Design and Frequency Control of Small Scale Photovoltaic Hydro Pumped Storage System

Hady H. Fayek A.Shenouda
Faculty of Engineering
Heliopolis University
Cairo, Egypt
hadyhabib@hotmail.com

Abstract— The world is directing its efforts towards achieving 100% renewable power generation. This paper presents design and frequency control of small scale photovoltaic hydro pumped storage system. The main problem of small scale hydro pumped storage system is its low efficiency. In this research to improve the performance of small scale hydro pumped storage system, a dual usage for the system and an intellgient control method are proposed. The storage tank design calculations are performed for traditional water usage. The traditional water usage includes covering water consumption, covering time needed for the disinfection, covering the requirements in emergency cases and firefighting demand. The calculations are carried out to predict the generated power for each design case. The frequency control is performed by using Non linear PID controller / PID controller and neural network at different operating conditions. The simulation and optimization are performed using MATLAB / SIMULINK 2017a.

Keywords—100% Renewable power generation, Frequency control, Non linear PID, Small scale hydro-pumped storage system and Neural network.

I. Introduction

Water systems are providing water to communities similar to power system which provides electricity. Both systems have the same requirements which are supply, transmission, storage and loads. The water system includes sources, pumps, tanks and valves [1].

In the recent years the penetration level of renewables is in continuous increase worldwide especially for the wind and PV generating systems. In 2016 the penetration level of renewables in Iceland reaches 100 %, some other countries achieved more than 90% like Norway and Costa Rica, also Canada and Brazil achieved more than 60%. The penetration level of renewables worldwide is 19.6 % [2, 3, 4]. With this continuous increase of those technologies, the power system behavior became more complex [5].

The developing countries world wide can achieve 100 % renewable power generation target by using distributed small scale renewable technologies. In Egypt, installing photovoltaic generators in the roof of buildings and in rural farming communities is in continuous increase [6]. To feed the building / communitiy in a standalone manner, energy storage system must be present. There are many types of energy storage facilities which are battery systems, flywheel, pumped hydro storage, compressed air and fuel cell.

The Pumped Hydro Storage system (PHS) represents the highest installed capacity world wide among all energy storage facilities. The most energy efficient storage facility in large scale is the PHS. In [7], a study was made on the feasibility and efficiency. The study concluded that small scale PHS is feasible but not efficient in comparison with other energy storage facilities.

Based on [8], The tank capacity of water storage in Egypt should be designed to cover the following from water engineering point of view:

i. The difference between max. daily and max. monthly of water consumptions
ii. Emergency water storage about (6 to 10 hours of flow).
iii. The contact time required for disinfection to take place.
iv. 80% of fire fighting storage.

One of the main reasons which may lead to total black out of electricity in a power system is the frequency instability. The frequency instability refers to the inability of the system to Settle a steady frequency after the occurrence of a disturbance [9].

In [10], a frequency control technique was presented in participation of high penetration level of wind energy. The research depends on the injection of power using energy storage facilities such as batteries, flywheel, compressed air and hydro pumped storage.

In [11], a model for a micro grid including photovoltaic power plant is presented. The contribution for grid frequency support was made also by using virtual inertia technique (storage-based support).

In [12], a microgrid model was presented which include photovoltaics, biogas and biodiesel generating systems. The model was controlled by conventional PID controllers designed by grasshopper method.

In this paper a standalone photovoltaic hydro pumped storage system is assumed to feed a building designed to cover water and energy needs as shown in Fig. 1. The paper is organized as follows section II is the system design. Section III presents system modeling while section IV illustrates the configuration of the control system. Section V illustrates how the controllers are designed in MATLAB. Section VI presents the simulation results and section VII summarizes the main conclusions of the research.

