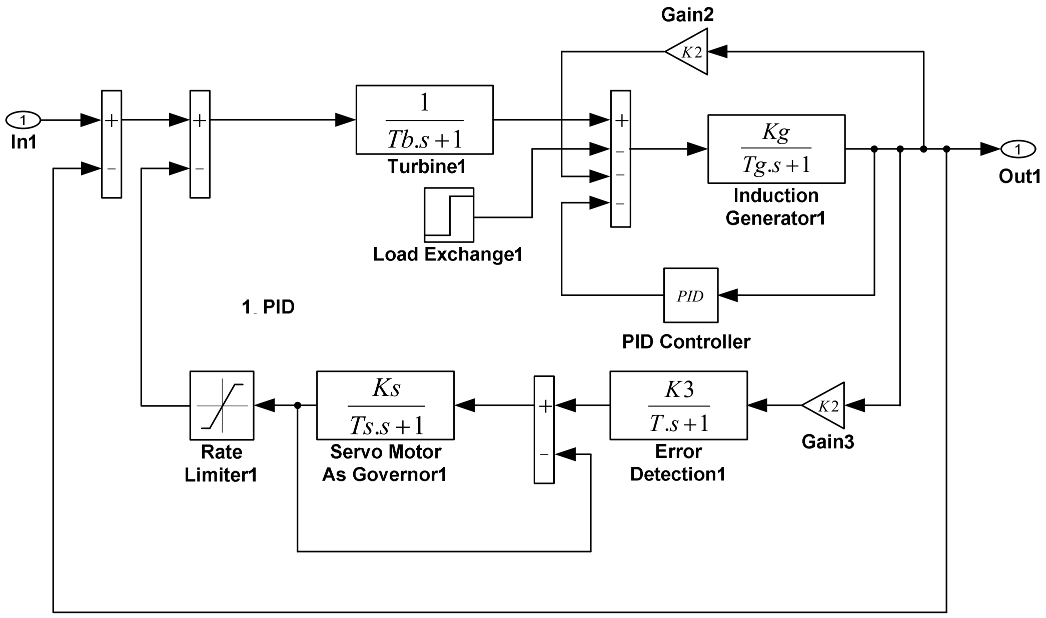

Figure 8. Micro Hydro Design with PID controller

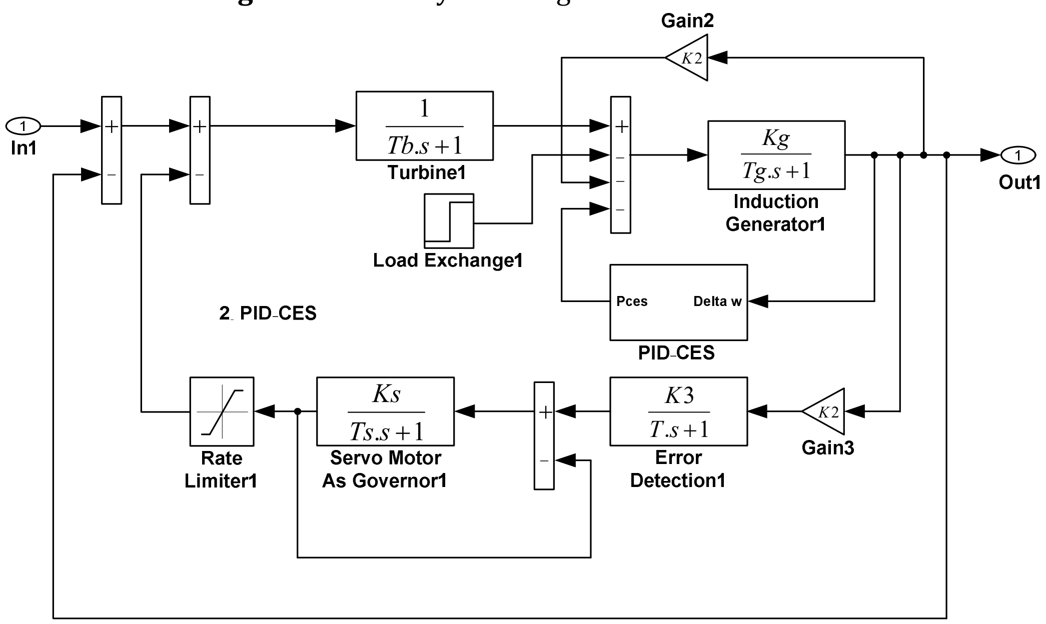

Figure 9. Micro Hydro Design with PID-CES controller

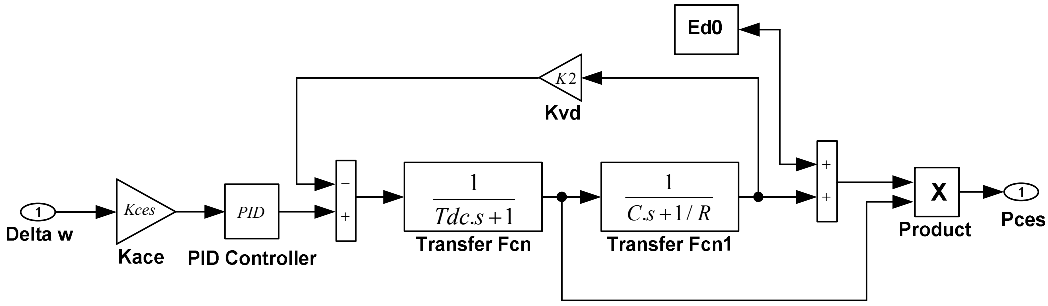

Figure 10. CES Controller Design

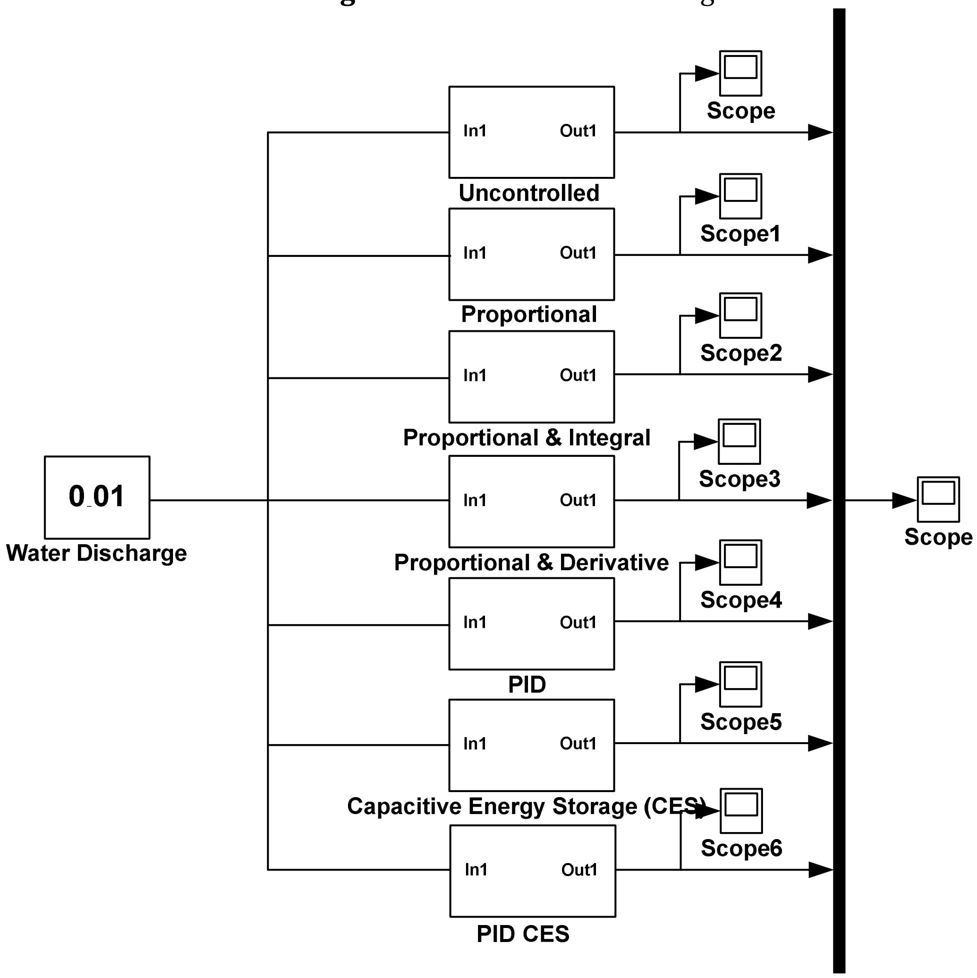

Figure 11. Micro hydro Controller Design

4. RESULT OF SIMULATION AND ANALYSIS

Time Domain Analysis

The first simulation is to see micro hydro response without controller/open loop system. Figure 12 shows the micro-hydro response without the controller. From the simulation of the system without control, it can be seen that the generator response is very bad. The overshoot generated on micro-hydro system without control is very large. Overshoot on micro-hydro system without control is -0.000318 with long settling time. The overshoot and settling time values generated from the simulated micro hydro power plant without controller are the largest overshoot and settling time values among all the simulations performed in this study. This is because the frequency control of the system is only done or charged from the governor, therefore on this system, it becomes the most unstable system among other systems given an additional controller.

