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Modelling and Simulation of Small Hydroelectric Generation

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Abstract:

Hydropower is a relative cheap, reliable, sustainable, and renewable source of energy that does not consume natural resources nor produces emissions and toxic waste. In fact, compared to all other energy sources, hydropower is the least expensive and most efficient method for generating electricity, with a price competitive to traditional energy sources such as fossil fuels, gas, and biomass. Most hydroelectric power that is being generated in the world today comes from (large) hydroelectric dams that generate electricity by converting the potential energy of falling or running water from human-made reservoir-fed plants distort significantly the local environment and ecosystem, and hence much opposition exists towards their use and construction. Finally, in this paper outside flow of river, we also looked at converting stagnant water in a big tank from its potential energy to kinetic energy where our hydro turbine will equally work to achieve the same or close result when compared to a river. Flywheel was employed to help this system in two ways; a).Multiplication of rotational output speed of the turbine b). Sustainability of generator power. From the Result, it is seen that the small hydropower system is stable and the steady-state frequency deviation is eliminated by the controller. Therefore, the low head, small hydroelectric generation system is stable and shows good transient and steady state performances which gave an impressive result with 75% efficient.

.Keywords **— Hydroelectric, Microgrid, Renewable Energy,**

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I. INTRODUCTION

Hydroelectric generation is one of the most reliable and developed renewable energy generations for the human being at present. It is also the largest renewable energy source that produces around 16% of the world's electricity and over 80% of the world's renewable electricity. Technological advancement has resulted into most power utilities to be interconnected into a single power grid in order to maximize efficiency of the generating stations. Due to increased load demands from consumers which may cause power system network to be in highly stressed conditions, the need for increasing the efficiency of the generating station is arising. The possible means of increasing this efficiency is to model and simulate the generating stations, which aid in describing the static and dynamic behavior of the whole network. These evaluations aim to assess the behavior of the power system in isolated operation, reserve capabilities and the stability analyzes in the whole power system through modeling and simulating of hydropower plant (SHPP). However, in recent years, the idea of the micro grid provides people more access to smaller-scale renewable energy. The micro grid is developed for localized electricity generation and distribution. Both of power source or load in a micro grid can be either grid connected.

Because of flexible distribution of the microgrid scheme, hydropower can be scaled to a smaller power rating for better utilization of the local reliable renewable resource. The micro

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hydropower concept is induced for fully utilizing the renewable energy from the flowing water. Micro-hydropower is typically rating from 5 KW to 100KW. Like other renewable resources in a microgrid, micro hydropower system can either deliver electric power to an isolated load or be connected to the grid.

There are many kinds of alternative clean and environment friend resources, such as wind, solar and micro hydro power generation, which are very appropriate for improving our environment conditions. In this thesis, the micro hydroelectric generations as energy resources usually serve for a local load and not require for high voltage transmission lines crossing through rural and urban landscapes are targeted. A model will be developed and simulated in MATLAB/SIMULINK environment. By implementing the prototype, the electricity can be supplied in the small or local rural area beside that it can reduce the cost of investment required for transmission line.

The aim of Modeling and simulations a small hydroelectric generation connected micro grid will achieve the following objectives

1. To develop a mathematical model for hydroelectric generation
2. To develop a Simulink model for small hydroelectric generation
3. To simulate the mathematical model
4. To validate the simulated model with existing hydroelectric generation

Table 1: Related works

S/N	AUTHOR NAME AND DATE	TITLE OF THEIR WORKS	EXPLAINATION AND RESULT	MERIT AND DRAW BACK	RESEARCH GAP
1	YU Tao and LIANG. 2012	*Smart power generation control for micro grids islanded operation based on reinforcement leaning*	They proposed an improved reinforce-ent learning method to minimize electricity costs on the premise of satisfying the power balance and generation limit of units in a micro-grid with grid-connected mode. Firstly, the micro-grid control requirements are analyzed and the objective function of optimal control for micro-grid is proposed	The analysis shows that the proposed method is beneficial to handle the problem of "curse of dimensionality" and speed up learning in the unknown large-scale world.	The smart does not meet up to optimal response
2	Fred and Mohammad 2015	Small Hydro As Green Power"	Their proposed a hydroelectric power and the place of small hydro in the world's energy generation portfolio. Differences between small hydro and fossil burning technologies are examined in light of the nature of their resource use, and the differences between large-scale hydro, and small hydro are discussed.	Their work produce Reliable electricity source but No reservoir required.	Does not meet up to optimal response
3	Anuradha and Loi 2011	Small Hydro Power Plant Analysis and Development " in Electric Utility Deregulation and Restructuring and Power Technologies	Small Hydro Power (SHP) plants have many advantages over large scale hydropower generation. SHP has been identified as a good alternative to conventional electricity generation for many developing countries around the world. Run-of-the river type SHP plants contain considerable economic advantages. However these are affected by various technical and economic challenges.	Suitable site characteristics required but Energy expansion not possible	Does not meet up to optimal response