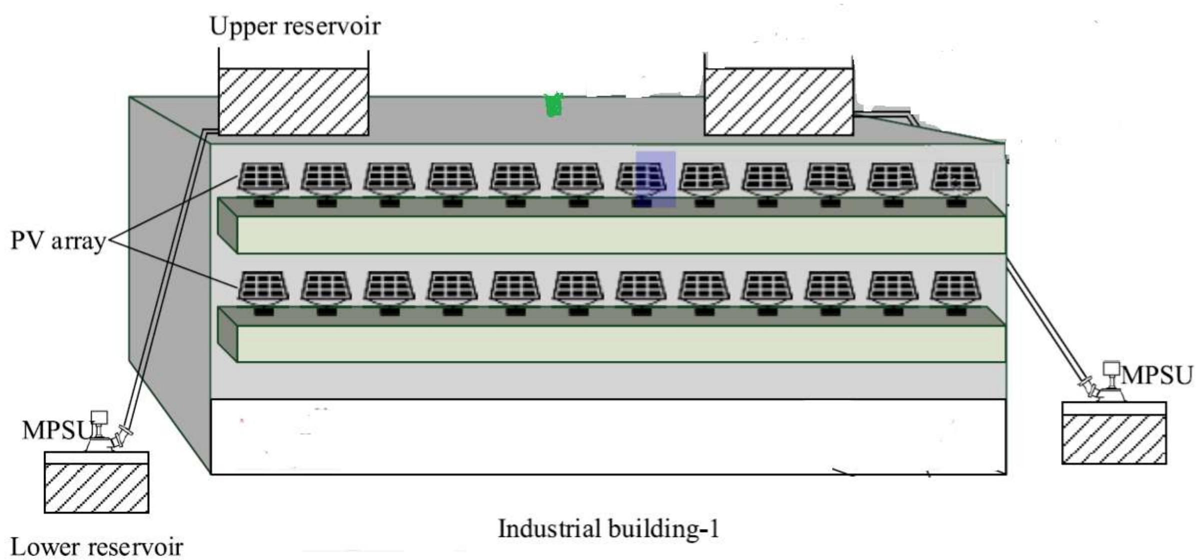

Fig. 1 Photovoltaic hydro pumped storage system in a building

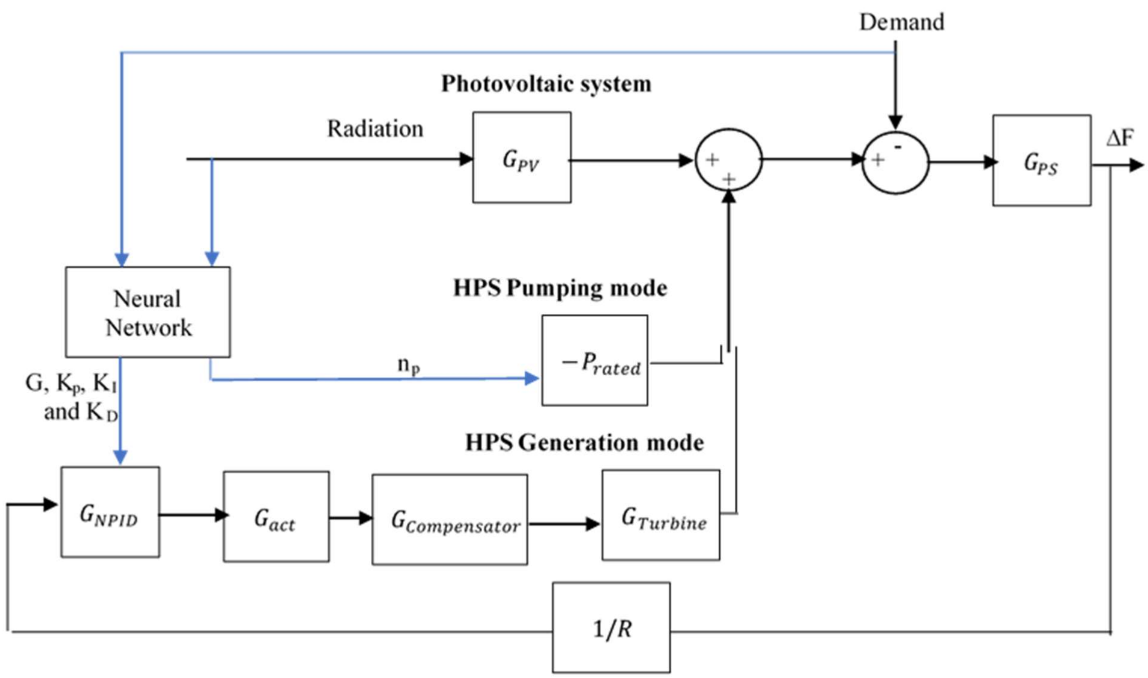

Fig. 2 Photovoltaic hydro pumped storage system model

II. System Description

The traditional usage of the tank is covering the following: The difference between maximum daily and maximum monthly consumptions (C_1), emergency storage about 4 to 10 hours of flow (C_2), the contact time required for disinfection to take place multiplied by production flow (C_3), and 80% of fire fighting storage that may be calculated by different methods (C_4) [8].

$$C_1 = \left(Q_{max.daily} - Q_{max.monthly}\right) \tag{1}$$

$$C_2 = \left(Q_{design} * (4 - 10\ hrs.)\right) \tag{2}$$

$$C_3 = \left(Q_{design} * (0.5\ hr.)\right) \tag{3}$$

$$C_4 = \left(80\% * \frac{Population}{1000} * 120\right) \tag{4}$$

For tank sizing calculation for water requirements, we assume that water consumption per capita= 300 l/C/D, and the tank will serve population 500 capita in an institute.

Therefore

$Q_{avg.} = (500*300) /100 = 150\ m^3/day$

$Q_{des.} = 1.5 * Q_{avg} = 1.5*150 = 225\ m^3/day$

$C_1 = 1.8\ Q_{avg} - 1.5\ Q_{avg} = 0.3 * 150 = 50\ m^3$

$C_2 = Q_{des.} * 8\ hrs. = 225 * (8/24) = 75\ m^3$

$C_3 = Q_{des.} * 0.5\ hr. = 225 * (0.5/24) = 4.7\ m^3$

