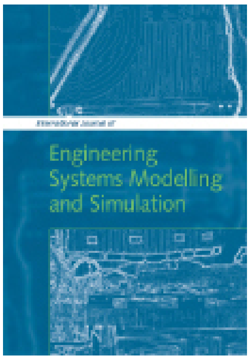

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Robust control of frequency considering operations of AC microgrid in islanded mode

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Abstract: Modelling and control of an autonomous microgrid with both governable and non-governable sources is discussed in this paper. Power sources utilised in microgrid are solar, wind, fuel cell (FC) and diesel-based generator (DG). Batteries, flywheels (FW), and aqua electrolyses (AE) are used as energy storage elements. Recently, due to the increased penetration of non-inertial distributed generations in the microgrid, frequency deviation has become a matter of concern. If the loading conditions and active power generation changes unexpectedly, then the power system frequency would deviate largely. The output of the flywheel, battery, diesel generator, FC, and aqua electrolyser is regulated using the proportional-integral-differential (PID) controller. In this paper, a novel mathematical framework is proposed to tune PID controllers. For zero frequency deviations in steady state, optimum values of proportional, differential, and integral gain coefficients are proposed. The importance of the proposed scheme is to achieve better steady state frequency response.

Keywords: diesel generator; frequency regulation; microgrid; PID control; renewable energy sources.

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1 Introduction

Generation of electrical energy is a major source of greenhouse gases in some cases. It is mainly due to non-conventional resources like coal, nuclear, diesel and other non-renewable sources that are used for electricity generation. Nowadays, with rapidly increasing demand of electricity, the cost of electricity generation is increasing due to the depleting nature of conventional energy sources. An alternative to this condition is the utilisation of distributed generation, which comprises of different non-conventional energy systems (Dondi et al., 2002; Hatziargyriou et al., 2007; Palma-Behnke et al., 2013). It would be very beneficial in multi aspects to use non-conventional energy sources, rather to utilise the conservative sources of energy. When a power grid is formed using interconnection of several small DGs, then it is known as microgrid (Molderink et al., 2010). The power outputs of different renewable generators are different and hence, to maintain the stability of the system of such complex system is quite difficult for the system operators. Hence, the operational stability problem analysis and controls has emerged as the thrust area of research (Senjyu et al., 2005; Lopes et al., 2006; Wang and Nehrir, 2008).

Microgrid consists of primary and secondary sources of energy. Primary sources are the key energy sources satisfying the load requirements. Secondary sources of energy are used for the suppression and elimination of different variations or disturbances in the microgrid. Secondary sources of energy provide power to manage the rising demand of electricity. However, frequency variations are still observed in the microgrid owing to the operational delays in secondary energy sources. Wind and solar are prime energy sources, while diesel generator, FC, aqua electrolyser, battery and flywheel are termed as secondary electricity sources. Solar and wind energy sources does not provide a constant output due to their intermittent nature. It means that their output varies with time. This variation in output causes instabilities in frequency and power parameters in the microgrid having these sources of energy (Chicco and Mancarella, 2009; Vandoorn et al., 2010, 2013). In order to minimise the fluctuations in frequency along with the optimal utilisation of energy, a suitable and robust controller is required (Mishra et al., 2012; Babazadeh and Karimi 2013; Sarkar et al., 2018).

Due to the potential of improving operational energy security and reliability, microgrid have attracted a lot of research attention. A load-side energy management system and a power balance scheme are presented by Detroja (2016). The goal is to ensure that important loads receive uninterrupted power while other non-critical loads are managed according to their priorities. For the scheduling of an energy storage system deployed in a wind–diesel isolated power system, a knowledge-based expert system is proposed (Ross et al., 2011). An optimal scheduling method for lowering the operational costs of an isolated microgrid by employing chance-constrained programming is presented, by simulating the uncertainty of spinning reserves given by energy storage with probabilistic constraints (Li et al., 2018). An optimal control technique based on a water cycle algorithm for achieving efficient functioning of an autonomous microgrid is proposed, in which proportional integral controllers are used as control approach (Hasanien and Matar, 2018). The influence of communication delays on secondary frequency control of an islanded microgrid with several distributed generators is investigated in the study (Liu et al., 2014). An overview of voltage and frequency regulation control techniques used in standalone and transition mode operating of hybrid microgrid is proposed by the authors (Malik et al., 2017). Authors presented a neuro-fuzzy inference systems (ANFIS) based control techniques for load frequency control of micro grids after islanding (Esmaeili et al., 2018). To improve the frequency regulation of a hybrid wind-diesel system, a genetically tailored fuzzy regulated super-capacitor energy storage system is proposed (Manzoor and Mufti, 2018). The authors propose a concept of resilient interconnected microgrid in terms of multiple renewable resources to provide clean and cheap energy to water pump equipment at farms during regular and emergency conditions (Othman and Gabbar, 2021).