II. Materials and Method

Materials used includes

(a). Hydro Turbine
(b). AC Synchronous Motor
(c). Fly Wheel
(d). Belt
(e). Micro Dam
(f). Tachometer, Multi-digital Meter
(g). MATLAb

Design Method: The method use to achieve the above objectives is as fellow; the environment will be characterized, the parameter will be outline and explained. Hence a mathematical model on hydroelectric model will be generated using a C++ programming language. A SIMULINK block will use to model a typical small hydroelectric model connected to a micro grid and the above program will be injected the

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Simulink environment to simulate the overall system in order to achieve the objective and the model will be validate with existing model to check the operation performance.

III. IMPLEMENTATION OF THE DEVELOPED SYSTEMS

(a) Characterization of various modeling components

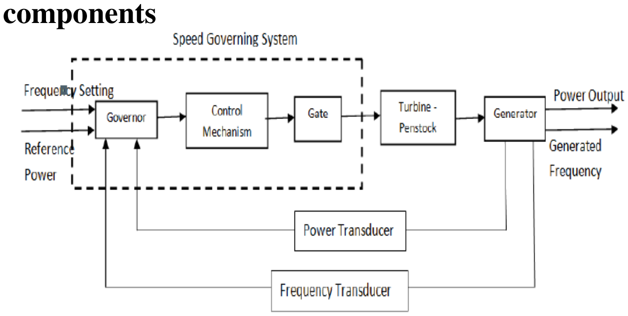

Figure.1 block diagram of hydroelectric plant

The block diagram of hydroelectric plant is show in fig.1. Water stored at certain head contains potential energy. This energy is converted to kinetic energy. When it is allowed to pass through the penstock, this kinetic energy is converted to mechanical energy (rotational energy) which allows water to fall on the runner blades of the turbine. Hence As the shaft of the generator is coupled to the turbine, the generator produces electrical energy by converting the mechanical energy into electrical energy. The speed governing system of turbine adjusts the generator speed based on the feedback signals of the deviations of both system frequency and power with respect to their reference settings. This ensures power generation at synchronous frequency.

(b) Mathematical Model of Hydro Turbine Governor System

In small hydroelectric systems, hydraulic turbines are used to drive synchronous generators. These hydraulic turbines convert the energy of flowing water into mechanical energy which in turn is converted into electrical energy

The representation of the hydraulic turbine and water column in stability studies is usually based on the following assumptions:-

i. The hydraulic resistance is negligible.
ii. The penstock pipe is inelastic and the water is incompressible.
iii. The velocity of the water varies directly with the gate opening and with the square root of the net head.
iv. The turbine output power is proportional to the product of head and volume flow.
v. Figure 2 shows the essential parts of a typical small hydraulic plant.

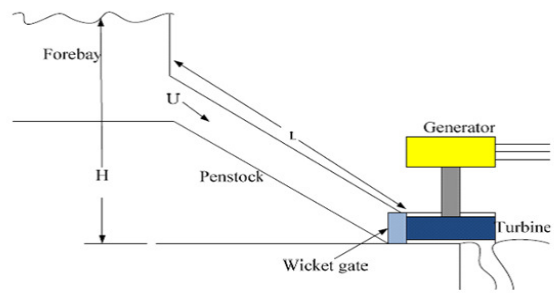

Figure.2 shows the essential parts of a typical small hydraulic plant.

Three basic equations are used to determine the characteristic of the turbine and penstocks are as followed

a. Velocity of water in the penstock
b. Turbine mechanical power
c. Acceleration of water column

The velocity of water in the penstock is given by

$$U = K_u G\sqrt{H} \qquad .1$$

Where

U=water velocity, G=gate position, H=hydraulic head at gate, Ku=a constant of proportionality

For small displacements about an operating point,

$$\Delta U = \frac{\partial U}{\partial H}\Delta H + \frac{\partial U}{\partial H}\Delta H \qquad .2$$