$C_4 = 0.8. * (500/1000) * 120 = 48\ m^3$

For tank sizing calculation for power generation, we assume that the height building = 60 m, Factor of Safety (F.S) =10% and Autonomy period in Seconds = 21600 seconds.

$Q\ max = (Power_{T.\ Nom.}) / (Pressure) = Power / (\rho * g * h)$

$C_5 = (1+ F.S) * T_a * Q_{max}$

The calculations are carried out to predict how much power will be generated if the tanks used as PHS (for energy production at night in each design case.

i. For the first case:

$C_1=C_5= (1+ F.S) * T_a * Q_{max} = 50\ m^3$

$50 = (1 +0.1) * 21600 *Q_{max}$

$Q_{max} = 0.0021\ m^3 /sec. = (Power_{T.\ Nom.}) / (Pressure)$

$Power_{T.\ Nom.} = 0.0021 * 1000 * 10 * 60$

$Power_{T.\ Nom.} = 1260$ Watt

ii. For the second case:

$C_2= C_5 = (1+ F.S) * T_a * Q_{max} = 75\ m^3$

$75 = (1 +0.1) * 21600 *Q_{max}$

$Q_{max} = 0.0032\ m^3 /sec. = (Power_{T.\ Nom.}) / (Pressure)$

$Power_{T.\ Nom.} = 0.0032 * 1000 * 10 * 60$

$Power_{T.\ Nom.} = 1920$ Watt

iii. For the third case:

$C_3=C_5= (1+ F.S) * T_a * Q_{max} = 4.7\ m^3$

$4.7 = (1 +0.1) * 21600 *Q_{max}$

$Q_{max} = 0.00019\ m^3 /sec. = (Power_{T.\ Nom.}) / (Pressure)$

$Power_{T.\ Nom.} = 0.00019 * 1000 * 10 * 60$

$Power_{T.\ Nom.} = 118.6$ Watt

iv. For the fourth case:

$C_4=C_5= (1+ F.S) * T_a * Q_{max} = 48\ m^3$

$48 = (1 +0.1) * 21600 *Q\ max$

$Q_{max} = 0.002\ m^3 /sec. = (Power_{T.\ Nom.}) / (Pressure)$

$Power_{T.\ Nom.} = 0.002 * 1000 * 10 * 60$

$Power_{T.\ Nom.} = 1212.12$ Watt

After carrying out the previous calculations, the case that will be chosen to design the tank will be case number two: covering the shortage in emergency case to achieve the maximum power generation (1.9 KW)

The tank dimensions will be calculated according to the following equation:

C = n * B * L* D where C is the capacity of the tank, n is the number of tanks >=2, B, L and D are the width, the length and the depth of the tank respectively.

We assume that there are 4 tanks connected in series, the width of each tank is half of its length, and the depth is 3 m

By carrying out the calculations, the storage system consists of 4 tanks to be installed with the dimensions of width, length and depths are 3.15 m , 6.3 m and 3 respectivly.

In this paper, the system is described to have a photovoltaic plant feeding the building and a hydro pumped storage system. The Simulink model is illustrated in Fig. 2.

The hydro pumped storage system is controlled in its two modes of operation (pumping and generating) through neural network. In its pumping mode the neural network will select the number of pumps which charge the tank based on the demand. During the generation mode, the neural network will select the optimal parameters of the NPID controller based on the demand.

III. SYSTEM MODELING

This section presents how photovoltaic generating system, energy storage facility and power system are modeled and simulated in MATLAB.

a) Photovoltaic power generation model:

The Photovoltaic power generators transform the sunlight directly to electricity through crystalline or thin film panels. In this study, it was assumed that the photovoltaic generating system is working using maximum power point tracking, so it has 100% efficiency without considering wiring losses. The power extracted from the photovoltaic system can be formulated as (5) [12].

$$P_{PV} = I \times A \times \eta_{PV} \times (1 - 0.005(T_a + 25)) \tag{5}$$

Where P_{PV} is the photovoltaic system output power Watt, I is the isolation in Watt/ m², A is the photovoltaic park field area in m², η_{PV} is the electricity conversion from sunlight efficiency, T_a is the ambient temperature. In this paper, it was assumed that P_{PV} linearly increase with I . The transfer function of the photovoltaic generating system can be modeled as (6)

$$G_{PV} = \frac{\Delta P_{PV}}{\Delta I} = \frac{1}{1+T_{PV}s} \tag{6}$$

Where T_{PV} is the time constant of the photovoltaic generating unit.

b) Hydro pumped energy storage facility

The energy storage systems have vital role in high penetration level of renewables power systems due to weather uncertainty. During the presence of surplus generated power from renewables, the storage systems absorb energy and during the presence of deficit power, the storage systems release power to feed the load requirements.

In this work, the hydro pumped energy storage system is used. The system during generation (discharging) consists of three parts which are actuator, compensator and the hydraulic turbine and during charging, it is modeled with number of pumps working. The modeling of each part of the system is illustrated in the following [13]:

i. Actuator

The actuator executes the control signal extracted by the controller, it transformes the small control signal to obtain adequate power to drive the turbine. The model of actuator is as follows in (7) :

$$G_{act} = \frac{1}{1+T_g s} \quad (7)$$

Where T_g is the time constant. Output of this actuator represents the opening deviation from nominal state of the guide vane

ii. Hydraulic turbine

The turbine converts the kinetic energy of the turbine to mechanical energy in terms of rotation. The turbine is coupled with a generator to produce the electric power. The model is illustrated in (8).

$$G_{Turbine} = \frac{1-T_W s}{1+0.5\,T_W s} \quad (8)$$

Where T_W is the starting time constant of the turbine.

iii. Compensator

The turbine transfer function is inherently of nonminimum phase because of the water inertia in pressure pipes, thus exhibiting unstable system dynamic responses. Based on [14], compensator equips the speed governor of the hydro turbine to ensure its stability. The compensator model is illustrated in (9).