Next simulation is using Proportional (P), controller. P parameters will be tuned using ICA algorithm. Figure 12 shows the micro-hydro response with a Proportional controller. From the simulation results with the Proportional controller, it shows an improvement of frequency response when compared to the system without control. From the experiment result graph, obtained overshoot of -0.0001254 pu, and settling time is getting better when compared to a system without a controller.

Next simulation is using the Proportional - Integral (PI), controller. The PI parameter is tuned using the ICA algorithm. Figure 11 shows the micro-hydro response with PI controller. From the simulation results with the PI controller, it can be seen that the generator response is similar to the previous Proportional controller model. Overshoot on this system is -0.000125 with better settling time compared to the system without control.

Next simulation is using Proportional-Derivative (PD), the controller. PD parameter is tuned using ICA algorithm. Figure 12 shows the micro-hydro response with the PD controller. From the simulation results with the PD controller, it can be seen that the generator response is similar to the previous P and PI control model. Overshoot on this system is -0.0001252, while settling time is still better than the system without control and almost the same with the system with P and PI controller.

Next simulation is using Proportional Integral Derivative (PID), the controller. PID parameter is tuned using ICA algorithm. Figure 11 shows the micro-hydro response with PID control. From the simulation result with PID controller, it can be seen that micro hydro response is better when compared to controller P, PI and PD before. Overshoot on this system is -0.0001249 with better settling time from controller model P, PI, and PD. The combination of PID here produces a good response for micro-hydro, of course with the proper PID parameter tuning.

The next simulation is using Capacitive Energy Storage (CES) controller, CES parameter is observed using ICA algorithm. Figure 12 shows the micro-hydro response with CES control. From the simulation results with the CES control, it can be seen that the generator response is better than the previous P, PI, PD and PID systems. Overshoot on this system is smaller ie -0.0001224 with better settling time than the system without control, P, PI, PD and PID before. From the performance of this micro-hydro response, will be a reference to design a micro-hydro generator frequency control model.

Based on the analysis of several types of control models for micro-hydro system, it will be proposed a combination controller model between

PID and CES for load frequency control system on micro hydro. PID and CES parameters are tuned using ICA algorithm. Figure 11 shows the micro-hydro response with PID-CES control combination. The parameters of each control model that have been analyzed before, are optimized using ICA based on the objective function used in this study. The objective function used to test the stability of the system is with Integral Time Absolute Error (ITAE). Here, Integral Time Absolute Error (ITAE) is done with equation (17).

CES is a device that can perform the storage and release of power in large numbers simultaneously. CES here serves to store energy in the form of an electric field on the capacitor. A CES consists of the storage capacitor and Power Conversion System (PCS) with integrated control and security functions. CES here serves to help governor performance to dampen the frequency oscillation quickly.

From the simulation result with PID-CES control, it can be seen that generator response is much better than control model P, PI, PD, PID, and CES. Overshoot on this system is -1.371e-05 with a better settling time of the system without control and other controls. Table 5 and Figure 11 show the summary of the overshoot results of all control models. The optimum parameter of optimization result using ICA for each control model can be seen in table 3. The correlation between ICA and PID-CES is represented as, the kingdom (In this case initialization parameter PID-CES), will compete for the highest power (Optimum PID-CES Parameter). When this algorithm is convergent, the computation process stops and the parameters of PID-CES have been found.

CES is a device that serves to store and release power in large numbers simultaneously. CES consists of storage capacitor and Power Conversion System (PCS) with integrated control and security functions. From Figure 2 it can be seen that, storage capacitors consist of several discrete capacitors connected in parallel. The leaked and dielectric losses of the bank capacitor at CES are modeled by the resistance R that is connected in parallel to the capacitor. The CES voltage should return to its initial value quickly, so that after the interruption occurs the CES unit is ready to work for the next disturbance. This can be shown in Figure 3.