Hence substituting the appropriate expressions for the partial derivatives and dividing through by

$$U_0 = K_u G_0\sqrt{H_0} \quad \text{Yields} \quad \frac{\Delta U}{U_0} = \frac{\Delta H}{2H_0} + \frac{\Delta G}{G_O}$$

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$$\Delta U = \frac{1}{2}\Delta H + \Delta G \qquad .3$$

Where, the subscript 0 denotes initial steady-state values, the prefix Δ denotes small deviation.
The turbine mechanical power is proportional to the product of pressure and flow; hence,

$$P_m = K_P H U \qquad .4$$

Linearizing by considering small displacements, and normalizing by dividing both sides by

$$P_{mo} = K_P H_0 U_0 \qquad .5$$

Hence

$$\frac{\Delta P_m}{P_{m0}} = \frac{\Delta H}{H_0} + \frac{\Delta U}{U_0} \quad \text{Or} \quad \Delta \bar{P}_m = \Delta \bar{H} + \Delta \bar{U} \qquad .6$$

Substituting for $\Delta \bar{U}$ from equation (3) yields

$$\Delta \bar{P}_m = 1.5\Delta \bar{H} + \Delta \bar{G} \qquad .7$$

Alternatively, by substituting for ΔH from equation (3.6) we may write

$$\Delta \bar{P}_m = 3\Delta \bar{U} - 2\Delta \bar{G} \qquad .8$$

The acceleration of water column due to change in head at the turbine, characterized by Newton's second law of motion, may be expressed as

$$\rho L A \frac{d\Delta U}{dt} = -A(\rho a g)\Delta H \qquad .9$$

L=length of conduit
A=pipe area
ρ=mass density
ag =acceleration due to gravity
ρLA =mass of water in the conduit
ρag ΔH =incremental change in pressure at turbine gate
t=time in second

By dividing both side by agHoUo, the acceleration equation in normalized form becomes

$$\frac{LU_0}{a_g H_0}\frac{d}{dt}\left\{\frac{DU}{U_0}\right\} = \frac{\Delta H}{U_0}$$

$$T_w \frac{d\Delta \bar{U}}{dt} = \Delta \bar{H} \qquad .10$$

Where by definition,

$$T_w = \frac{LU_0}{a_g H_0} \qquad .11$$

Here Tw is referred to as the water starting time. It represents the time required for a head Ho to accelerate the water in the penstock from standstill to the velocity Uo. It should be noted that Tw varies with load. Typically, Tw at full load lies between 0.5s and 4.0s.
Equation .7 represents an important characteristic of the hydraulic plant. A descriptive explanation of the equation is that if back pressure is applied at the end of the penstock by closing the gate, then the water in the penstock will decelerate. That is, if there is a positive pressure change, there will be a negative acceleration change.
From equations .8 And .10 it can express the relationship between change in velocity and change in gate position as

$$T_w \frac{d\Delta \bar{U}}{dt} = 2(\Delta \bar{G} - \Delta \bar{U}) \qquad .12$$

Replacing d ⁄dt with the Laplace operator s, we may write

$$T_w s \Delta \bar{U} = 2(\Delta \bar{G} - \Delta \bar{U}) \qquad .13$$

Or

$$\Delta \bar{U} = \frac{1}{1+\frac{1}{2}T_w s}\Delta \bar{G} \qquad .14$$

Substituting for $\Delta \bar{U}$ from equation .7 and rearranging, we obtain

$$\frac{\Delta P_m}{\Delta G} = \frac{1 - T_w s}{1 + 0.5 T_w s} \qquad .15$$

Equation .10 represents the classical transfer function of a hydraulic turbine. It shows how the turbine power output changes in response to a change in gate opening or an ideal lossless turbine.

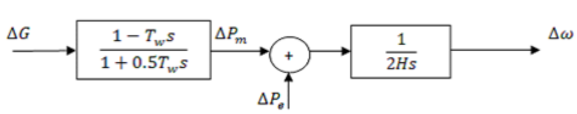

Figure 3: Block diagram of a hydraulic turbine and a generator

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(c) Modeling the Load

As shown in Figure.3 the electrical load connected to the synchronous generator is of consumer load. The change in the total electrical load is due to changes in the consumer load

$\Delta P_e = \Delta P_{CL}$ .16

Where, ΔPCL is change in consumer load.

The consumer load on a small hydroelectric system consists of various types of electrical devices. Generally, the consumer load can be divided into two: non-frequency sensitive and frequency sensitive loads. Loads such as lighting and heating are independent of frequency whereas motor loads are sensitive to changes in frequency. How a load is sensitive to frequency depends on the composite of the speed-load characteristics of all the driven devices.