$$G_{Compensator} = \frac{1+T_1 s}{1+T_2 s} \quad (9)$$

Where T_1 and T_2 are the compensator time constants.

c) Power system dynamics model

Since the system consists of photovoltaic generating units in addition to hydro pumped storage facility. The active power equation of the system can be written as shown in (10).

$$\Delta P_e = P_{PV} \pm P_{PHS} - P_D \quad (10)$$

Where P_{PV} is the power generated by photovoltaic generating units while P_{PHS} is the power generated / absorbed from / by the pumped hydro storage system. P_D is the power absorbed by the demand. ΔP_e is the change in electrical power.

The overall generator dynamics for the whole system can be illustrated in the transfer function illustrated in (11).

$$G_{PS} = \frac{\Delta f}{\Delta P_e} = \frac{1}{D+M_{eq}s} \quad (11)$$

Where Δf is the change in frequency, D is the damping constant of the power system and M_{eq} is the equivalent inertia constant of the power system.

TABLE I. SYSTEM PARAMETERS

Parameter	Value
T_{PV}	1.8 sec
K_T	1
T_g	0.08 sec
K_S	1.8
T_W	1 sec
T_1	10 sec
T_2	5 sec
R	2.4
M_{eq}	20 sec
D	1

IV. CONTROLLERS

1) Nonlinear PID controller

It has been noticed in the recent years that the modifications on PID controllers may reach to better system performance than the conventional ones. One of those modifications is the nonlinear PID (NPID). NPID controller is presented as one of the most appropriate and effective methods for industrial applications. The NPID control has found in form two broad categories of applications. The first category particular to nonlinear systems, where NPID control is used to absorb the nonlinearity while, the second category deals with linear systems, where NPID control is used to obtain enhanced performance not realizable by a linear PID control, such as reduced overshoot, diminished rise time for step or rapid command input, obtained better tracking accuracy and used to compensate the nonlinearity and disturbances in system, which is considered in this research. The NPID controllers have the advantage of high initial gain to achieve a fast dynamic response, continued with a low gain to avoid an unstable behaviour. The underlying concept of NPID is to create continuous dynamic nonlinear function rather than gain-scheduling by creating a nonlinear gain function with combination of error, integration of error and error derivative to achieve a reference point [14].

It’s shown in (12) the typical structure of PID, the proportional, integral and derivative actions are produced by the error signal e (t), and the resulting signal is summed to form the u (t) control signal which is applied to the plant. It has been noticed in the recent years that the modifications on PID controllers may reach to better system performance than the conventional ones. One of those modifications is the nonlinear PID (NPID). NPID controller is presented as one of the most appropriate and effective methods for industrial applications. The NPID control has found in form two broad categories of applications. The first category particular to nonlinear systems, where NPID control is used to absorb the nonlinearity while, the second category deals with linear systems, where NPID control is used to obtain enhanced performance not realizable by a linear PID control, such as reduced overshoot, diminished rise time for step or rapid command input, obtained better tracking accuracy and used to compensate the nonlinearity and disturbances in system, which is considered in this research. The NPID controllers have the advantage of high initial gain to achieve a fast dynamic response, continued with a low gain to avoid an unstable behavior. The underlying concept of NPID is to create continuous dynamic nonlinear function rather than gain-scheduling by creating a nonlinear gain function with combination of error, integration of error and error derivative to achieve a reference point.

$$U_{PID}(t) = \left[K_P \Delta f(t) + K_I \int_0^t \Delta f(t)dt + K_D \frac{d\Delta f(t)}{dt}\right] \quad (12)$$

$$U_{NPID}(s) = \frac{e^{(G x \Delta f)} + e^{-(G x \Delta f)}}{2} [(K_P + \frac{K_I}{s} + K_D s)\Delta f] \quad (13)$$

The term G indicates to the nonlinearity lies between 0 and 1, when G=0, the NPID controller turns to conventional PID controller. In this work, the aim of the nonlinearity term to enable minimum frequency deviation.

