Load Frequency Control of a Power System with 100% Renewables

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Abstract— The world is directing its efforts towards achieving 100% renewable power generation. This paper presents frequency control of a single area power system. The power system is feeding from renewable technologies and storage facilities only which are Photovoltaics, Biogas, Biodiesel, Solar thermal, battery storage and flywheel storage systems. The paper presents a model for each renewable energy technology and energy storage facility. The frequency is controlled by using Nonlinear PID controller (NPID), Fractional Order PID controller (FOPID) and Nonlinear FOPID controller (NFOPID). The three controllers are designed by using genetic algorithm at different operating conditions. A comparison between the three controllers at different operating conditions is presented. The results show that NFOPID has better performance than the other two controllers. The simulation and optimization are performed using MATLAB / SIMULINK 2017a.

Keywords—100% Renewable power generation, Load frequency control, NFOPID controller, FOPID controller, NPID controller, Biogas generator and Biodiesel generator.

I. Introduction

The world is highly directing its efforts towards smarting the power grids. The smart grid features include real time control, real time protection and self-healing in the presence of high penetration level of renewables [1].

One of the main reasons which may lead to total black out of a power system or even regions in a power system is the frequency instability. The frequency instability refers to the inability of the system to Seattle a steady frequency after the occurrence of a disturbance [2].

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 % [3, 4, 5]. With this continuous increase of those technologies, the power system behavior became more complex [6].

The developing countries worldwide can achieve 100 % renewable power generation target by using bio energy especially in remote villages of those countries. Since using of renewable technologies such as photovoltaics, solar thermal and wind turbines are not that reliable generators due to the stochastic nature of sun and wind. Diesel generator is always used with the renewable resources which has a high carbon dioxide emission [7]. In this paper we replace the conventional diesel generator with biodiesel and biogas generators which have less emissions. The main idea is illustrated in Fig. 1.

Biogas is a mixture of gases produced in absence of oxygen due to break down of manure, plant, farming wastes or even sewage. It can be produced through fermentation biodegradable materials or anaerobic digestion with anaerobic organisms inside biodigester [8]. It consists of methane (CH_4), carbon dioxide (CO_2), and aphoristic galore of hydrogen sulphide (H_2S). CH_4 and CO and be combusted and then can produce electricity through turbine generator (GTG) [9, 10]. This is modelled as biogas-turbine generator (BGTG) in this action.

Biodiesel is a carbon neutral eco-friendly alternative to fossil diesel. Biodiesel is produced from vegetable oil, animal fats or tallow through transesterification. The Transesterification process is the chemical reaction of a triglyceride (fat/oil) with an alcohol to form esters and glycerol. During the esterification process, the triglyceride is reacted with alcohol in the presence of a catalyst, usually a strong alkaline like sodium hydroxide then biodiesel can be produced [11]. The biodiesel is used in an engine to instantaneously produce demanded electricity like the conventional diesel generator but with special requirements [12, 13].

Various control schemes were used to control the frequency of interconnected systems such as PID controller, H∞ controllers and FOPID controllers. In [14], a comparison between the three controllers was presented to control the frequency of hybrid power system. The system achieved best performance using FOPID controller.

In [15], a frequency control technique was presented in participation of high penetration level of wind farms. The research depends on the injection of power using energy storage facilities such as batteries, flywheel, compressed air and hydro pumped storage.

In [16] and [17], a model for a micro grid including photovoltaic power plant is presented. The contribution for grid frequency support achieved by storage facilities discharge.

In [7], a microgrid model which include photovoltaics, biogas and biodiesel generating systems was presented. The model was controlled by conventional P, PI, PD and PID controllers designed by grasshopper method. The results show that PID controller leads the system to the best performance.

In this paper, the main contributions are: i) presenting a model for a single area system powered by solar and bioenergy technologies only, ii) controlling the power system frequency by using three modern control schemes which are NPID, FOPID and NFOPID controllers, iii) comparing between the three schemes with the conventional PID.

