PERFORMANCE EVALUATION OF MODEL PREDICTIVE AND PID WITH FUZZY CONTROLLERS FOR LOAD FREQUENCY DEVIATION CONTROL OF AN ISOLATED MICROGRID

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Abstract-

Frequency and voltage stability are crucial parameters for satisfactory operation of micro-grids under isolated mode of operation. For maintaining the system stability, it is desired to control the frequency and voltage of the micro-grid feeding a load remotely in isolated operation. In this mode of operation, the critical load demand is provided by the distributed generators present in the micro-grid. Any mismatch of real power between the load demand and the generation results in the frequency deviation of the system voltage consequently, causing circulating current impingement into the system. The performance of traditional PI and PID controllers had been better in mitigating the frequency deviations under certain limited system perturbations. But their performance is not able to match the desired requirements of frequency deviations under wide range of working conditions. This paper therefore, proposes to suggest a more secure and reliable load frequency control for micro-grids with the help of a hybrid PID-fuzzy controller. The performance of two different controllers such as model predictive controller (MPC) and a hybrid PID-fuzzy controller have been evaluated. A comparative assessment of obtained results, suggest that the fuzzy-PID controller performed better than the MPC in mitigating the effect of frequency deviations.

Index Terms-Micro-grid, Frequency stability, Model predictive controller, Fuzzy-PID control

INTRODUCTION

Load frequency control (LFC) refers to the control of distributed generator's real power generation in response to changes in load frequency and tie line power, in order to keep them within their specified limits, when there is a variation in the load on the system. Load frequency control an important aspect of modern power system is part of automatic generation control (AGC). Conventional controller involves a speed governor used with each generating unit for providing primary frequency control within the power system. When there is a change in the system frequency, the speed, governor regulates the turbine input by opening or closing the valve. This governor-based system provides primary control in the real time operation. Galuset et. al. (2011) discussed that the primary control was incapable of minimizing the frequency deviations within a narrow range and hence, insufficient for maintaining the power system stability [1]. The secondary controls therefore pitches into frequency regulation task when primary control fails to perform. It is always desired that the load operates at a standard frequency of 50 Hz. However, the narrow range of frequency variations can lie between 49.5-50.50 Hz.

The most common controllers being used for LFC are PID controllers. These, controllers having fixed gains designed along particular operating point are however, manifested with slow dynamic response. Therefore, their performance is often sluggish and unsatisfactory during the rapidly varying frequency deviations. PID controllers are therefore finetuned using optimization techniques such as genetic algorithm, particle swarm optimization, ant colony optimization etc. to adapt the gains in such a manner that the controller performance is optimized along certain operating points [2]. In this paper a performance comparison of PID, model predictive and a hybrid-fuzzy-PID controller has been performed for minimizing the load frequency variations in isolated micro-grid. The performance of these different controllers has been tested under different cases of load frequency deviations.

This paper is structured as follows:

Introduction in section 1 is followed by a literature survey of existing load frequency control methods in section 2. Section 3 contains an overview of methodologies followed and the techniques for design of MPC and fuzzy-PID controllers for isolated micro-grid. Finally, the results & discussions of the case studies are presented in section 4, and conclusions of the study are incorporated in the section 5.

Literature Survey

This section deals with the overview of previous research works performed in the field of frequency deviation control in microgrids. The research works presented below are helpful in grasping the concept of load frequency instability problem and various control schemes adopted in dealing with the load frequency deviations in isolated micro-grids.

Guerrero et al. (2011) introduced a conventional strategy for droop control of load frequency in ac as well as in dc microgrid. A general approach to hierarchical control for micro-grids was presented in this paper. This paper highlighted the difference between the conventional features of frequency control in the ac micro-grids and some novel features of hierarchical control in the dc micro-grid systems.

Bevraani et. al. (2012) presented meta heuristic optimization techniques such as particles swarm optimization (PSO) with fuzzy logic, and PID with PSO techniques used for load frequency control in micro-grids. The paper analyzed in detail the affect of wind power and solar irradiance changes as well as dynamical perturbations like damping coefficient and inertia constants which can significantly influence the system frequency in an islanded micro-grid with renewable sources. They also highlighted the affect of above parameters on the micro-grid frequency control problem. These factors were addressed by robust control techniques such as H-∞ control implemented in the secondary loop for frequency control.

Pandey et. al. (2013) presented an extensive literature review on the LFC problem in power systems. This paper presented better insight on the various control techniques or hierarchical control methods used for minimizing the load frequency deviations in distribution network. In both conventional and distributed generation-based power systems, the various configurations of power system models and control strategies involving LFC issues have been addressed. Investigations into LFC challenges involving BESS/SMES storage devices, FACTS devices, wind–diesel and PV systems, have also been discussed in this paper.

Olivares et. al. (2014) has presented the idea of recent trends and desirable features for control of micro-grid. The paper also included the most relevant challenges in micro-grid control and protection. Moreover, the frequency control problem and strategies for frequency stability improvement have also been discussed in this paper.

Hossain et. al. (2014) discussed about control design scheme for power system with multi distributed energy resources distributing power in either interconnected or islanded modes. The paper starts with an overview of micro-grids and its various control loops. Further, frequency regulations in the presence of disturbances, uncertainties and load changes in ac micro-grids have been presented. This paper also delves into depth the process of developing controllers by taking into account the dynamics of voltage sensitive loads.

Haan et. al. (2015) proposed an effective control strategy for reducing system frequency deviation caused by load fluctuation and renewable sources in a smart micro-grid system with attached storage.