The speed load characteristic of a composite load is given by

$\Delta P_{CL} = \Delta P_L + D\Delta\omega$ .17

Where ΔP_L and $D\Delta\omega$ are non-frequency-sensitive and frequency sensitive load changes in the consumer load respectively. D is the load damping constant and is expressed as percent change in load divided by percent change in frequency.

Substituting Equation (.16) in Equation (.17), we have

$\Delta\omega(s) = \frac{1}{2HS}[\Delta P_m(s) - \Delta P_L(s) - D\Delta\omega(s)]$ .18

The simplified equation is

$\Delta\omega(s) = \frac{1}{2HS+D}[\Delta P_m(s) - \Delta P_L(s)]$ .19

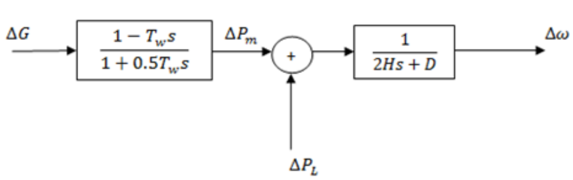

Figure 4: Turbine, generator and load block diagram

(d) Modeling the load controller (PI controller)

The load controller is modeled in the same way the governors of medium and large scale hydropower systems are modeled. Therefore, understanding the principle of operation of mechanical or electronic hydraulic governors is crucial. In medium or large scale hydropower systems, governors are designed to permit the speed to drop as the load is increased. The steady-state characteristic of such a governor is shown in figure 3.5 below:

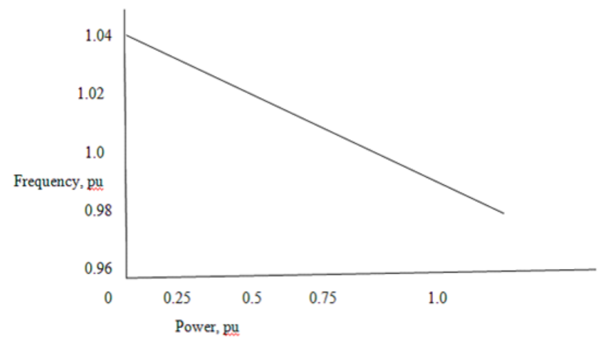

Figure 5: Governor steady-state speed characteristics

The slope of the curve represents the speed regulation R (usually 5 to 6%) and the input of the governor action is

$\Delta P_g = \Delta P_{ref}(s) - \frac{1}{R}\Delta\omega$ .20

Where ΔPref is the Load reference set point. In s-domain,

$\Delta P_g(s) = \Delta P_{ref}(s) - \frac{1}{R}\Delta\omega$ .21

To eliminate frequency error, a reset action is given to the load reference setting through an integral controller to change the speed set point.

Thus, Equation (.17) becomes

$\Delta P_g(s) = \frac{-k1}{s}\Delta\omega(s) - \frac{1}{R}\Delta\omega(s)$ .22

Where K1 is an integral constant.

The second term in Equation (.22) is similar to a proportional controller. Hence, Equation (.19) is obtained.

$$P_g(s) = \frac{-k1}{s}\Delta\omega(s) - K_p\Delta\omega(s)$$

$$\Delta P_g(s) = \Delta\omega(s)\{\frac{-k1}{s} + K_p \qquad .23$$

Where K_p = 1/R.

The governor action is similar to the switching, in binary and phase delay load configuration, and the DC motor, in mechanical load configuration. Therefore, it is concluded that the load controller is approximated by a PI controller.

(d) Modeling the stepper motor

A permanent magnet stepper motor is used in controlling the spear valve of a small hydroelectric system. The mechanical part of the permanent magnet stepper motor model can be expressed by

$$j\frac{d^2\theta}{d^2t} + D\frac{d\theta}{dt} + N_r n\emptyset_M i_A \sin\left(N_r(\theta-\lambda)\right) + Csin\left(\frac{d\theta}{dt}\right) + T_L = 0 \qquad .24$$

This equation is the complete model of the permanent magnet stepping motor consists of the rotor dynamic equation.

where*J* is the moment of rotor inertia (*Kg.m*2),

D is the viscous damping coefficient (*N.m.s.rad1*),

C is the coulomb friction coefficient, *iB*,

*iA*are the currents in windings *A* and *B*,

Nr is the number of the rotor teeth,

nΦM is the flux linkage,

Θ is the rotational angle of the rotor

And λ is the tooth pitch in radians and *TL* is the load torque.

