Scientific Research Publishing

Smart Grid and Renewable Energy, 2022, 13, 160-171
https://www.scirp.org/journal/sgre
ISSN Online: 2151-4844
ISSN Print: 2151-481X

Modelling and Simulation of Performance of the Microgrid Frequency Stability Control during Unplanned Islanding: The Case Study of Mwenga Hydropower

Eligard Kyaruzi Francis, Arthur M. Omari, John P. John

Department of Electrical and Power Engineering, Mbeya University of Science and Technology, Mbeya, Tanzania
Email: eligardfrancis@gmail.com

How to cite this paper: Francis, E.K., Omari, A.M. and John, J.P. (2022) Modelling and Simulation of Performance of the Microgrid Frequency Stability Control during Unplanned Islanding: The Case Study of Mwenga Hydropower. *Smart Grid and Renewable Energy*, **13**, 160-171.
https://doi.org/10.4236/sgre.2022.137010

Received: June 4, 2022
Accepted: July 23, 2022
Published: July 26, 2022

Abstract

A grid connected microgrid connects to the grid at a point of common coupling. Due to the great inertia of the grid which accelerates and decelerates the generator when its frequency tends to deviate, the grid connected microgrid operates at a frequency of the infinity bus. Frequency instability is one of the major challenges facing the grid connected microgrid during islanding. The power demand variation causes the variation in rotor speed, resulting to frequency deviation. Frequency can be brought back to standard by varying the power generation to match with the varying load. The performance of the frequency stability control system at Mwenga hydroelectric microgrid has been studied. Through site visitation, the power demand and generation status data were collected and analysed for model preparation. The results of the study indicate that, during islanding, the Mwenga rural electrification project is observed to be subjected to power imbalance which leads to frequency instability. Although the frequency control system tries to keep the system at a nominal frequency by maintaining the continuous balance between generation and varying load demand, however the system still operates with large magnitude of overshoot, undershoot and longer settling time.

Keywords

Modelling, Frequency Stability, Unplanned Islanding, Mwenga

1. Introduction

Island mode means a mode of operation when a Microgrid with a self-generation station which generally operates in grid-connected mode is disconnected from the utility grid at the Point of Common Coupling. Unplanned islanding happens when a grid connected microgrid electrically unintentionally disconnects from the main grid, however the isolated part continues to be energized through the microgrid self-generation stations [1]. The main objective of distributed generation is to supply reliable and quality energy to people residing distant away from the utility grid [2]. Exploration has shown that Tanzania has potential of private power producers generating and injecting power into the main utility grid to ensure the grid with quality, sufficient and reliable power supply. The Mwenga Rural Electrification Project is a hydroelectric based grid connected microgrid located at Isipii village in Mufindi District, Southern highlands of Tanzania. The site operates a 4 MW hydro-power-station supplying about 21.5 GWh per annum of grid-quality, renewable electricity to the National Utility (TANESCO), to the local tea industry as a back-up source, as well as to 32 villages in the Mufindi district. The plant uses vertical-axis Francis turbine at a flow rate averaging to 8 cubic meters per second and a Run-off river designed at a head of 8 meters along a gauged Mwenga river

Mwenga hydro station uses Siemens PLC as controller to control the pressure, flow and temperature within the plant. The flow control is related to the amount of power demand, where the controller is required to provide command to vary the position of hydraulic valve using fluids. A PID control function is implemented in PLC controller which increases the level of precision by controlling the output based on the adjustments of the gain set points. The controller gains are proportional, integral and derivative gains which improve the rise time, reduce the overshoot and reduce the steady state error.

Frequency instability is the major challenge to many local grid connected distribution generations [3]. This is due to mismatching between generation and consumption in microgrid especially when it unintentionally disconnects from the main grid. During unplanned islanding, if the amount of active power generated by the microgrid is large compared to demand status, the sudden energy unbalance results in microgrid which causes the voltage and frequency fluctuation. The microgrid gets subjected to longer frequency settling time, the situation which affects the sensitive loads along the microgrid. The microgrid control system tries to adjust the control parameter gains to retain the system into a stable mode [4]. A well known frequency control status helps to enforce system performance improvement. The aims of this work are to study the performance of the microgrid frequency stability control during the unplanned islanding mode.