Renewable energy sources are associated with frequency and voltage deviations due to their inherent stochastic nature. A microgrid containing fossil fuel generators and renewable energy sources with a small, fast-acting battery-based storage system has been considered as the case study. Despite the presence of significant (model) uncertainties, the authors could develop effective control strategies for reducing the frequency deviation.

Pahasa et. al. (2016) implemented the MPC to control the blade pitch angle of wind generators and plug-in hybrid electric vehicles (PHEVs) for load frequency control of microgrids. The MPC is a model based predictive control that uses an optimization method to calculate future control signals based on the plant model, current signals, and past signals of the system. The results could satisfactorily verify the efficacy of the designed MPC for LFC.

Annamraju et. al. (2018) addressed the secondary frequency control problem of autonomous micro-grids with a two-stage adaptive FLC. In the presence of multiple disturbances and parameter uncertainties, a traditional PI controller fails to provide better performance in practice. In order to address this issue, the proposed controller was proposed in order to reduce the effects of disturbances and parameter uncertainties in micro-grid frequency control.

Kljajic et. al. (2020) provided an overview of the voltage and frequency stability control techniques that can be used on micro-grids. The authors in addition to providing a quick overview of the micro-grid classification also proposed a few voltage and frequency as well as hierarchical control methods.

Materials and methods

The material and methods used in this research work are introduced in this section. A brief description of the overall micro-grid system where the MPC and PID-Fuzzy control techniques have been implemented for minimizing the system frequency variations has been presented. This section also contains the mathematical models of each component in the micro-grid. Finally, the various control schemes such as MPC and PID fuzzy implemented on the micro-grid has also been discussed in detail.

Micro-grid system

The isolated micro-grid system depicted in figure 1 consists of a 20 MVA diesel generator, 4 MW wind generator, 800 kW PV generation, 2 MW Fuel cell, 0.5 MW battery energy storage system (BESS) and a load of impedance (10 + j2) MVA. The base power for the micro-grid is taken as 20 MVA for calculating the per unit (p.u.) values of the various quantities. Each component of the micro-grid has been modelled by its linear transfer function or a mathematical equation [1], [3]. The detailed mathematical models for each component are presented in the subsequent sections. The micro-grid system under test contains a different variety of generators. Wind and solar-PV system are the two non-conventional type stochastic input parameter-based generators with varying output along with and diesel and fuel cell generators generating rather fixed output. The modelling of each component is presented in the sub-sections below.

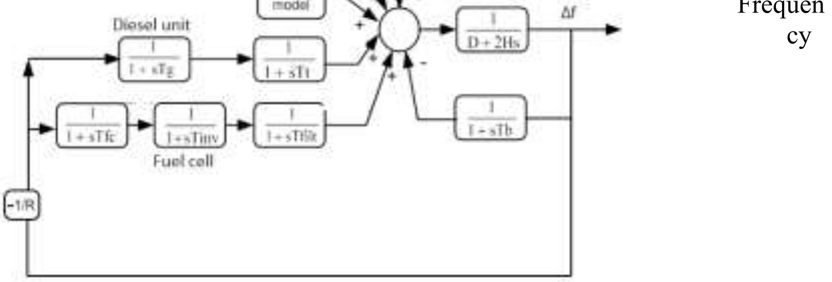

Figure. 1.: Isolated microgrid system [1]

Wind generator model

The wind generator converts the kinetic energy in the blowing wind stream into electrical energy. The wind generators generally contain a wind turbine coupled with a suitable electrical generator either directly or through a gear-box. The blowing wind stream strikes the turbine blades producing lift forces propelling the rotor blades due to pressure gradients created on both the sides of the turbine rotor [4]-[7]. The output power from the wind generators is modelled according to equation (1).

$$P_w = \frac{1}{2}\rho A C_p(\lambda, \beta) V_w^3 \quad (1)$$

Where, P_W is the power output from the wind generator,
P is air density
A is the rotor swept area in m^2
$C_p$is the Betz coefficient depending on the tip-speed ratio (λ) and the bled pitch angle (β)

Solar PV model

The solar arrays are a subsystem in microgrid which converts energy coming from sun in the form of light into electrical energy. This subsystem consists of a large number of solar-PV modules which are mounted on support structures placed on the ground. The power output from the PV panels are fed into the grid or load through power electronic devices [8]. For efficient working of the PV plant, the system is operated with the help of at maximum power point tracker (MPPT). The output power of solar system is given by, equation (2).

$$P_{solar} = P_{pv} * \frac{G}{G_{stc}} * \left[1 + K_t * [T_a + 0.0256 * G - T_{stc}]\right] * \eta_{mppt} \quad (2)$$

Where,
P_{PV} =power generated in a PV array
P_{solar} =output power of solar system power
G = solar irradiance
G_{stc}= sun irradiance value at standard test conditions
η_{mppt} = efficiency of maximum power point tracking
T_a = ambient air temperature
T_{stc} = temperature value at standard test conditions

The PV array is modelled by equation (3)

$$TF_{pv} = \frac{\Delta P_{pv}}{\Delta P_{\varphi}} = \frac{K_{pv}}{1+ST_{pv}} \quad (3)$$

Where,
P_{PV} =Change in solar power
P_{ϕ} =Change in solar radiation
K_{PV}= Gains of PV model
T_{PV} =Time constant of PV

Diesel generator (DEG) model

The uncontrollable energy sources like solar pv system and wind generation are intermittent in nature because of variations in their input. The outputs from wind generators and PV are fluctuating & also non predictable. Normally, for operating a micro-grid in stand-alone mode a mixture of renewable energy and non-renewable energy generators are used in the micro-grid. All the generators are supposed to work in coordinated manner for supplying the load demands depending on the load requirements and the availability of power from the generators. If the energy produced by renewable sources and by the battery are insufficient to supply high priority consumers, then the extra power will be supplied using DEG [9]. The DEG combines with synchronous generator and renewables operated by connecting in parallel to fulfill the load demand. The diesel engine generator system is equipped with speed governor and operates when changes or variation comes into the system. The mathematical model of DEG is given as in Figure 2.