On the other hand, the electrical part of a permanent magnet stepper motor model is described by voltage equations for the stator windings.

$$V - ri_A - L\frac{di_A}{dt} - M\frac{di_B}{dt} - \frac{d}{dt}(n\,\emptyset_M \cos(N_r\theta)) = 0 \qquad 3.25$$

$$V - ri_B - L\frac{di_B}{dt} - M\frac{di_A}{dt} - \frac{d}{dt}(n\emptyset_M \cos(N_r(\theta-\lambda))) = 0 \qquad .26$$

These two equations are differential equations for current equation. Where *V* is the DC terminal voltage supplied to the stator windings (volt), *L* denotes the self-inductance of each stator phase (*mH*), *M* represents the mutual inductance between phases (*mH*) and *r* is stator circuit resistance (*ohm*). Those equations are nonlinear differential equations. Since it is very difficult to deal with nonlinear differential equations analytically, linearization is needed.

The equilibrium position of the stator is Θ=λ/2. When both motor windings will differentiate by δΘ therefore, is $\Theta = \lambda/2 + \delta\Theta$. then the nonlinearities expressed by sine and cosine functions in equations of the above will be approximated with knowledge of trigonometric identities and when $Nr\delta\Theta$ is small angle: $cos(Nr\delta\Theta) = 1$ and $sin(Nr\delta\Theta) = Nr\delta\Theta$. then, the linearized model can be expressed by

$$j\frac{d^2\theta}{d^2t} + D\frac{d\theta}{dt} + 2N^2rn\emptyset_M i_0 \cos\left(\frac{N_r\lambda}{2}N_r(\theta - \lambda)\right) + Csin\left(\frac{d\theta}{dt}\right) + T_L = 0$$

$$r\delta i_A + L\frac{d(\delta i_A)}{dt} + M\frac{d(\delta i_B)}{dt} - N_r n\Phi_M \sin\left(\frac{N_r\lambda}{2}\right)\left(\frac{d\theta}{dt}\right) = 0$$

Where, $cos(Nr\lambda\backslash 2)$ and $sin(Nr\lambda\backslash 2)$ are constants.

The permanent magnet stepping motor transfer function is derived from equations of above are

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with the aid of Laplace transform. The coulomb friction coefficient *C* is considered to be zero.

The resulting form of the transfer function in two-phase excitation is:

$$\frac{\Theta_o}{\Theta_i} = \frac{\frac{r}{L}w^2np}{s^3+\left(\frac{r}{L_p}+\frac{D}{J}\right)s^2+\left(\frac{rD}{L_pJ}w^2np(1+K_p)\right)s+\left(\frac{r}{L_p}\right)w^2np} = G_p(s) \qquad .28$$

Where:

$$L_p = L - M, w^2np = \frac{2N^2 rn\Phi_M I_o \cos\left(\frac{N_r\lambda}{2}\right)}{J}$$

$$K_p = \frac{n\Phi_M \sin^2\left(\frac{N_r\lambda}{2}\right)}{L_p I_o \cos\left(\frac{N_r\lambda}{2}\right)}$$

Neglecting the higher orders of the transfer function it can be simplified to the equation shown below. The transfer function model of the PM stepper motor is required. The transfer function between the desired and the output angle of a permanent magnet stepper motor is given by

$$\frac{\theta_0(s)}{\theta_i(s)} = T(s) = \frac{K_m I_p N_r}{Js^2+\beta s+K_m I_p N_r} \qquad .29$$

where Θo is the output angle, Θi is the desired angle, J is the moment of inertia of the rotor, Km is the torque constant of the permanent magnet stepper motor, Ip is the phase current, Nr is the number of rotor teeth, and ʙ is viscous friction coefficient. The stepper motor is controlled by a controller. The controller calculates the deviation in the desired angle based on the frequency deviation in the small hydropower system. In general, the block diagram in Figure 3.6 is obtained. Here again, the controller is assumed to be proportional integral controller similar to the load controller.

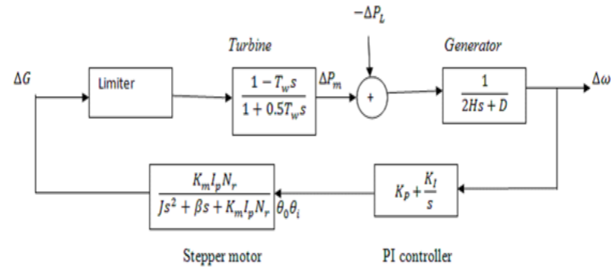

Figure 6: Flow control model of a small hydroelectric generation

(e) MATLAB/Simulink of small hydroelectric generation Simulink block diagram

The individual sub-models like hydro turbine governor, synchronous generator, excitation system and 3-phase RLC load are now connected together to form the complete block diagram of micro hydro power plant (Figure .7).