The paper is organized as follows section II is the system description. Section III presents system modeling while section IV illustrates the configuration of the controllers. 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.

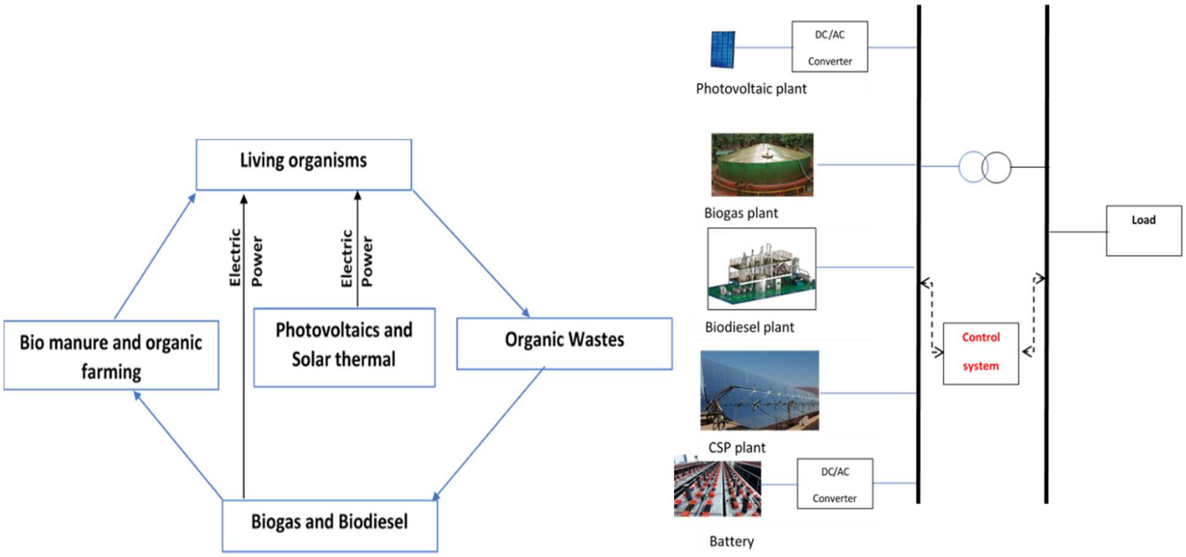

Fig. 1 Solar Bioenergy idea and system

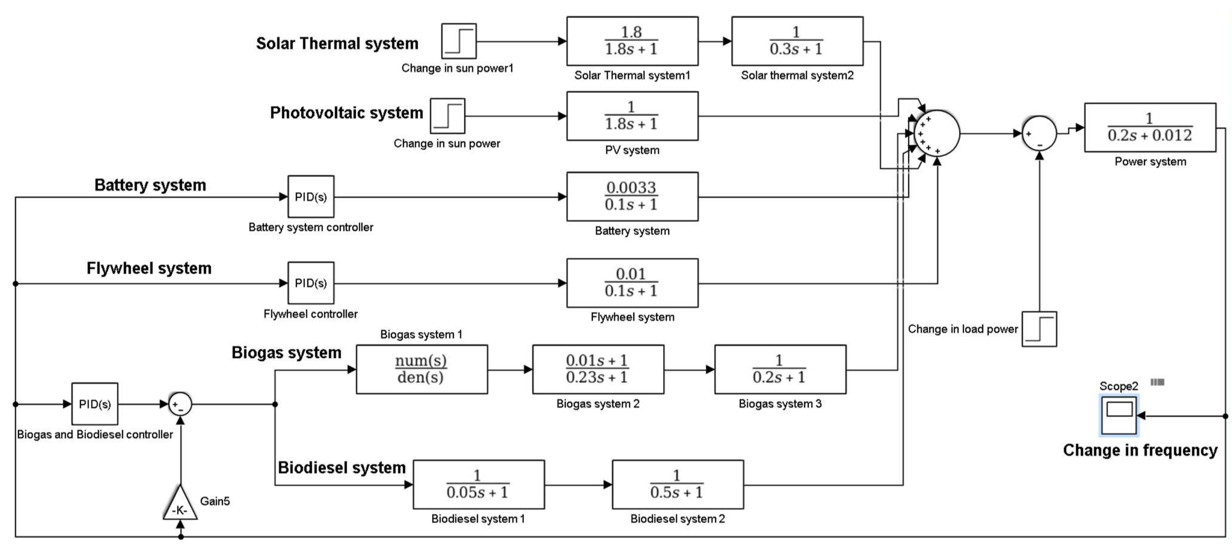

Fig. 2 Power system SIMULINK model

II. System Description

The single area power system described in this paper is feeding from technologies operating by renewable resources. The power system integrates the solar energy with the bioenergy. The solar energy technologies used are photovoltaics and solar thermal power generation systems. The bio energy technologies are the biogas and biodiesel technologies. Two energy storage facilities are used: battery and flywheel systems. The Simulink model is illustrated in Fig. 2.

The power system includes three controllers, the first one to control both biodiesel and biogas. The second controller controls the flywheel storage system and the third one controls battery storage system. Each controller is responsible to let the technology respond to the frequency deviations. In this research the three controllers are from the same type at each simulation running time.

III. System Modeling

This section presents how each renewable technology, 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 (1) [9].

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

Where P_{PV} is the photovoltaic system output power Watt, I is the isolation in Watt/ m^2, A is the photovoltaic park field area in m^2, 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 (2)

$$G_{PV} = \frac{\Delta P_{PV}}{\Delta I} = \frac{1}{1+T_{PV}s} \quad (2)$$

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

b) Solar thermal generating system:

Solar thermal systems are widely used nowadays to produce either heat energy or electrical or even both. The solar thermal power technologies are parabolic trough collectors, parabolic dish, central receiver and linear Fresnel. Those technologies are mainly depending on reflecting the heat of the sun to a point or a line to heat a medium (usually oil or molten salt because they have high boiling points) to a high temperature. The highly heated mediums exchange the temperature with water to produce steam which can rotate a turbine then creates electrical energy. The solar thermal system has a transfer function illustrated in (3).

$$G_{STS} = \frac{K_T}{1+T_T s} \cdot \frac{K_S}{1+T_S s} \quad (3)$$

Where T_T is the charging time constant of the turbine, K_T is the gain of the turbine, T_S is the solar collector time constant and K_S is the solar collector gain.

c) Biogas generating system

Biogas can be used for power production; it is mainly extracted from animal wastes. The biogas power generating system includes gas valve actuator, speed governor, turbine, fuel system and combustor. The output power extracted from the biogas generating system is mainly depending on the gas inlet valve control action, governor action and turbine /combustor actions. The transfer function can be written as illustrated in (4) [10].

$$G_{BGGS} = \frac{1+sX_c}{(1+sY_c)(1+sb_B)} \cdot \frac{1+sT_{CR}}{1+sT_{BG}} \cdot \frac{1}{1+sT_{BT}} \quad (4)$$

Where T_{CR}, T_{BG}, X_c, Y_c, b_B and T_{BT} are combustion reaction delay, biogas delay, lead time, lag time, valve actuator and discharge time constants of biogas generating system, respectively.

d) Biodiesel generating system

Through transesterification, biodiesel can be extracted from energy crops with properties similar to that of the conventional diesel. The rate of work done by biodiesel generating system is illustrated in (5).

$$\frac{dW}{d\theta} = \frac{\Re T V_d}{2}\left(\frac{0.5\, sin2\theta}{\sqrt{2\left(\frac{L}{S}\right)^2 - sin^2\theta}} - sin\theta\right) \quad (5)$$

Where $\Re, T, , L, S, V_d$ and θ are the universal gas constant, the instantaneous temperature in Kelvin at any crank angle θ, the length of connecting rod in m, the stroke length in m, the displacement volume in m^3 and the angular displacement with respect to bottom dead center in degree of the biodiesel generating system respectively [11].