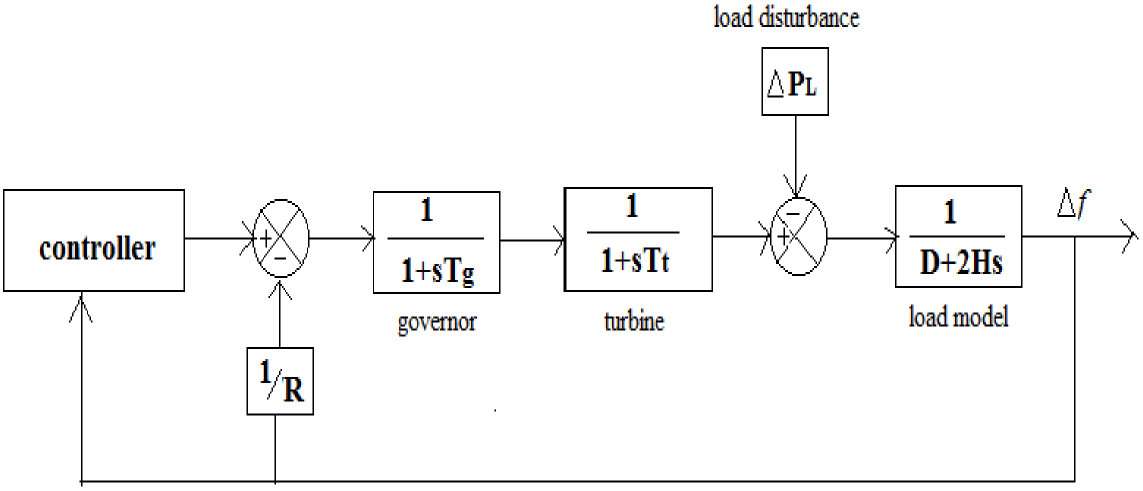

Figure 2: Diesel generator model

Battery energy storage systems (BESS)

Batteries are electrical storage systems which have the capability of storing the electrical energy in the form of chemical energy. The batteries can be charged or discharged depending upon the load requirements with the help of bi-directional power electronic converters. In a microgrid the rapidly changing load frequency situations are normally handled by using the DEG. These generators usually having large time constants exhibit sluggish response. The fast response behaviors of batteries are able to handle this problem by supplying the desired power when required during load frequency deviations [10].

The battery energy storage system represented in transfer function block is given by equation (4).

$$TF_{BESS} = \frac{\Delta P_{BESS}}{\Delta f} = \frac{K_{BESS}}{1+ST_{BESS}} \qquad (4)$$

T_{BESS} = time constant of the battery
ΔP_{BESS} = change in battery power
Δf = change in frequency

The charging and discharging of BESS is controlled by the frequency deviations. The battery is considered in charging mode if the frequency deviations are positive and in discharging mode if the deviations are negative. The parameters of the transfer function model of BESS are presented in table 1.

Fuel cell model

Fuel cells are static generators which produces electrical power from hydrogen and oxygen. The fuel cells are connected in the micro-grids to cater the disturbances generated from fluctuations in the wind and the solar PV generators and improving the overall system stability. The fuel cell transfer function used in proposed model is given by equation (5) and the complete block diagram representation of the fuel cell is depicted in figure 3 and the parameters of the transfer function of the various components are given in table 1.

$$TF_{fc} = \frac{\Delta P_{fc}}{U_c} = \frac{K_{fc}}{1+sT_{fc}} \qquad (5)$$

ΔP_{fc} = deviations in power output from fuel cell
ΔP_{Cf} = change in Control inputs of fuel cell
T_{fc} =Fuel cell time constant
K_{fc} = Fuel cell gain
TF_{fc} = Transfer function of fuel cell

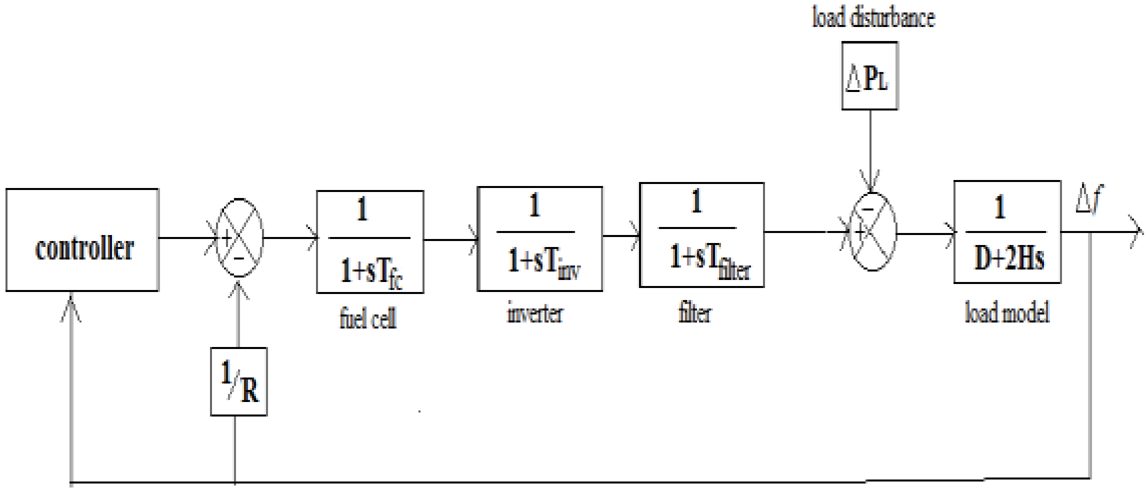

Figure. 3: Mathematical model of Fuel cell [1]