Tabel 5. Overshoot and settling time value results

Control Method	Overshoot (pu)	Settling Time (s)
Uncontrolled	-0.000318	9
Proportional	-0.0001254	5.5
Proportional-Integral (PI)	-0.000125	5.5
Proportional-Derivative (PD)	-0.0001252	5.5
Proportional-Integral-Derivative (PID)	-0.0001249	3.8
Capacitive Energy Storage (CES)	-0.0001224	5.5
PID-CES	-1.371e-05	1.5

Source: Result Analysis

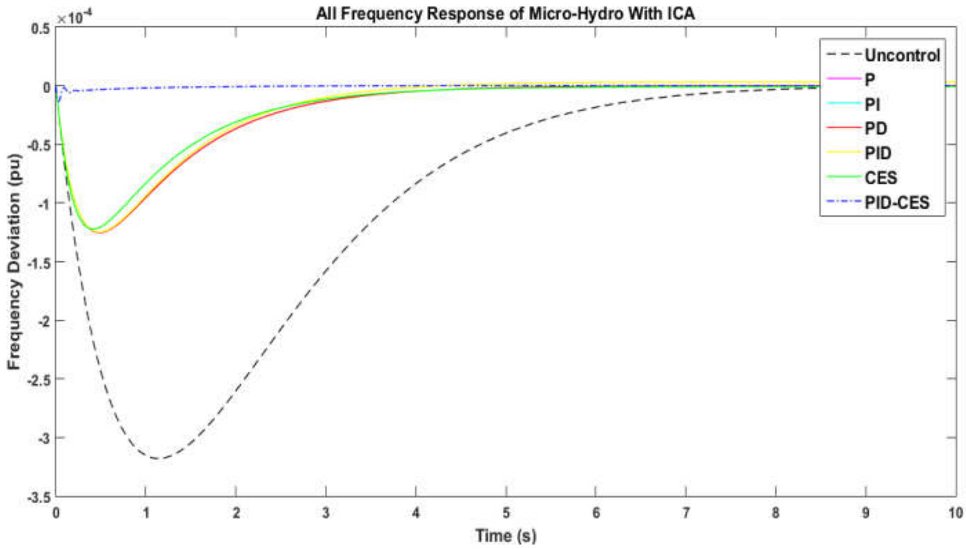

Figure 11. Micro Hydro Frequency Response Comparison

Eigenvalue Analysis

Next is a system stability analysis by investigating eigenvalue. Table 6 illustrates the eigenvalue comparison under different scenarios, while Figs. 13-14 show the eigenvalue trajectories with and without a proposed method (CES-PID optimized by ICA).