2. Review on Microgrid Stability

2.1. Microgrid Architecture

A microgrid is usually positioned and interconnected at the low voltage distribution system of the main grid. It is connected to the medium voltage substation at a Point of Common Coupling mostly, by a circuit breaker [5]. A centralized controller required to manage the supply of power between microgrid and utility grid is placed at the low voltage side of the point of common coupling. It act as a backbone of the system, detects islanding and provide command to auxiliary devices. The loads are also positioned alongside the lines through load controllers [5].

2.2. Microgrid Stability

It is the capacity of a system to remain in equilibrium operating condition or to get returned to the point of equilibrium after being subjected to a disturbance. The microgrid stability has been categorized as indicated in **Figure 1** below (Soroush, 2021).

2.2.1. Rotor Angle Stability

It is the capability of interconnected synchronous generators in a microgrid to stay in a synchronism operating condition even after being subjected to disturbance. It is determined measured by its capacity to keep the system in equilibrium between mechanical and electromagnetic torque of all the machines in the system [6]. The instability in the generator is caused by increasing the angular swing.

2.2.2. Frequency Stability

It is the ability of microgrid device to keep the frequency value within the specified deviation range (±0.5 hertz) at the state of disturbance or during normal operating condition. The common disturbance is the generation and load mismatch, when this mismatch takes place, the rate and or frequency varies leading to frequency instability [7].

When electrical electrical load exceeds the input mechanical energy difference get compensated by the stored kinetic power of the rotating shaft leading to decline in turbine velocity in order to keep a constant alternator output. This causes the reduction in generator output frequency as seen in Equation (2.1)

$$\omega = 2\pi f \tag{2.1}$$

The symbol w stands for the turbines speed in rad/sec while f represents the system frequency in hertz.

2.3. Micro Hydro Frequency Stability Control

The power system must always generate power which is equal to load available.

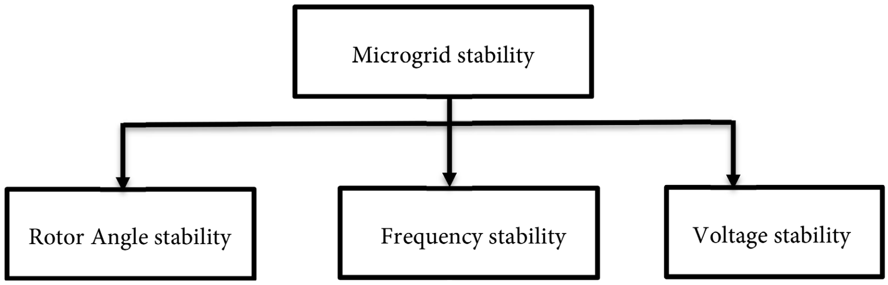

Figure 1. Classification of micro grid stability.

It is important to keep the production and consumption of electricity equal in order to maintain frequency stability of the electric grids. In the alternating current grids, imbalance between generation and consumption results to rising and falling of the grid frequency.

2.4. Micro Hydro Microgrid Generation System Modelling

The hydroelectric models are created basing on physical standards of conservation of mass, strength and momentum. The process involves generation of the partial differential equations which are implemented in the modelling of the hydropower plants. Partial differential equations-based model is mostly applied when considering the plant utilizing long pipe penstock in the design. However, partial differential equations is less considered if the hydropower plant is of a run-of-river scheme, at which longer conduits are rarely used [8].

2.4.1. Gates

The water control devices; permit and stop the water flow between two points. For a plant with run-of-river scheme and without a discharge manipulate action, they are usually used to monitor and control the level of the upper water reservoir [9]. Gates also depend on the principle of conservation of mass where the sum of outward flows is equals to the sum of outward flows.

2.4.2. Turbine

These are mechanical rotating machines driven by water, where by the hydraulic energy of flowing water get converted into mechanical energy [4].

If the efficiency of the turbine is known, the power output of the hydraulic turbine-generator can be calculated.