S. No.	Parameter	Value
1.	Damping coefficient (D)	0.015
2.	Inertia of rotating masses (2H)	0.1667
3.	Time constant of fuel cell (T_{fc})	0.26
4.	Time constant of inverter circuit (T_{inv})	0.04
5.	Time constant of filter (T_{filt})	0.004
6.	Time constant of governor (T_g)	0.08
7.	Time constant of turbine (T_t)	0.4
8.	Frequency droop (R)	3
9.	Time constant of battery (T_b)	0.1

Table 1 Fuel cell parameters

Methodology

The different control schemes adopted for load frequency control in the micro-grid system is presented in this section.

PID controllers

PID controller has three components called proportional, integral and derivative components as depicted in figure 4. The proportional component generates the control action proportionate to the value of error signal. If the value of error signal is zero, then no corrective action will be taken by the controller while a large value of error will generate large proportional control signal [9], [11].

The integral component (I) describes the previous values of errors. It integrates all the errors upon time to generate integral constant term. It means that if residual error is present in the system after taking the control action by proportional controller, the integral term is used to reduce the error. When error gets reduced, the integral term is terminated and this will reduce the effect of proportional effect as the error decreases. The differentiation component however, is used to evaluate future errors. It will estimate the control signal based on its present rate of change. Thereby reducing the peak overshoot and the damping frequency. This component takes care of the rate of change of error. If the rate of change is more there will be greater controlling or damping effect.

Mathematical form of PID controller

A balanced response of the PID controller can be achieved by tuning the controller in a proper manner for achieving proposed control. The tuned parameters are generally the gains K_P, K_i and K_d for achieving the appropriate corrective action. The affect of the values of theses parameters will be clear from the characteristic equation of the controller [10], [11].

The overall control function for the PID control is given by equn. (6).

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{d}{dt} e(t) \tag{6}$$

where like K_P, K_i and K_d are denoted as the coefficient for the proportional, integral and derivative terms. The general layout of the PID controller is depicted in figure 4.

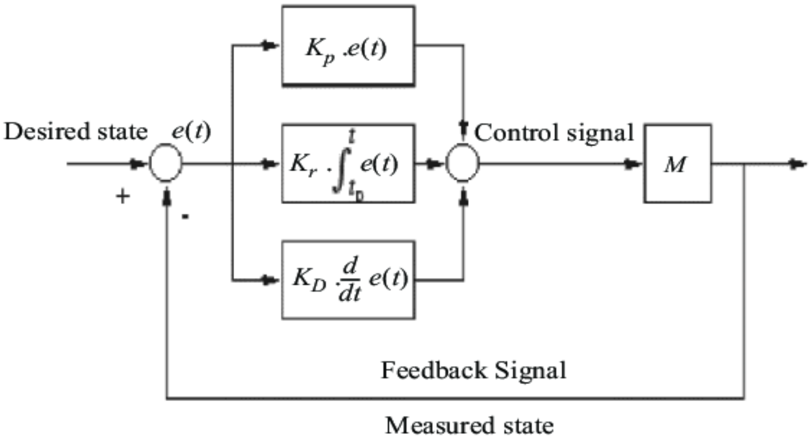

Figure 4 PID block diagram

The major drawback of PID controller is that the gain constants are tuned around a specific operating point and are fixed. Hence, the deviation in the operating points may not experience the control action to be as accurate as the designed operating points. In the case of load frequency control, the range of frequency deviations are uncertain. Hence, a controller with fixed gain may not be able to take fast and accurate corrective actions in the cases of rapid variations in the load frequency [8].

Model predictive control (MPC)

In MPC the main goal is to adjust a single manipulated variable (or actuator) u to keep a single output y at a reference value (or setpoint) r as depicted in figure 5. The MPC is intended to accomplish a control goal necessitates the creation of a plant model, which establishes the mathematical relationship between the plant's inputs and outputs. This model is used by the controller to forecast plant behavior.

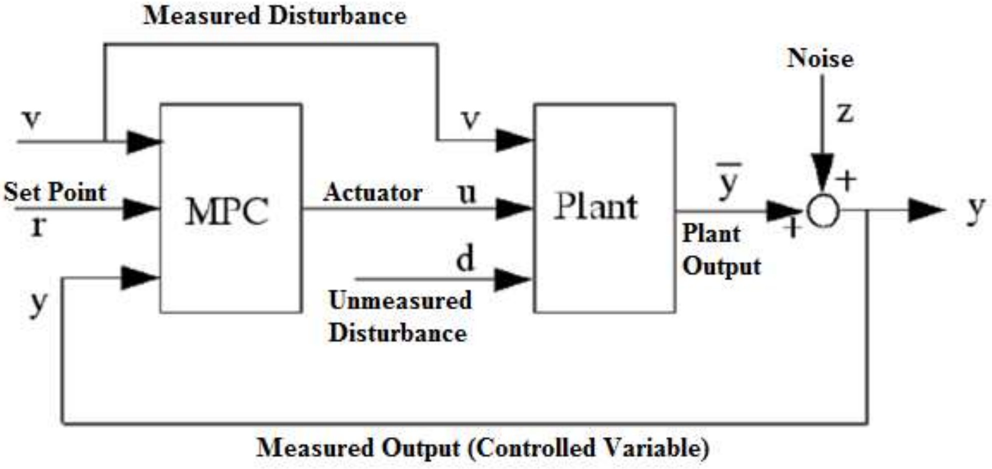

Figure 5: MPC block diagram

MPC predicts future outputs over some predictive time horizon. The reference trajectory y(k) is obtained based on the set point values. The set point is calculated by using real time optimization (RTO). Future values of state variable $\dot{y}(-)$ can be predicted by using plant model for process and it considers the recent measurements at k_{th} sampling instant for a given sequence of future control u(k) [5], [7]. The manipulated variables u(k) are calculated for future time horizon, so that they minimize an optimal function.