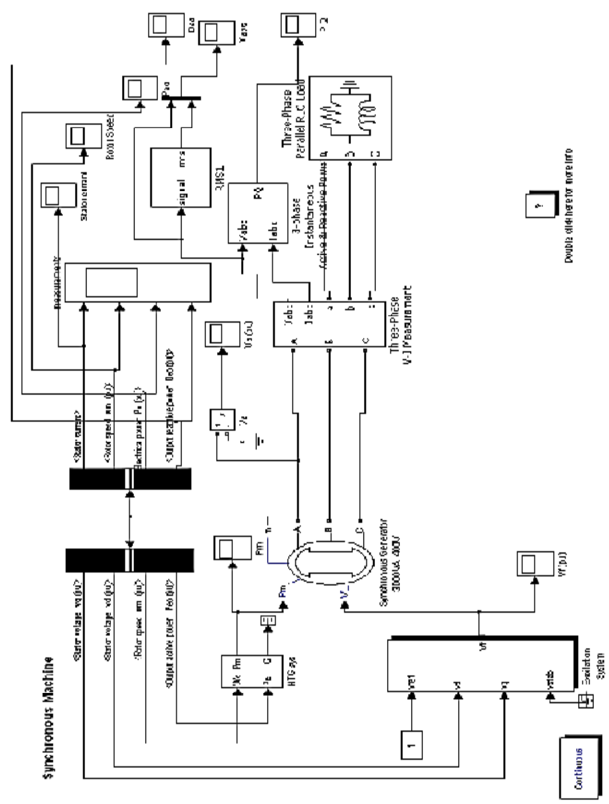

Figure 7: complete block diagram of micro hydro power plant

IV. RESULTS AND DISCUSSIONS

The frequency controller was modeled, designed and analyzed in the methods section of this paper. The transient response of a practical control system often exhibits damped oscillations before reaching steady state

The transfer function model of a small hydroelectric generation system with is shown in above Simulink model. This model with and without the controller was simulated using a MATLAB code from appendix 1

The step response of the frequency deviation of a 1492 kW, low head, and small hydroelectric generation system for a 3% load change is shown in Fig 9 in appendix 2. From the figure, it is seen that the small hydropower system is stable and the steady-state frequency deviation is eliminated by the controller. Therefore, the low head, small hydroelectric generation system is stable and shows good transient and steady state performances

Table 2: With and without controller low head small hydropower system

Proposed model	Settling time	Rise time	Overshoot	Steady state
	69.1	0	-	0
Existing model	4.45	0.631	25.3	0.66

The graph below is shown the MATLAB code from appendix 1resented the simulation result in the graph.

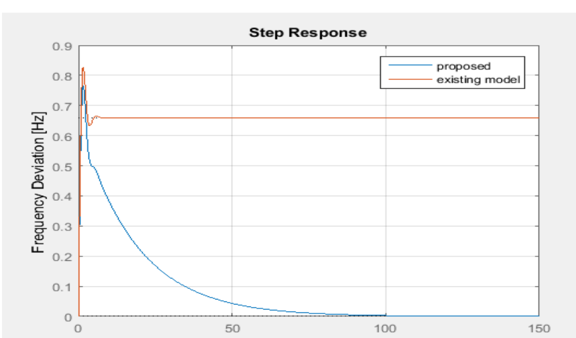

Figure 8: Simulation result with proposed and existing model low head, small hydro power.

Generally, to test the effectiveness of the frequency controller, similar tests had been done for low, medium and high head small hydropower systems. Figure 9 shows the frequency deviation step responses of the three types of small hydroelectric generation systems for a 3% load change from appendix 1.MATLAB code of three head small hydroelectric generation

Table 3: Transient performances of small HPs with Frequency Control Mode for different heads

Parameter For H=0.87,D=1.5%	Low head small HPs	Medium head small HPs	High head small HPs
Settling time	69.1	56.6	54.7

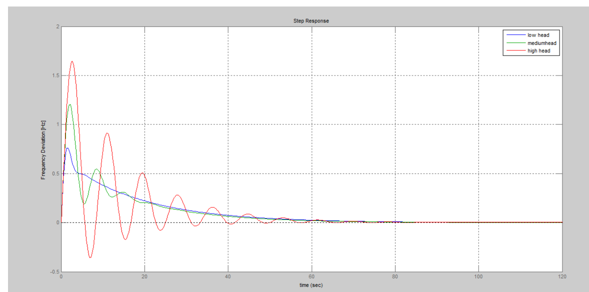

Figure 9: Frequency deviation step responses of low, medium and high head small HPs

As it is observed from Figure 9 and Table 3 the frequency controller shows good transient and steady-state performances during flow control of different heads. Beside this, the controller was also tested for different capacities of small hydropower systems.