In this proposed work, microgrid modelling in the perspective of automatic generation control (AGC) has been taken into consideration. Also, the gain values of the controller along with bias are determined by the trial and error approach (Karimi et al., 2010). The tuning of a typical PID controller is accomplished using the scheme known as Ziegler and Nichols method (Katiraei and Iravani, 2006; Tsikalakis and Hatziargyriou, 2011). Once adjusted for a certain operating point, the controller improvements are only recommended for small changes in that stability point. As an outcome, using a classical approach of tuning the controller (Bouzid at al., 2015; Hamzeh et al., 2016) does not satisfy the robust operation requirements. In this paper, PID controller tuning is performed using a mathematical value approach. The results of the applied mathematical method reflect the robust operation of the system in terms of frequency deviations. The novelty of the present work is that we have utilised the three energy storing elements, i.e., batteries, FW, and AE; which were not utilised altogether in the previous work. Also, the results achieved using the proposed method, i.e., MVM are more accurate than the previous work.

In the present work authors' contributions are that, a truthful microgrid modeling for the analysis of frequency regulations is proposed. A novel mathematical value method (MVM) is utilised for the PID regulator parameters optimal tuning. Also, the parameters of secondary controllers of microgrid are tuned systematically using the traditional PID scheme gain tuning for the frequency regulation.

The paper is organised as follows: Section 2 pronounces the suggested microgrid system with explanations of its constituents. Section 3 gives insights about the power and frequency relations of the microgrid system. Section 4 reflects the proposed mathematical tuning of the controller. Results of the simulation along with discussion are revealed in Section 5, for different load conditions. Finally, Section 6 depicts the conclusions regarding the proposed work.

2 Proposed hybrid system

Diesel generator, wind power, solar PV, battery (storage), FC, fly wheel and aqua electrolyser are utilised as the energy components in the microgrid. The total power output of this system is around 500 kW. Battery is exclusively deployed to provide power during the transient periods in microgrid operation. The power produced by wind source and solar PV source are intermittent and varies with time and therefore cannot be predicted. Aqua electrolyser absorbs the fluctuations from the outputs of solar and wind source. It also helps in harnessing hydrogen, which in turn is utilised as fuel for the FC. Also, a constant power modelling of the components are exploited in this work. Figure 1 illustrates the block diagram of the considered hybrid microgrid system. Here, $\Delta F(s)$ (frequency changes) is the output of the system.

The components of the microgrid system are:

a Solar PV (as intermittent source)

A photovoltaic system utilises solar energy to generate electricity. The power generated is given by (P_s). The main components of a PV system are solar panels, inverter and battery bank. Solar cells present in solar panels generate DC power which can be converted to AC by inverters. Battery bank is used to store DC energy. The solar PV system also utilises MPPT technique for obtaining the maximum power output and therefore it is also preserved as an intermittent energy source. A 250kW solar PV energy source is utilised in the proposed system.