MPC for LFC of Isolated Microgrid

The block diagram representation of the MPC based LFC for the isolated micro-grid is depicted in figure 6 below.

MPC has two components an optimizer and a state estimator.

(a) Optimizer: Optimizer ensures the tracking of future plant outputs in accordance with the reference input. MPC optimizer selects the most optimum amongst the multiple future scenarios. This optimization problem can be solved by using optimization techniques in MPC based controllers that tries to minimize the error between reference output and predicted output.

(b) State estimator: System states denote its operating point. Many times it is required to estimate the system states to obtain its actual operating point. The measured system states are fed to the MPC which checks for its values from the inbuilt plant model and generate control action for minimizing the error among the measured and estimated states. State estimator will generate 100 possible control combinations by following error and trial method and optimizer will select best among them.

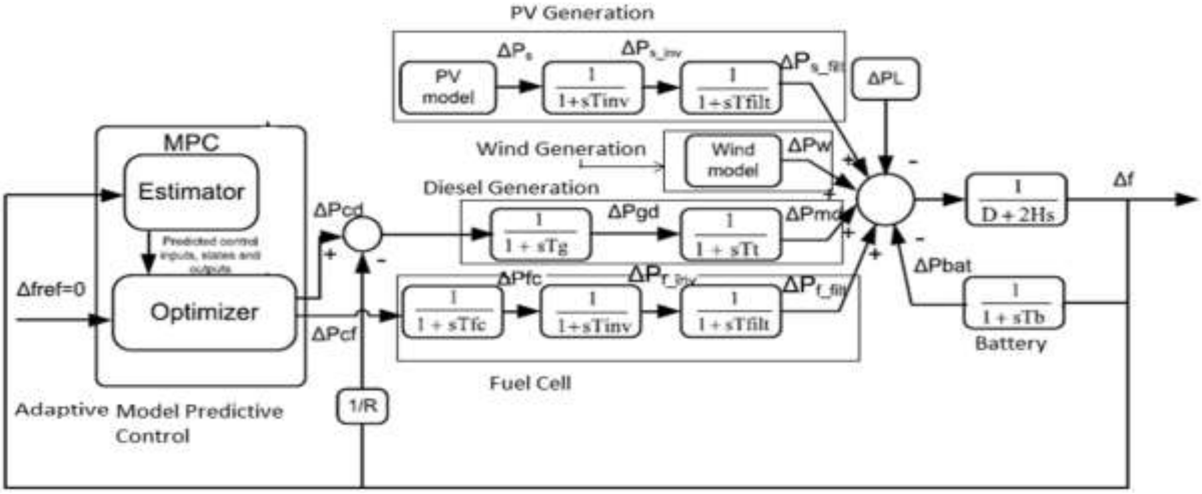

Figure.6: MPC for LFC

MPC based controller uses control strategy which applies the optimization technique at every sample time of the control time horizon for evaluating possible control action.

Fuzzy-PID control

The Fuzzy-PID controller is implemented by replacing the MPC controller in Figure 6 by a fuzzy PID controller depicted in Figure 7. The idea behind the hybrid controller is to use the benefits of both the fuzzy and PID control actions for controlling the load frequency deviations in the micro-grid. This is achieved by tunning the gains of the PID controller by obtaining the optimized gain values from the fuzzy block. The fuzzy block receives the error in the frequency deviation and change in the error as input and calculates the value of change in the gains from the previous values using on the fuzzification rules, membership functions and the de-fuzzification rules [10], [11].

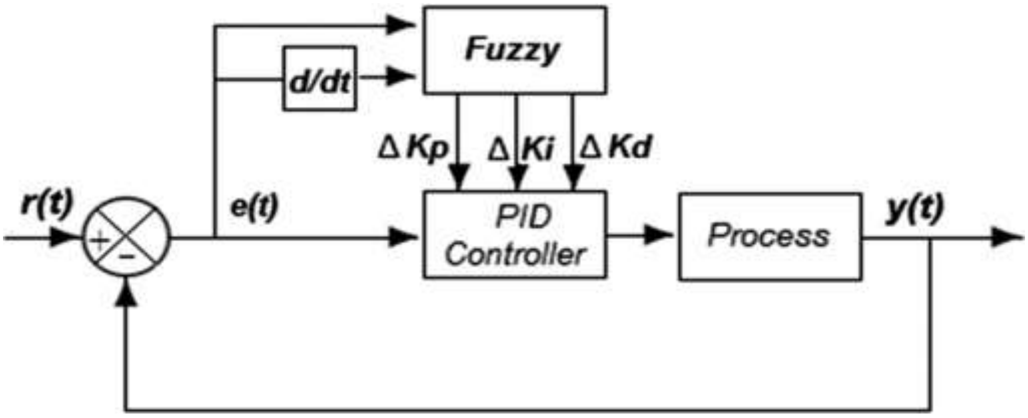

Figure. 7: PID with fuzzy logic control

Results and discussion

The results obtained by implementing the MPC and Fuzzy PID control schemes for load frequency control of an isolated micro-grid system in fig 1 is presented in this section. The performance of the control schemes has been tested under different conditions. The results of various case studies obtained through simulation are also presented in this section.