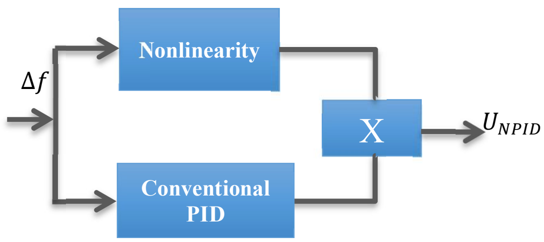

Fig. 3 Nonlinear PID controller configuration

V. CONTROLLERS DESGN

I. During generation (charging) mode

The design of the controllers will be performed for each operation condition at discharging (generation) mode separately using Genetic Algorithm (GA) tool box in MATLAB to enable reaching minimum frequency deviation at this condition. The optimization problem is described as follows: Objective Function: Minimizing integration of square error (Δf):

- Objective Function: Minimizing integration of square frequency deviation (Δf):

  $\text{Min} \int_0^t (\Delta f)^2 dt \quad (14)$
- Variables: controllers' parameters.
- Constraints: G limits.

The controller parameters differ from controller to another. In NPID controller, the variables are (G, K_P, K_I and K_D) and the constraint considered in its design is $0 \leq G \leq 1$ only.

The design was made in offline mode first for the three controllers in the power system at the same time for each case of study. After the design is made, the controlled system is tested as illustrated in the next section.

The GA is an iterative optimization technique, working with a number of candidate solutions (known as a population). If knowledge of the problem domain, is not available a priory, the GA begins its search from a random population of solutions [15]. The GA applied in this work is performed by using the double vector population type with population size of 20. The Elite count reproduction is 2 and the crossover fraction is 0.8. To avoid possibility to fall into the local optimum condition, after the optimization stop, we increase mutation rate and start the optimization again with the optimal values resulted in the first optimization process.

II. During charging (pumping) mode

In charging mode, the motor absorbed power from the PV to pump water to the top of the building mainly in the morning. When the demand increase, the pumping absorbed power should be reduced to allow the PV production to cover the demand. This could happen through artificial intelligence (or expert system) based on what-if analysis [16]. The artificial intelligence element which will be used is the neural network. Such that the demand change and radiation are the inputs while the output is the number of pumps (n_P) lifting the water to the top. The neural network will be used also to select the optimal parameters of the NPID during generation mode.

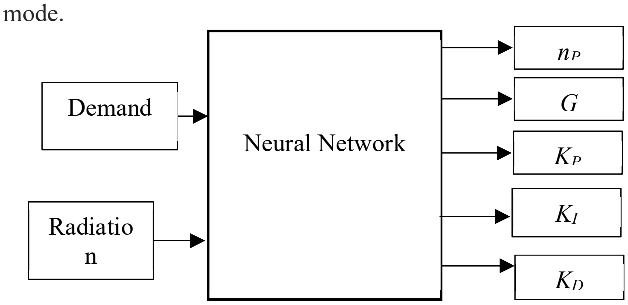

Fig. 4 Neural network to control photovoltaic PHS.

The neural network used in this work consists of two inputs, five outputs and a hidden layer having 10 neurons. The network was trained by the well-known Lavenberg-Marquardt backpropagation method.

VI. SIMULATION RESULTS

The system is subjected to three tests, load increase at night, morning and robustness test.

Test 1: load increase at night (generating mode)

The system is subjected to load increase by 20% after 1 second from starting simulation. The optimal controller parameters are calculated by GA for each controller and stored in neural network. Fig. 5. shows the frequency deviation of the system using NPID and conventional PID controllers. The results show that NPID controller has better performance than that of PID controllers in terms of maximum undershoot. Fig. 6. shows that system with NPID has better performance that that with PID controller in terms of overshoot and less power generated.