2.4.3. Synchronous Generator

It is an electric machine coupled to the turbine shaft purposely to convert the mechanical energy from the turbine shaft into electrical output energy. The characteristic of synchronous generator depends on whether the system is grid connected isolated.

At no load and without brake application at the generator power of the torque resistance becomes proportional to the product of the loss factor and the speed w square. On the other hand, for grid connected alternator power of the torque resistance is equal to power input, provided that the rotational speed is brought to zero and the rotational speed is kept constant and equal to the value of a frequency at 50 Hz. In this state, the hydroelectric unit is considered running with parameters of the infinity bus when it is grid connected [10].

2.4.4. Hydro-Turbine Governor System

The control system of the plant automatically controls the runner blade by a PID control enhanced automation system, it receives the position of the gate in order to obtain the reference of the position of the runner blade depending with the blade and gate characteristics for optimal performance. The structure of the PID controller consists of three main terms: proportional gain (P), Integral gain (I) and Derivative gain (D). It ensures faster speed response by adjusting the values of the gain parameters stated above to keep the plant frequency at constant value [2].

2.5. Grid Code on Power System Frequency Stability

The grid code has provided regulation and standards regarding to frequency stability in three categories basing on the load sensitivity and capacity of the plant summarized as follows.

Primary frequency control should be triggered automatically, right after the over and under-frequency event has sensed. Secondary frequency control should also be triggered within tens of seconds. Tertiary frequency control is required to be triggered within a few minutes in case the over and under-frequency event does not correct itself through primary or secondary frequency control mechanisms [11]. In general, from the power system frequency stability grid code, the frequency should be stable within a time limit ranging from micro seconds to some few minutes depending with the plant category and type of load to be connected.

3. Material and Methods

3.1. Feasibility Study and Data Collection

Important data required for frequency stability control study was collected physically through a site visitation at Mwenga hydropower project. The data was analysed to obtain the data necessary for frequency control model design.

Data Collection

This study uses secondary source of data collected through site visit. The data collected from the site is used for the design of the model. The gathered data includes: System operating voltage, system operating frequency, controller gain parameters, power demand and site generation status. The site supplies two sets of villages, where two transformers of 6.6/0.4 kV each are used to step down the generated voltage to meet the village demand voltage (**Table 1**).

3.2. System Frequency Control Modelling

Deviation of the grid frequency from a nominal value is determined by the Equation (3.1) [4]

$$P_{\text{production}} - P_{\text{consumption}} = J_{eqv} w_{el} \frac{\mathrm{d}w_{el}}{\mathrm{d}t} \tag{3.1}$$

where $P_{\text{production}}$ is the production in (W), $P_{\text{consumption}}$ represent consumed power in (W), the J_{eqv} (kgm^2) represent the grid inertia, while the electrical angular velocity is represented by ω_{el} (rad/s) from Equation (3.1) above, the grid frequency f_{el} (Hz) is proportional to the angular speed.

An imbalance between generation and demand, for example, lower production

Table 1. Mwenga hydroelectric microgrid load profile data.

S/N	Item	Amount
1	Power station capacity	4 MW
2	Grid feeder ratings	15 MW
3	Power fed to Grid	0 - 3.3 MW
4	Power delivered to villages	0.1 - 0.3 MW
5	Power delivered to tea industry	0.4 MW
6	System Voltage	33 kV
7	System frequency	50 Hz
8	Type of controller used	Siemens PLC S2000
9	Gain Parameters of controller	180, 3200 and 1
10	Number of villages saved	2
11	Line length	50 km
12	Number of step-up transformers	1(6.6/33kV)
13	Number of step-down transformers	2(6.6/0.4kV)
14	Number of spur lines	2
15	Number of mainline	1

makes the left-hand side of Equation (3.1) to become negative meaning that the derivative of the frequency must also become negative.