DER's connected in the microgrid with load change of 0.01 p.u.

The isolated microgrid connected with all DERs such as diesel, battery storage, fuel cell, WTG and PV solar plant are simulated for load frequency deviations in this case. The case study considers the frequency deviation in the micro-grid with a step load change of 0.01 p.u. and the deviations in the solar power ΔP_s with 0.2 p.u. at a constant wind velocity of 1m/sec. Under these situations as the microgrid is operated in standalone mode, the frequency control is handled by the controllable sources. A comparison of the responses obtained from various controllers such as PID, MPC and Fuzzy-PID are presented in figure 8. The value of peak overshoot without control is 0.048 Hz, with PID controller is 0.029 Hz, with fuzzy-PID controller is 0.012 Hz and with MPC it is 0.004 Hz. The Settling time value without control is 1.5 sec, with PID controller is 1.48 sec, with fuzzy-PID controller is 1.18 sec and with MPC it is 0.62 sec. A comparison of the above parameters from the curves in figure 8 it can be observed that the MPC performs better than PID and Fuzzy-PID controllers. The simulation time is taken as 5 sec sampled at 0.01 sec. For tuning the MPC controller the prediction horizon is taken as 20 and control horizon is taken as 2.

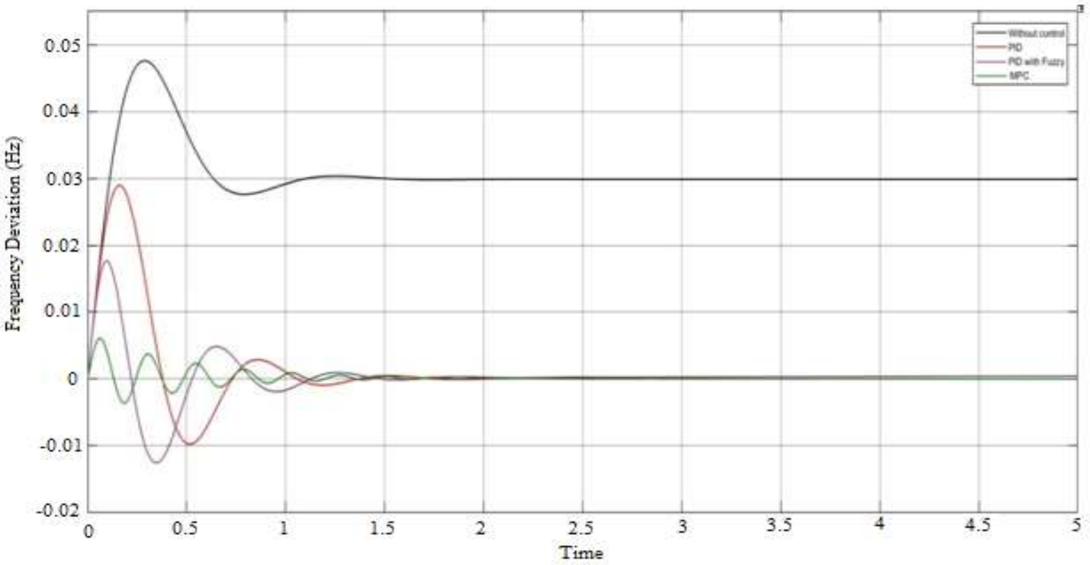

Figure 8: Controller responses to frequency deviation with 0.01 p.u. load change

Controller response with dispatchable DERs

The case study shows the performance of different controllers in minimizing the frequency deviations when dispatchable DERs like diesel engine generator, fuel cell generation and battery are acing in the system. In this case the load disturbance is taken as step change of 0.02 p.u. It can be observed from the curves in figure 9 that the frequency deviation becomes negative in value for step change in load and as a result the value of control signal increases to reduce the frequency deviation. The controller responses depicted in figure shows that the value of peak overshoot without control is 0.018 Hz, with PID controller is 0.012 Hz, with fuzzy-PID controller is 0.0075 Hz and in for MPC is 0.002 Hz. The value of T_s without control is 1.45 sec, with PID controller is 1.4 sec, with fuzzy-PID controller is 1.01 sec and with MPC is 0.6 sec. From the results in figure 9 it can be concluded that the performance of MPC is best among all the controllers.

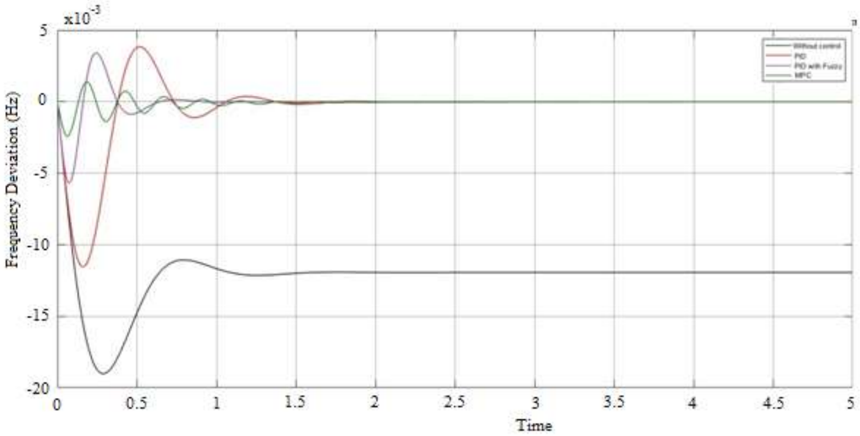

Figure 9: Controller response with dispatchable DER

Controller response with series of step load variation

The case study tests the performance of controllers in mitigating the frequency deviations for a series of step changes in the load. The response obtained for each controller is presented in figure 10. From the curves it can be observed that the peak overshoot without control is 0.02 Hz, with PID controller is 0.018 Hz, with PID fuzzy-PID it is 0.01 Hz and in case of MPC is 0.007 Hz. Similarly, the values of settling time without control is 1.3 sec, with PID control it is 1sec, with fuzzy-PID control it is 0.8 sec and in case of MPC its value is 0.3 sec. From the curves in figure 10, it can be concluded that the performance of MPC was best amongst all the controllers in controlling the frequency deviations.