The power extracted from biodiesel generating system is mainly depending on the biodiesel inlet valve action, and the internal combustion (IC) engine action, the transfer function can be written as illustrated in (6).

$$G_{BDGS} = \frac{K_{VA}}{1+T_{VA}s} \cdot \frac{K_{BE}}{1+T_{BE}s} \quad (6)$$

Where K_{VA}, T_{VA}, K_{BE} and T_{BE} are the valve gain, valve actuator delay, engine gain and time constants of biodiesel generating system respectively.

e) Energy storage facilities

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 there are two energy storage technologies used Battery and flywheel storage systems. The transfer function of battery technologies is illustrated in (7) and flywheel storage system is illustrated in (8).

$$G_{BESS} = \frac{K_{BESS}}{1+T_{BESS}s} \quad (7)$$

$$G_{FWSS} = \frac{K_{FWSS}}{1+T_{FWSS}s} \quad (8)$$

Where K_{BESS} and T_{BESS} are gain and time constants of battery storage system, respectively while K_{FWSS} and T_{FWSS} are gain and time constants of flywheel storage system, respectively.

f) Power system dynamics model

Since the system consists of four renewable technologies generating units in addition to two storage facilities. The active power equation of the system can be written as shown in (9).

$$\Delta P_e = P_{PV} + P_{STGS} + P_{BGGS} + P_{BDGS} \pm P_{BESS} \pm P_{FWSS} - P_D \quad (9)$$

Where P_{PV}, P_{STGS}, P_{BGGS} and P_{BDGS} are the power generated by photovoltaic, solar thermal, biogas and biodiesel generating units respectively while P_{BESS} and P_{FWSS} are the power generated / absorbed from / by the battery and flywheel storage systems respectively. 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 (10).

$$G_{PS} = \frac{\Delta f}{\Delta P_e} = \frac{1}{D+M_{eq}s} \quad (10)$$

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_T	0.3 sec
K_S	1.8

T_S	1.8 sec
T_{CR}	0.01
T_{BG}	0.23 sec
X_c	0.6 sec
Y_c	1
b_B	0.05
T_{BT}	0.2 sec
K_{VA}	1
T_{VA}	0.05sec
K_{BE}	1
T_{BE}	0.5 sec
K_{BESS}	0.0033
T_{BESS}	0.1 sec
K_{FWSS}	0.01
T_{FWSS}	0.1 sec
M_{eq}	0.1 sec
D	0.012

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 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.

In (11) the typical structure of PID is shown, the proportional, integral and derivative actions are produced by the error signal Δf (t), and the result 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.

As the proposed nonlinear PID (NPID) controller consists of two parts. The first one is a sector bounded nonlinear gain (G) while, the second part is a linear fixed-gain PID controller (K_P, K_I, and K_D). So, the nonlinear gain (G) is a sector-bounded function of the error Δf (t). The configuration of the nonlinear PID is shown in Fig.3, and The NPID control action law is shown in (12) [17].

$$U_{PID}(t) = \left[K_P\Delta f(t) + K_I\int_0^t \Delta f(t)dt + K_D\frac{d\Delta f(t)}{dt}\right] \qquad (11)$$

$$U_{NPID}(s) = \frac{e^{(G x \Delta f)} + e^{-(G x \Delta f)}}{2}\left[(K_P + \frac{K_I}{S} + K_D s)\Delta f\right] \qquad (12)$$

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.