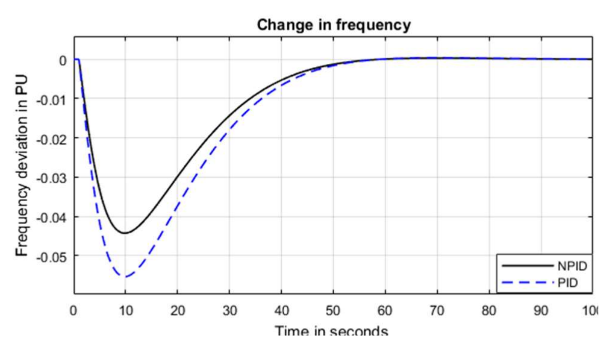

Fig. 5 Frequency deviation responses when the system subjected to Test 1

Test 2: load increase at the morning (pumping mode)

Assume that the system is subjected to load increase at 10 a.m by 20% after 1 second from starting at the morning, the radiation is shown in Fig. 7 The optimal controllers' since during the morning, it is the pumping mode, during the demand increase the neural network will turn one of the pumps off to keep only three of them on. This turn off allowed the PV to cover the demand increase and keep zero frequency deviation as shown in Fig. 8. The result proved the effectiveness of the neural network to reduce the frequency deviation.

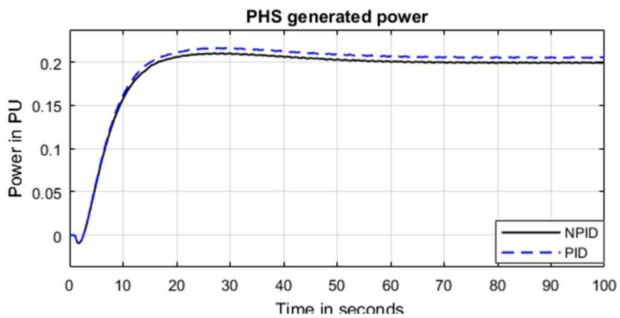

Fig. 6 Storage system generated power at Test 1

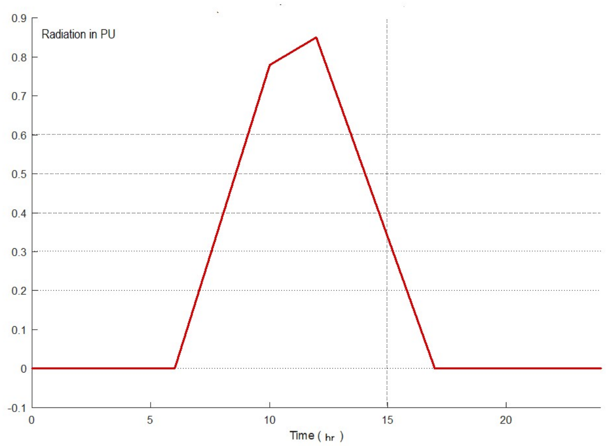

Fig. 7 Average radiation in Cairo

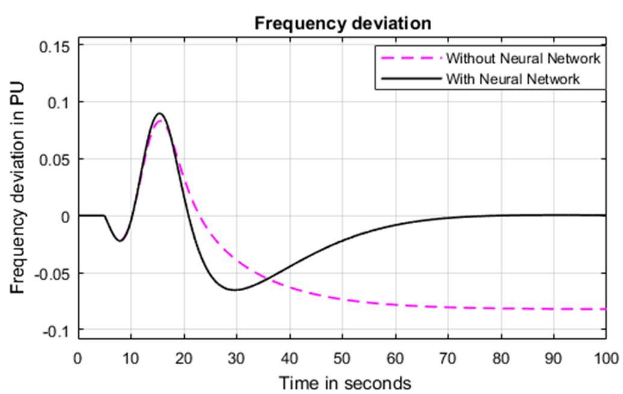

Fig. 4 Frequency deviation responses when the system subjected to Test 2

VII. Conclusion

The paper presented a different techniques to design the hydro pumped storage system to satisfy both energy and water requirments in a building. The results show that design of the tank to satisfy emeregency storage of water to satisfy water needs will produce the largest amount of power. The paper presented a model for photovoltaic hydro pumped storage system. The paper proved NPID controller has better performance than PID to respond for the demand changes at generation mode (at night) due to the presence of the non-linearity gain. The results show that the neural network improve the system performance at the the pumping mode by controlling the pumps when demand changes. The results also show that NPID will lead the system to save energy than PID controller.