The principle objective of the microgrid frequency controller is to maintain reasonably uniform frequency and to divide the load between generators when operating at islanded mode. The change in frequency can be sensed which is a measure of change in rotor angle δ the error Δf to be corrected. The error signal, ie Δf is amplified, mixed and transformed into real power command signal ΔP_D which is sent to the prime mover to call for an increment in the torque. Considering the no load voltage of the generator E, the terminal voltage of the generator V_g, the infinity bus voltage V and by neglecting losses in the system, for a grid connected my microgrid, the real power generated should be equal to the power transferred to the infinity bus. The active power generated may then be written as:

$$P_G = |E||I|\cos(\Phi + \delta) = |V||I|\cos\Phi \tag{3.2}$$

From the above equation, we then get the relation,

$$|E|\sin\delta = |I| X \cos\Phi \rightarrow |I|\cos\Phi = \frac{|E|\sin\delta}{X} \tag{3.3}$$

From Equations (3.2) and (3.3), we get

$$P_G = \frac{|E||V|}{X}\sin\delta \tag{3.4}$$

where, $X = X_d + X_e$.

X_d = Synchronous reactance of the generator.

X_e = Reactance of the transmission system from the generator terminals up to the infinite bus. δ = Angle between stator axis and rotor axis of synchronous machine.

Equation (3.4) represents the power P_G per phase. If however, $|E|$ and $|V|$ are line voltages in kilovolts, the results are total three phase power in megawatts. From Equation (3.4), it can then be concluded that the real power is proportional to the load angle 'δ'. So, real power is directly proportional to the frequency 'f'.

As the frequency changes, the motor load changed being sensitive to speed.

Rate of change of load with respect to frequency $\frac{\partial P_D}{\partial f} = B$ where,

B = Damping coefficient in MW/Hz.

Value of damping coefficient is positive for motor load

$$\Delta P_G - \Delta P_D = B\Delta f \quad (3.5)$$

Writing power balance equation,

$$\Delta P_G - \Delta P_D = \frac{2HP_r}{f_0}\frac{\mathrm{d}}{\mathrm{d}t}(\Delta f) + B\Delta f \quad (3.6)$$

Dividing by P_r, we get

$$\Delta P_{G\,p.u.} - \Delta P_{D\,p.u.} = \frac{2H}{f_0}\frac{\mathrm{d}}{\mathrm{d}t}(\Delta f) + B_{p.u.}\Delta f$$

Taking Laplace transform on both sides, we get

$$\Delta P_G(s) - \Delta P_D(s) = \frac{2H_s}{f_0}\Delta F(s) + B\Delta F(s)$$

$$\Delta P_G(s) - \Delta P_D(s) = \Delta F(s)\left[\frac{2H_s}{f_0} + B\right]$$

$$\Delta F(s) = \frac{\Delta P_G(s) - \Delta P_D(s)}{B\left[1 + \frac{2H_s}{Bf_0}\right]}$$

$$\Delta F(s) = \Delta P_G(s) - \Delta P_D(s)\left[\frac{k_p}{1 + sT_p}\right] \quad (3.7)$$

where,

$k_p = \frac{1}{B}$ = power system gain and $T_p = \frac{2H}{Bf_0}$ = power system time constant.

The system frequency become stable when there is no difference between power generated and power demand i.e., from Equation (3.7), ΔF becomes zero when the difference between ΔP_G and ΔP_D is zero. This can be achieved through proper tuning of the controller gain parameters k_p and proper power system time constants T_p of Equation (3.7).

3.3. Data Analysis and System Modelling

The system is initially considered to operate at grid connected mode where it supplies power to both grid and local loads (Table 2).

During the grid connected mode the total load demand is 4 MW, while the total load demand at islanding mode is 0.7 MW (Table 3).

During transition from grid connected to islanding mode, the controller stabilizes the system frequency by regulating the input power with respect to demand status to keep generation equal to power demand. Consider a transition period at which the system initially operates at peak load of 4 MW, which is the maximum power demand of the village load, tea factory and utility grid, and 0.7 MW which is the village load and tea factory load demand during islanding. At this instant, the controller gain parameters being 180, 3200 and 1, the system frequency control is required to keep the microgrid at a frequency of 50 Hz basing on frequency objective function of the math model given in Equation (3.7) (Figure 2).