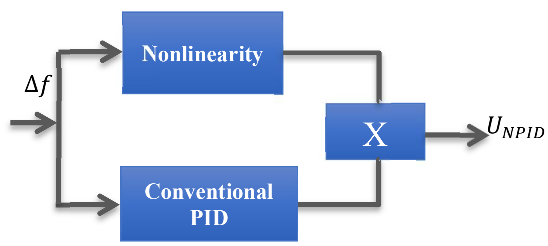

Fig. 3 Nonlinear PID controller configuration

2) FOPID Controller

FOPID is a controller widely used over the last two decades; the idea of this controller is that controlling two extra variables (λ and μ) more than conventional PID may lead to better performance. The integral power λ and differential power μ both varies between 0 and 1. Many researchers have used the FOPID in many fields like DC motor control, load frequency control in power systems and finally in vehicles. The FOPID controller control action is shown in (13) [14].

$$G_{FOPID}(s) = K_P + \frac{K_I}{s^{\lambda}} + K_D s^{\mu} \qquad (13)$$

3) NFOPID controller

NFOPID controller is the nonlinear fractional order PID which means that it has 6 variables (G, K_P, K_I, K_D, λ and μ) for each controller which gives more flexibility for the controlled system for better performance. The control action of NFOPID is shown in (14) [18]. The controller configuration is shown in Fig. 5.

$$U_{NFOPID}(s) = \frac{e^{(G x \Delta f)} + e^{-(G x \Delta f)}}{2}(K_P + \frac{K_I}{s^{\lambda}} + K_D s^{\mu})\Delta f \qquad (14)$$

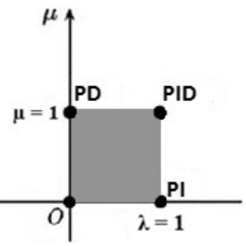

Fig. 4 FOPID controller modes of operation

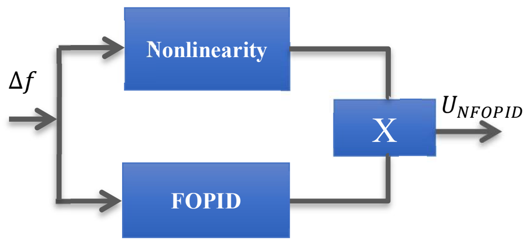

Fig. 5 NFOPID controller configuration

V. CONTROLLERS DESGN

The design of the controllers will be performed for each operation condition separately using Genetic Algorithm (GA) toolbox 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):

  $$\text{Min} \int_0^t (\Delta f)^2 dt \tag{14}$$

- Variables: controllers' parameters.
- Constraints: G, λ and μ 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. In FOPID, the variables are (K_P, K_I, K_D, λ and μ) and the constraints considered are $0 \leq \lambda \leq 1$ and $0 \leq \mu \leq 1$ only. In NFOPID controller the six parameters are the variables and the limits of G, λ and μ are considered as constraints.

The design was made first in offline mode 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 [25]. 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.

VI. SIMULATION RESULTS

The system is subjected to three tests, in each test the three controllers were designed to reach minimum frequency deviation.

Test 1: load increase only

The system is subjected to load increase by 20% after 1 second from starting simulation. The optimal controllers' parameters are calculated by GA for each controller. Fig. 6. Shows the frequency deviation of the system using each type of controllers. The results show that NFOPID controller has better performance than that of NPID and FOPID controllers in terms of maximum overshoot and undershoot.

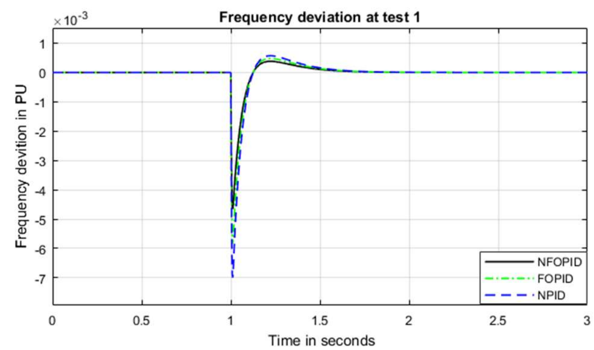

Fig. 6 Frequency deviation responses when the system subjected to Test 1

Test 2: load increase when there's no sun and no biogas

The system is subjected to load increase by 20% after 1 second from starting simulation when there is no sun and no biogas. The optimal controllers' parameters are calculated by GA for each controller. Fig. 7. Shows the frequency deviation of the system using each type of controllers. The results show that NFOPID controller has better performance than that of NPID and FOPID controllers in terms of maximum overshoot and undershoot.