VIII. References

[1] M. Rouholamini, C. Wang, C. J. Miller and M. Mohammadian, "A Review of Water/Energy Co-Management Opportunities," 2018 IEEE Power & Energy Society General Meeting (PESGM), Portland, OR, 2018, pp. 1-5.

[2] B. Kroposki et al., "Achieving a 100% Renewable Grid: Operating Electric Power Systems with Extremely High Levels of Variable Renewable Energy," in IEEE Power and Energy Magazine, vol. 15, no. 2, pp. 61-73, March-April 2017.

[3] Frede Blaabjerg, Yongheng Yang, Dongsheng Yang, Xiongfei Wang, "Distributed Power-Generation Systems and Protection", Proceedings of the IEEE, vol. 105, pp. 1311-1331, 2017

[4] P. Denholm, R. Margolis, "Energy storage requirements for achieving 50% solar photovoltaic energy penetration in California" in Golden, CO:NREL, Aug. 2016.

[5] Renewable Energy Policy Network For The 21st CENTURY Annual Report 2017, http://www.ren21.net

[6] Egyptian Ministry of Electricity & Energy, New and Renewable Energy Authority, http://www.nrea.gov.eg/Technology/PhotovoltaicCell

[7] Silva, Guilherme de Oliveira, and Patrick Hendrick. "Pumped hydro energy storage in buildings." Applied energy 179 (2016): 1242-1250.

[8] Egyptian Code for Design and Implementation of Pipelines for Drinking Water and Sewage Networks, https://www.susana.org/_resources/documents/default/3-2851-7-1503411435.Egyptian%20Code%20for%20Design%20and%20Implementation%20of%20Pipelines%20for%20Drinking%20Water%20and%20Sewage%20Networks%20Sixth%20Editionpdf

[9] Hady H. Fayek, "Robust Controllers Design of Hybrid System Load Frequency Control", MSc., Helwan University, Egypt, (2014).

[10] D. Lee and L. Wang, "Small-Signal Stability Analysis of an Autonomous Hybrid Renewable Energy Power Generation/Energy Storage System Part I: Time-Domain Simulations," in IEEE Transactions on Energy Conversion, vol. 23, no. 1, pp. 311-320, March 2008.

[11] M. Tavakoli, J. Adabi and S. Zabihi, "Improving load frequency control through PV contribution in a hybrid generation grid," 2015 Smart Grid Conference (SGC), Tehran, 2015, pp. 7-13

[12] A. K. Barik and D. C. Das, "Expeditious frequency control of solar photovoltaic/biogas/biodiesel generator based isolated renewable microgrid using grasshopper optimisation algorithm," in IET Renewable Power Generation, vol. 12, no. 14, pp. 1659-1667, 29 10 2018.

[13] Y. Xu, C. Li, Z. Wang, N. Zhang and B. Peng, "Load Frequency Control of a Novel Renewable Energy Integrated Micro-Grid Containing Pumped Hydropower Energy Storage," in IEEE Access, vol. 6, pp. 29067-29077, 2018.

[14] D. V. L. N. Sastry and M. S. R. Naidu, "An Implementation of Different Non Linear PID Controllers on a Single Tank level Control using Matlab," Int. J. Comput. Appl., vol. 54, no. 1, pp. 6–8, 2012.

[15] O. H. Abdalla, A. M. A. Ghany and H. H. Fayek, "Coordinated PID secondary voltage control of a power system based on genetic algorithm," 2016 Eighteenth International Middle East Power Systems Conference (MEPCON), Cairo, 2016, pp. 214-219

[16] Hady H. Fayek, "Voltage and Reactive Power Control of Smart Grid", Ph. D., Helwan University, EGYPT, (2018).