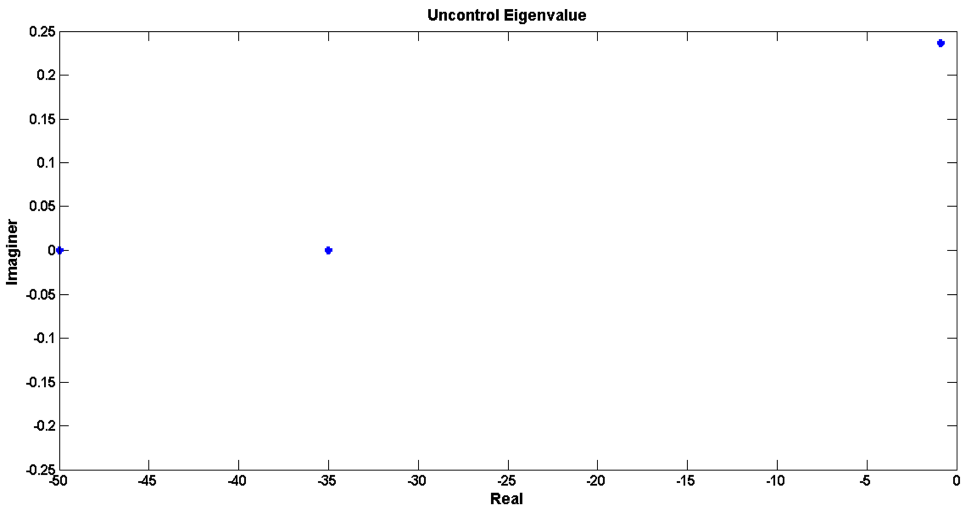

Figure 13. Micro Hydro Eigenvalue without uncontrolled

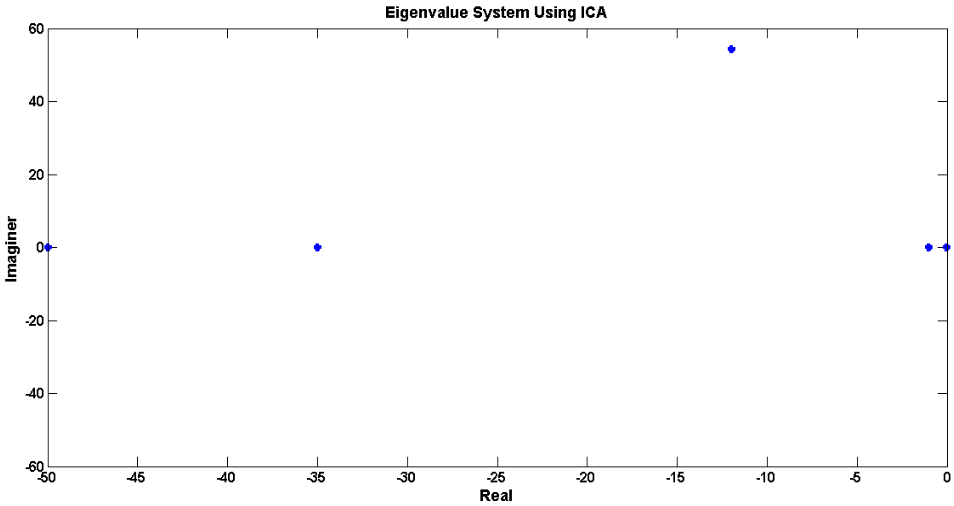

Figure 14. Micro Hydro Frequency Response Using ICA

Table 6. Eigenvalue System

Uncontrolled	ICA
-0.8570 + 0.2360i	-11.9730 +54.2567i
-0.8570 - 0.2360i	-11.9730 -54.2567i
-49.9999 + 0.0000i	-50.0000 + 0.0000i
-35.0001 + 0.0000i	-35.0000 + 0.0000i

The negative value for the real eigenvalue component gives a stable meaning to a system, this corresponds to a negative exponential as given in (18).

$$y(t) = \frac{\left|K\left(a + jb\right)\right|}{b} e^{at} \sin\left(bt + a\right) \tag{18}$$

If the negative eigenvalue for the real component (α), then the graph will fall (convergent) close to 0. The condition like this shows the system will be muffled well. If the eigenvalue is positive for the real component, then the system response will diverge away from the value 0, so the system will never return to steady state. If the eigenvalue of the real component (α = 0), it will oscillate harmonics, which means the system will never be stable.

Based on the book [21] that the system is said to be stable if all the real components of the eigenvalue are negative. This system has four eigenvalues and all of them are negative, so the system is a stable Steady state (steady).

From several models of load frequency control in micro-hydropower systems, and in terms of frequency response graphs, it can be concluded that a micro hydropower plant absolutely requires a controller as a frequency oscillation damper due to load changes. The PID-CES controller proposed in this study has a significant influence on the oscillation damping and is suitable for use in micro-hydro plants. The ICA method as an intelligent method inspired by power competition can be a method for parameter optimization of PID and CES. With optimal PID and CES parameters, micro-hydro performance will be more optimal in controlling the dynamics of load changes.

Based on the results of this study, another energy storage-based controlling model will be developed for load frequency control in micro hydro. Another controlling model is Superconducting Magnetic Energy Storage (SMES). The SMES application on renewable energy systems has been widely applied and shows excellent results [22], [23]. Therefore, the SMES application for load frequency control on micro hydro will be discussed in subsequent research.

5. CONCLUSIONS

This research proposes an additional controller for load frequency control at a micro hydropower plant using PID-CES. The PID-CES parameters are optimized using smart methods, ICA algorithms, which can find the optimal value of PID-CES.

From the analysis results, obtained on the P controller, overshoot of -0.0001254, with PI Controller -0.000125, with PD Controller -0.0001252, with PID controller -0.0001249, with CES controller -0.0001224, and with PID-CES -1.371e-05.

The PID-CES controller proposed in this study has a significant influence on the damping of the oscillations. Therefore, it is proposed to be applied to micro-hydro.

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