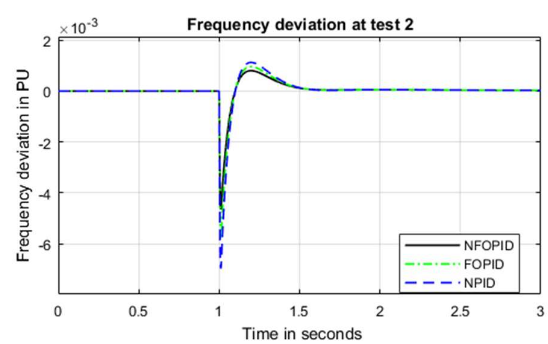

Fig. 7 Frequency deviation responses when the system subjected to Test 2

Test 3: Storage parameters variation (controllers robustness test)

The system is subjected to *Test 2* again with increasing the parameters of Battery and flywheel by 20%, the controllers' gains are kept the same as in *Test 2* to examine the robustness of the controllers. Fig. 7. Shows the frequency deviation of the system using each type of controllers. The results show that NFOPID controller has better performance than that of

NPID and FOPID controllers in terms of maximum overshoot and undershoot.

Table II shows a complete comparison of the three control schemes in addition to the conventional PID control scheme at each operating condition. Table III shows the steady state contribution of each renewable technology / storage facility to cover the demand increase at each case. The results show that biodiesel and biogas contributed to the demand change faster than the storage systems.

VII. CONCLUSION

The paper presented a single area power system feeding from 100% renewable power generation. The paper presented a model for the biogas and biodiesel power generation systems. The research results show that the biogas and biodiesel generating systems contribute faster than the storage facilities to the change of demand. The paper investigated the application of three different types of controllers on the system which are NFOPID, FOPID and NPID. The results show that the system with NPID achieved less undershooting and overshooting than PID by 15% and 47% respectively. System with FOPID has better performance than that with NPID due to the presence of an additional variable. System with NFOPID controller has better performance than that of FOPID due to the presence of the non-linearity gain. The results also proved that NFOPID is more robust than FOPID and NPID in terms of the energy storage parameter variation test.

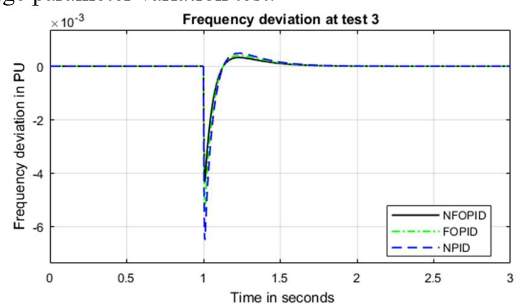

Fig. 8 Frequency deviation responses when the system subjected to Test 3

TABLE II. COMPARISON BETWEEN THE SYSTEM PERFORMANCE WITH DIFFERENT CNTROLLERS

Test	Undershooting (%)				Overshooting (%)			
	PID	NPID	FOPID	NFOPID	PID	NPID	FOPID	NFOPID
1	11	7	6	5	0.16	0.08	0.06	0.03
2	9.7	6.8	5.8	4.2	0.23	0.12	0.09	0.06
3	9.5	6.6	5.4	4.2	0.13	0.06	0.04	0.02

VIII. SUMMARY

The paper presented model to study load frequency control of a power system feeding only from renewable energy technologies. The paper proved that NPID, FOPID and NFOPID control schemes leads the power system to better performance than conventional PID. The results show that NFOPID control scheme leads to the best performance.

TABLE III. CONTRIBUTION OF EACH GENERATING SYSTEM AT EACH TEST AFTER DISTURBANCE

Test	Steady state contribution in PU			
	Biogas	Biodiesel	Battery	Flywheel
1	0.16	0.05	0	0
2	0	0.2	0.005	0.005
3	0	0.2	0.005	0.005

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