The inertia constants for small hydropower systems range from 2.seconds to 10 seconds. Generally, to test the effectiveness of the frequency controller, similar tests had been done for low, medium and high head small hydropower systems

As it is observed from Figure 10 and Table 4 the frequency controller shows good transient and steady-state performances during flow control mode for different heads. Beside this, the controller was also tested for different capacities of small hydropower systems. The inertia constants for small hydropower systems range

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from 2.8 seconds to 10 seconds. The steady state frequency error is zero in all the cases and the transient performances for ranging capacities of small hydropower systems are summarized in Table 4.

Table 4: Transient performances for different capacities of low head small HPs

Inertia Constant (H), D=1.5%, 3% load change, low head	Settling time
0.87	69.1
2.8	71.1
4	69.1
5	66.7
7	59.8
10	82.1

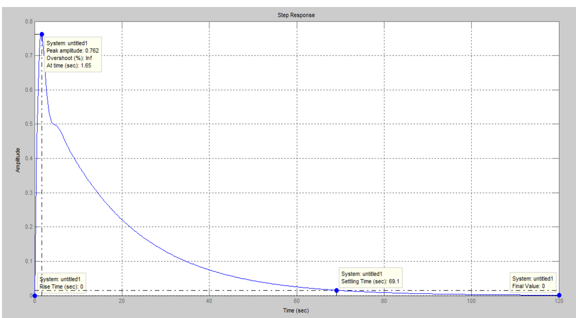

Figure 10: Frequency deviation step responses of low head small HPs

V. CONCLUSION

Over the years the impact of inter cell interference has hindered the full realization of HetNet potentials. This problem ICI is inevitable and can only be managed to ensure quality of service. This problem was solved in this research using a cell coordination framework which ensures that the multi cells do not transmit with the same resource block at the same time. This was implemented with simulink and tested. The result showed that the algorithm was able to mitigate interference and achieve average throughput of 72% which is an indicator or quality of service.

Recommendations

This thesis will provide hard ware materials to accomplish in practically. But, now in this year it has not provided the practical materials that are very expensive to buy it. For the future thesis that are similar to our thesis that are frequency control for small hydropower system the department would as much as possible be provided the electrical material used to hard ware implementation. In our thesis we cannot make hard ware implementation because of the expensiveness of power generator, tribune, stepper motor and other electrical materials that are used to implement the hard ware implementation of our thesis.

Generally, we are recommending to the department for the future thesis it must be providing the electrical materials which are used to hard ware implementation.

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APPENDICES

Appendix A:

Raw data for design, analysis and simulation

Table 52.1: Specifications of 1FC2-283-4 synchronous generator

Parameter	Value
Current rating	888A
The moment of inertia	3 kgm2
Power factor	0.8
Load damping coefficient	1.5%
Power rating	225kvA
Voltage rating	400 v
Speed	1500rpm
Number of pole	4

Table 4.3: Stepper motor specifications

Parameter	Value
Model	43HS2A165-654
Number of teeth (Nr)	50
Rated phase current	6.5A
Phase resistance	0.65ohm

Phase inductance	14mH
Lead wire	4
Weight	11kg
Holding torque	26.0Nm
Step angle	1.8o
Inertia constant	0.0013kg-m2
Torque constant	4 N-m/A
Viscous friction constant(assume)	0.5N-m/rad/sec