3.4. System Simulation

In this study, the system modelling is achieved using MATLAB software to identify the system frequency response when it disconnects from the utility grid. The model was validated through simulation using MATLAB SIMULINK simulation. The results of model simulation for grid connected mode and microgrid islanded mode is as presented in Figure 3.

4. Results and Discussion

Grid connected micro grid always operate at a frequency of the grid known as infinity bus. The microgrid when connected to grid becomes stable within a short period of time. As the system frequency in Tanzania is 50 Hz, it is observed in Figure 3 that, the Mwenga hydroelectric microgrid when grid connected attains a frequency stability of 50 Hz immediately, *i.e.*, after a time of less than a

Table 2. Load profile during grid connected mode.

S/N	ITEM	LOAD(MW)
1	Grid power requirement	3.3
2	Village Load requirement	0.3
3	Tea factory load requirement	0.4

Table 3. Load profile during islanding.

S/N	ITEM	LOAD (MW)
1	Grid requirement	0
2	Village load requirement	0.3
3	Tea factory load requirement	0.4

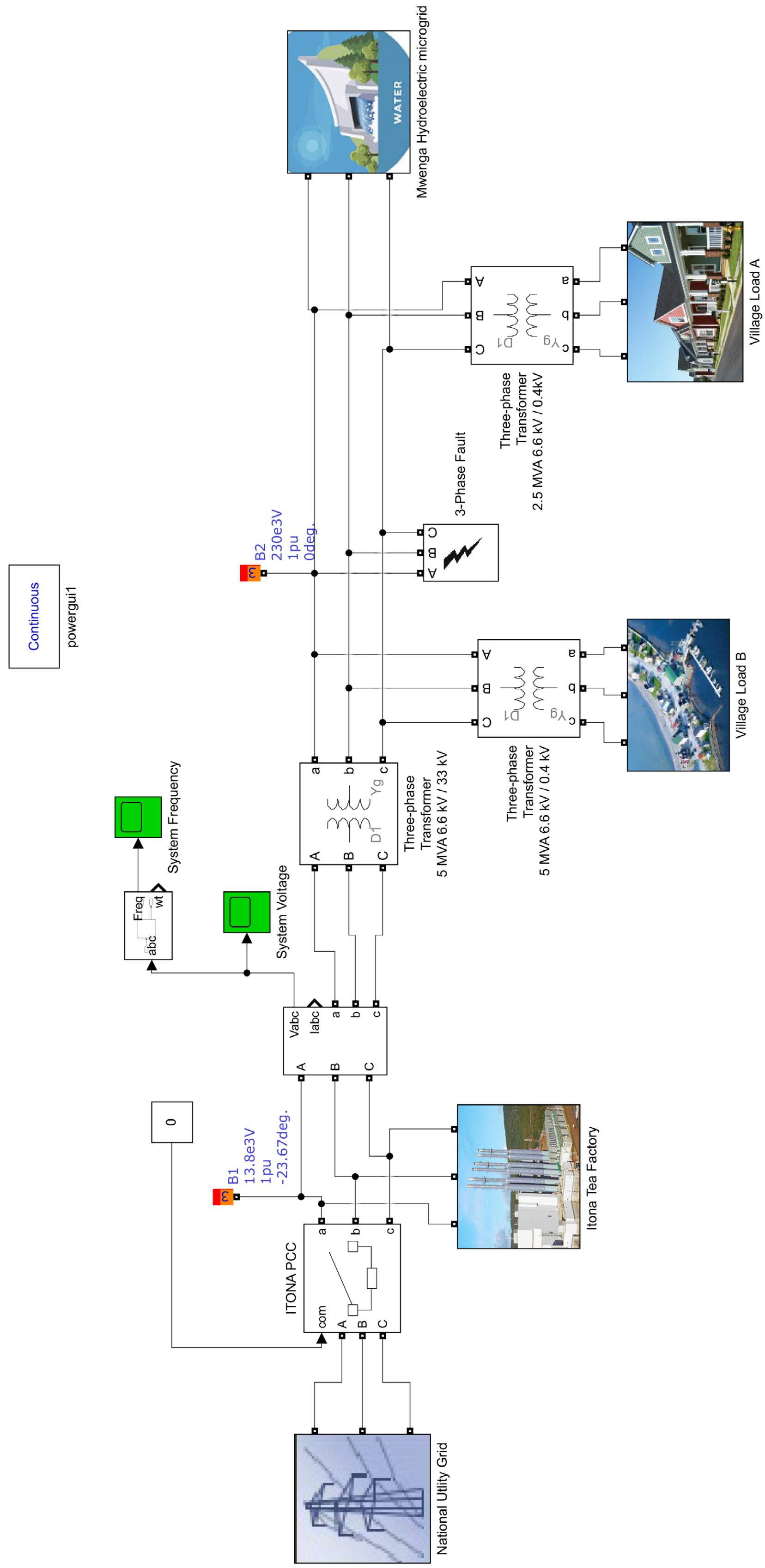

Figure 2. Mwenga grid connected hydroelectric microgrid model.

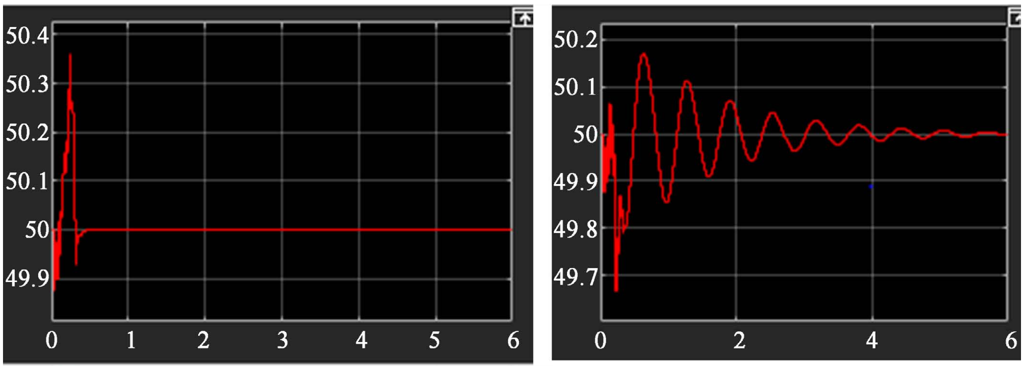

Figure 3. Frequency control at grid connected mode and islanding mode respectively.