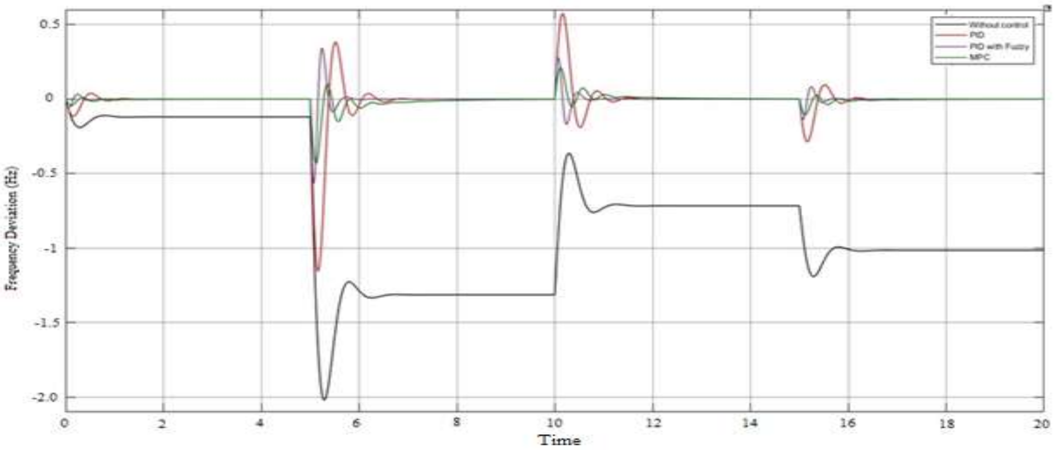

Figure 10: Controller response with series of step load variation

Controller response with wind perturbation of 2 msec

In this case the effect of wind speed variation from 2 m/s to 6 m/s on the frequency deviation has been taken into account. The value of generation from solar PV is taken as constant at 0.5 p.u. In this response of controllers have been represented by the curves in figure 11. In this case, the peak overshoot without control is 0.08 Hz, with PID controller it is 0.049 Hz, in case of fuzzy-PID controller, the value is 0.035 Hz while in case of MPC the value is 0.026 Hz. The value of T_s without control is 30 sec, with PID controller is 8 sec, with fuzzy-PID controller it is 4 sec and in case of MPC it is1.9 sec. From the curves in figure 11, it can be inferred that the performance of MPC was best amongst all the controllers.

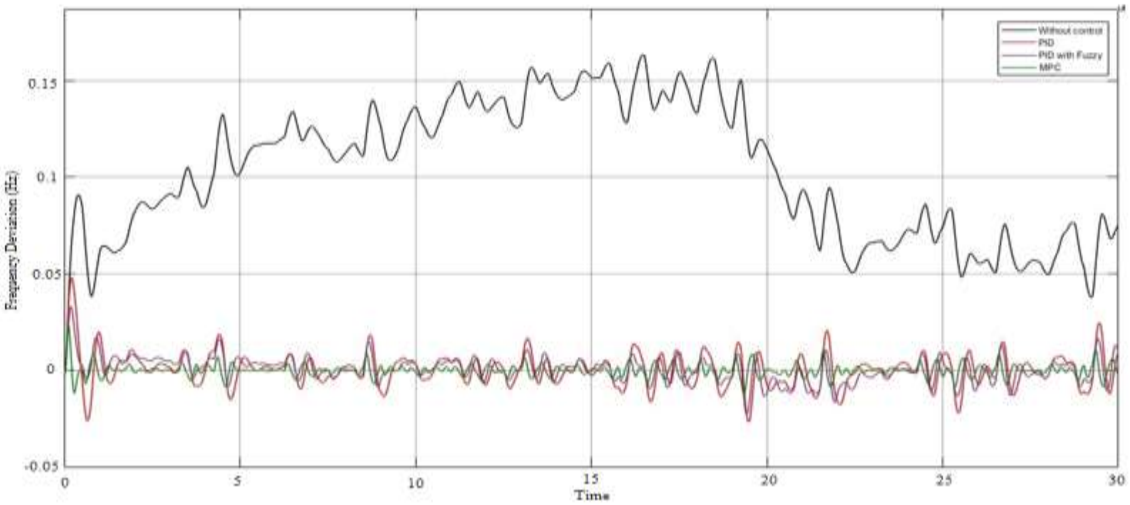

Figure 11: Controller response with wind perturbation of 2 msec.

Controller response with increasing step variation in solar generation

Figure 12 depicts the performance of the controllers for step variations in the solar-power generation, and a regular time interval and a constant wind power deviation ΔP_W at the value of 0.05 p.u. Change in the load ΔP_L is taken as 0.02 p.u. The value of peak overshoot without control is 0.049 Hz, for PID controller it is 0.029 Hz, for fuzzy-PID controller it is 0.01 Hz and in case of MPC its value is 0.007 Hz. T_s without control is 1.8 sec, for PID control it is 1.6 sec, with fuzzy-PID controller the value is 1.2 sec and in case of MPC it is 0.9 sec. From the curves in figure 12 it can be inferred that the MPC performed best as compared to all the controllers.