APPENDIX B: MATLAB CODES

Appendix B.1: Matlab Code with and without Controler

```
%programmer: power engineerers
% Date: 2016
%Program: This program plots the step response of frequency of small
%hydropower system with FCM for low heads
%load change = 3%
TI=8; % the integral time constant
kp=1; %proportional gain
ki=kp/TI; % integral gain
Gen=tf(1,[2*0.87 1.5]); % synchronous generator %transfer function
% H = 0.87 sec and D = 1.5%
%---------------with controller---------------
PMstepper=tf(162.5,[0.0013 0.5 162.5]); %transfer function of the stepper
motor
PI=tf([kpki],[1 0]); % PI controller
Hturbine=tf([-1 1],[0.5 1]); %turbine transfer function
Hs=PI*PMstepper*Hturbine; %feedback transfer function
Gc=feedback(Gen,Hs);  %Closed loop transfer function
step(50*0.03*Gc) %Step response
hold on
%-------------without controller
PMstepper=tf(162.5,[0.0013 0.5 162.5]); %transfer function of the stepper
motor
Hturbine=tf([-1 1],[0.5 1]); %turbine transfer function
Hs=PMstepper*Hturbine; %feedback transfer function
Gc=feedback(Gen,Hs);  %Closed loop transfer function
step(55*0.03*Gc) %Step response
ylabel('Frequency Deviation [Hz]');
xlabel('time');
legend('with controller', 'without controller');
grid on
```

Appendix B.2: Matlab Code Of Power Error

```
%programmer: power engineers
% Date: 2016
%Program: This program plot the step response of power error
%of a low head small hydropower system with FCM
%load change = 3%
%capacity = 1492 kW
TI=8; % the integral time constant
kp=1; % proportional gain
ki=kp/TI; % integral gain
Gen=tf(1,[2*0.87 1.5]); % synchronous generator %transfer function
% H = 0.87sec and D = 1.5%
PMstepper=tf(162.5,[0.0013 0.5 162.5]); %transfer function of the stepper
motor
PI=tf([kpki],[1 0]); % PI controller
Hturbine=tf([-1 1],[0.5 1]); %turbine transfer function
Hs=PI*PMstepper*Hturbine; %feedback transfer function
perr= 1/(Gen*Hs+1);
step(1492*0.03*perr,-1492*0.03*perr); %step response
ylabel('power error [kW]');
xlabel('time');
title('Power error of low head small hydropower system');
legend('delPL=-14.76 kW', 'delPL=14.76 kW');
grid on
```

Appendix B.3: Matlab Code of low head Small Hydro Power

```
%programmer: power engineers
% Date: 2016
%Program: This program plots the step response of frequency of small
%hydropower system with FCM for different heads
%load change = 3%
TI=8; % the integral time constant
kp=1; %proportional gain
ki=kp/TI; % integral gain
Gen=tf(1,[2*0.87 1.5]); % synchronous generator %transfer function
% H = 5 sec and D = 1.5%
PMstepper=tf(162.5,[0.0013 0.5 162.5]); %transfer function of the stepper
motor
PI=tf([kpki],[1 0]); % PI controller
%----------------- low head small hydropower system ----------------------
Hturbine=tf([-1 1],[0.5 1]); %turbine transfer function
Hs=PI*PMstepper*Hturbine; %feedback transfer function
Gc=feedback(Gen,Hs); %Closed loop transfer function
step(50*0.03*Gc) %Step response
```

Appendix B.4: Matlab Code of three Head Small Hydropowers

```
%programmer: power engineering
% Date: 2016
%Program: This program plots the step response of frequency of small
%hydropower system with FCM for different heads
%load change = 3%
TI=8; % the integral time constant
kp=1; %proportional gain
ki=kp/TI; % integral gain
Gen=tf(1,[2*0.87 1.5]); % synchronous generator %transfer function
% H = 5 sec and D = 1.5%
PMstepper=tf(162.5,[0.0013 0.5 162.5]); %transfer function of the stepper
motor
PI=tf([kpki],[1 0]); % PI controller
%----------------- low head small hydropower system ----------------------
Hturbine=tf([-1 1],[0.5 1]); %turbine transfer function
Hs=PI*PMstepper*Hturbine; %feedback transfer function
Gc=feedback(Gen,Hs); %Closed loop transfer function
step(50*0.03*Gc) %Step response
hold on
%----------------- medium head small hydropower system ---------------------
Hturbine=tf([-2.5 1],[1.25 1]); %turbine transfer function
Hs=PI*PMstepper*Hturbine; %feedback transfer function
Gc=feedback(Gen,Hs); %Closed loop transfer function
step(50*0.03*Gc) %Step response
hold on
%----------------- high head small hydropower system ----------------------
Hturbine=tf([-4 1],[2 1]); %turbine transfer function
Hs=PI*PMstepper*Hturbine; %feedback transfer function
Gc=feedback(Gen,Hs); %Closed loop transfer function
step(50*0.03*Gc) %Step response
holdon
ylabel('Frequency Deviation [Hz]');
xlabel('time');
legend('low head','mediumhead','high head');
grid on
```

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