second. On the other hand, the figure indicates that, during islanding it take longer time to become stable. The results of simulation show that, during islanding, the system attains its stability after more than 9 seconds of time. Ali Nandar, C. S. [12] performed a load frequency stabilization of microgrid power system using PI control, resulted with 5 seconds settling time. Bhateshvar, Y. K., Mathur, H. D., Siguerdidjane, H., & Bhanot, S. [13], developed a frequency stabilization for multi-area thermal-hydro power system using optimized fuzzy logic controller in deregulated environment and resulted with 4.5 seconds settling time. Khamis, A., Ghani, M. R. A., Kim, G. C., Kamarudin, M. N., & Aras, M. S. M. [14] performed a voltage and frequency control of microgrid systems with demand response and obtained 0.4 per unit overshoot and 4 seconds setting time. Basing on the results of the above optimized frequency stability control systems discussed above, the performance of Mwenga hydroelectric microgrid frequency stability control is considered to be poor.

5. Conclusion and Recommendation

5.1. Conclusion

The modelling and simulation of operation of the grid connected microgrid when it is grid connected and during islanding has been achieved, however the performance of its frequency stability control has also been studied. The findings indicate that the microgrid which operates in grid-connected mode stabilize within a short period of time, increases system flexibility and smooth the influence of power exchange between grid and microgrid. The findings also indicate the system takes too much time to stabilize due to weak performance of frequency controller during system islanding.