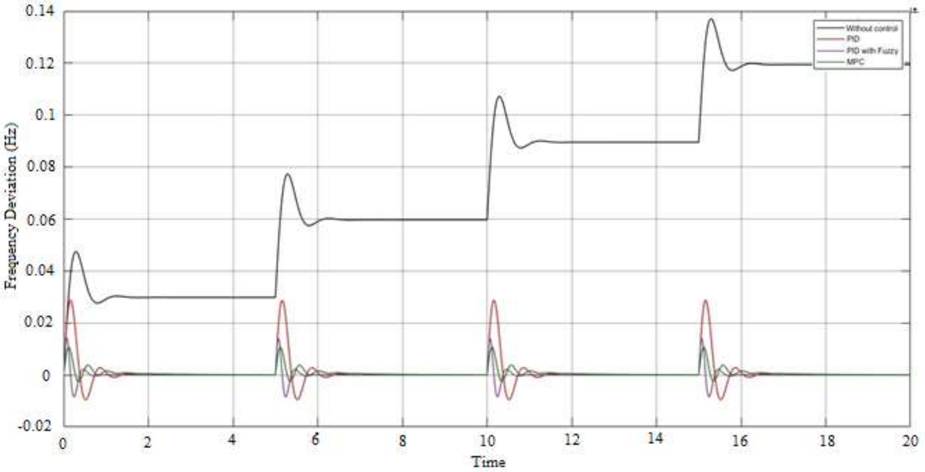

Figure 12: Controller response with increasing step variation in solar generation

Controller response with random disturbances from wind power solar power and load

Figure 13 represents the case of random disturbances in the power from wind and solar generators along with the disturbances in the load. The performance of each controller under this condition was analyzed after applying all the disturbances simultaneously. From the curves obtained it can be inferred that the performance of MPC was the best in mitigating the load frequency deviations under the condition of random disturbances in the wind and solar power generation. The values peak overshoot and settling time for different case studies mentioned in the above sections are presented in table 2& table 3 below.

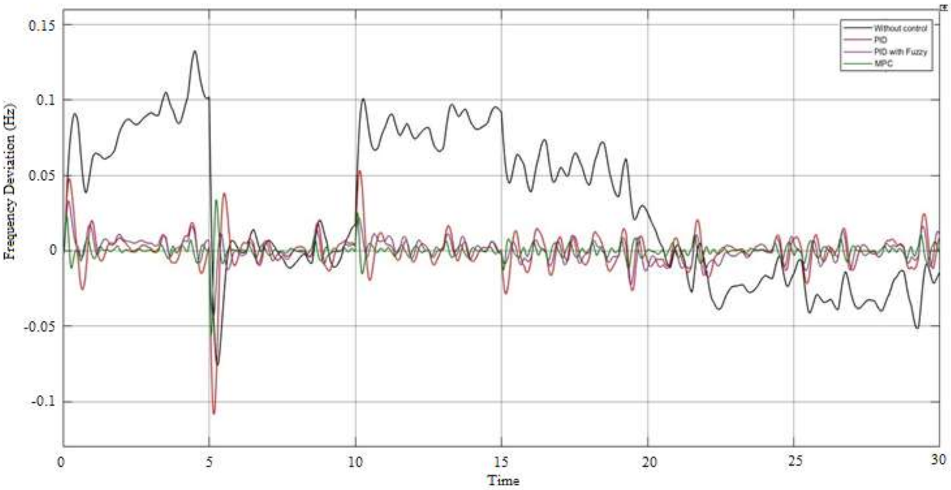

Figure 13: Controller response with random disturbances from WTG, solar PV power and load

Cases	Without controller	I controller	D with fuzzy logic controller	PC controller
Case-1	0.032	0.0052	0.0041	0.0027
Case-2	0.0126	0.00056	0.00041	0.00032
Case-3	0.109	0.0091	0.0072	0.0051
Case-4	0.076	0.016	0.009	0.0078
Case-5	0.109	0.0089	0.0074	0.0061
Case-6	0.047	0.016	0.0098	0.0056

Table 2: Peak overshoot values of frequency deviation in different cases.

ses	ithout controller	ID controller	ID with fuzzy logic controller	MPC controller
se-1	1.5	1.48	1.18	0.62
se-2	1.45	1.4	1.01	0.6
se-3	1.3	1	0.8	0.3
se-4	30	8	4	1.9
se-5	1.8	1.6	1.2	0.9
se-6	6	5.3	4	1.8
se-7	1.6	1.37	0.092	0.068

Table 3: Settling time (sec.) for different cases.

Conclusions

This paper presents MPC for providing the control of frequency deviations in an islanded microgrid. The paper examines in detail the performance of different controllers for various cases of load and deviations in the power output from various distributed generation sources connected in the microgrid. The results shown through case studies illustrate that the control technique using MPC shows optimized performance in reducing the frequency deviations during disturbance in load and disturbances from non-conventional energy sources.

The simulation results obtained shows that the control technique adopted here deals clearly or satisfactorily cater the effect of variations in non-conventional energy sources i.e. wind speed and change in solar irradiance on the load frequency deviation. Moreover, MPC gives satisfactory response for uncertainty entering into the system. Hence, the proposed MPC controller is effective to regulate the load frequency in advanced power grid applications.

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