5.2. Recommendation

Shifting of operation mode from grid connected to island operation mode find a microgrid being subjected to power imbalance which causes the microgrid frequency fluctuations. Longer system settling time becomes a serious problem when the system is used to power highly sensitive loads. The performance of the microgrid frequency control has to be optimized using robust artificial intelligent approach to stabilize the system immediately after it has been subjected to disturbance especially in case of unintentional islanding.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Alayi, R., Zishan, F., Seyednouri, S.R., Kumar, R. and Ahmadi, M.H. (2021) Optimal Load Frequency Control of Island Microgrids via a PID Controller in the Presence of Wind Turbine and PV. *Sustainability*, **13**, 10728. https://doi.org/10.3390/su131910728

[2] Sahoo, B.P. and Panda, S. (2018) Improved Grey Wolf Optimization Technique for Fuzzy Aided PID Controller Design for Power System Frequency Control. *Sustainable Energy*, *Grids and Networks*, **16**, 278-299. https://doi.org/10.1016/j.segan.2018.09.006

[3] Mir, M., Dayyani, M., Sutikno, T., Mohammadi Zanjireh, M. and Razmjooy, N. (2020) Employing a Gaussian Particle Swarm Optimization Method for Tuning Multi Input Multi Output-Fuzzy System as an Integrated Controller of a Micro-Grid with Stability Analysis. *Computational Intelligence*, **36**, 225-258. https://doi.org/10.1111/coin.12257

[4] Zhang, Z., Wang, Z., Chen, Z., Wang, G., Shen, N. and Guo, C. (2019) Study on Grid-Connected Strategy of Distribution Network with High Hydropower Penetration Rate in Isolated Operation. *Processes*, **7**, 328. https://doi.org/10.3390/pr7060328

[5] Alzahrani, A., Ferdowsi, M., Shamsi, P. and Dagli, C.H. (2017) Modeling and Simulation of Microgrid. *Procedia Computer Science*, **114**, 392-400. https://doi.org/10.1016/j.procs.2017.09.053

[6] Borkowski, D. and Majdak, M. (2020) Small Hydropower Plants with Variable Speed Operation—An Optimal Operation Curve Determination. *Energies*, **13**, 1-20. https://doi.org/10.3390/en13236230

[7] Nömm, J., Rönnberg, S.K. and Bollen, M.H.J. (2018) An Analysis of Frequency Variations and Its Implications on Connected Equipment for a Nanogrid during Islanded Operation. *Energies*, **11**, 2456. https://doi.org/10.3390/en11092456

[8] Peña-Pupo, L., Martínez-García, H., García-Vílchez, E., Fariñas-Wong, E.Y. and Núñez-álvarez, J.R. (2021) Combined Method of Flow-Reduced Dump Load for Frequency Control of an Autonomous Micro-Hydropower in AC Microgrids. *Energies*, **14**, 8059. https://doi.org/10.3390/en14238059

[9] Indonesia, S., Indonesia, S. and Indonesia, S. (2020) The Modeling of Cross Flow Runner with Computational Fluid Dynamics on Microhydro Tube. *E3S Web of Conferences*, **202**, 08008. https://doi.org/10.1051/e3sconf/202020208008

[10] Magdy, G., Shabib, G., Elbaset, A.A. and Mitani, Y. (2018) Frequency Stabilization of Renewable Power Systems Based on MPC with Application to the Egyptian Grid. *IFAC-PapersOnLine*, **51**, 280-285. https://doi.org/10.1016/j.ifacol.2018.11.715

[11] Dahlborg, E. Grid Frequency Stability from a Hydropower Perspective.

[12] Ali Nandar, C.S. (2013) Robust PI Control of Smart Controllable Load for Frequency Stabilization of Microgrid Power System. *Renewable Energy*, **56**, 16-23.

https://doi.org/10.1016/j.renene.2012.10.032

[13] Bhateshvar, Y.K., Mathur, H.D., Siguerdidjane, H. and Bhanot, S. (2015) Frequency Stabilization for Multi-Area Thermal-Hydro Power System Using Genetic Algorithm-Optimized Fuzzy Logic Controller in Deregulated Environment. *Electric Power Components and Systems*, **43**, 146-156. https://doi.org/10.1080/15325008.2014.977462

[14] Khamis, A., Ghani, M.R.A., Kim, G.C., Kamarudin, M.N. and Aras, M.S.M. (2017) Voltage and Frequency Control of Microgrid Systems with Demand Response. *International Journal of Simulation*: *Systems, Science and Technology*, **17**, 25.1-25.6.