MPPT is a controller algorithm that extracts the maximum available power from solar PV modules under specified conditions. The core issues handled by MPPT technology is that the efficiency of power transfer from the solar cell is dependent on the amount of sunlight falling on the solar panels, the temperature of the solar panels, and the electrical characteristics of the load. The load characteristic that provides the best power transfer efficiency changes when these variables changes. When the load characteristic changes, the system's property is adjusted to obtain the maximum possible power transfer efficiency. The maximum power point is the name given to this load feature. The technique of locating this point and maintaining the load characteristic is known as MPPT.

b Wind power (as intermittent source)

A conversion system of wind energy uses energy from wind to generate mechanical power which can be converted to electric power using a generator. The power generated is given by (P_w). Wind energy system uses MPPT technology to obtain maximum power output on different atmospheric conditions as input as well as for different load conditions. But one of the disadvantages of MPPT technology is that the system loses its output control capability. Also, it is treated as an uncontrollable source in this work due to its intermittent nature. A 250 kW (rated) wind energy source is utilised in this study.

c Diesel generator (as governable source)

Diesel generators consist of mainly two components, an engine (diesel) and an electrical generator. The power generated is given by (P_{dgt}). Governor control and speed droop is used to fulfill the load demand. A governor is used to regulate the fuel as input to the engine. The engine in turn drives the electric generator to generate electricity. In this study, a 350 kW (rated) diesel generator is employed. The transfer function of first order [shown by $G_{dg}(s)$] is exploited to represent the governor of a generator (diesel), as per below equation (1).

$$G_{dg}(s) = \frac{1}{1 + sT_{dg}} \tag{1}$$

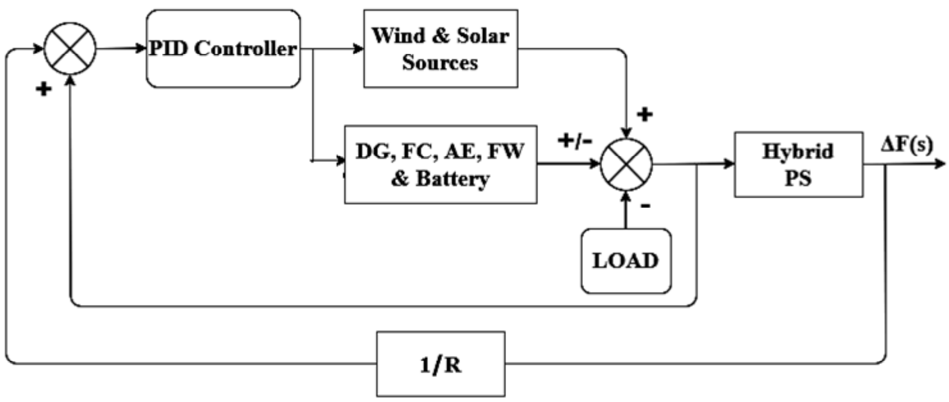
where, T_{dg} (in sec) denotes the governor time constant.

Likewise, transfer function [shown by $G_{dt}(s)$] based modelling of the generator (diesel) is presented by the below equation (2)

$$G_{dt}(s) = \frac{1}{1 + sT_{dt}} \tag{2}$$

where, T_{dt} represents the turbine time constant (in sec).

Figure 1 Proposed microgrid block diagram



Henceforth, the composite transfer function of the system is represented by $G_{dgt}(s)$ and shown by equation (3)

$$G_{dgt}(s) = \frac{1}{(1+sT_{dg})(1+sT_{dt})} \tag{3}$$

d Battery module (as governable source)

Power obtained from renewable energy sources (like wind and solar) is fluctuating in nature. This fluctuation is owing to the reason that the rate of wind flow is not constant throughout the day and similarly more amount of solar energy is obtained on a sunny day rather than on cloudy day. The battery power is given by (P_{bs}). Subsequently, secondary supply is used in this system to reduce the fluctuations in load or primary source, henceforth, non-conventional energy sources could not be utilised directly in secondary source of energy supply. Therefore, battery energy storage is utilised to store the power generated from renewable energy sources. Afterwards this stored power is utilised to compensate the primary source fluctuations. By using the battery storage system, we are able to use renewable energy and obtain constant power supply at the same time. A 30 kWh battery is used in this study. The transfer function given by $G_{bs}(s)$ implemented in microgrid is expressed through equation (4)

$$G_{bs}(s) = \frac{1}{1+sT_{bs}} \tag{4}$$

where T_{bs} (in sec) denotes the time constant of the battery system.

e F-cell (as governable source)

A FC generates power by means of the reaction of electrochemical nature between oxygen and hydrogen. The power generated/consumed by FC is given by (P_{fc}). Voltage yielded through a solo cell (fuel) is very less; therefore, these are connected in the fashion of series/parallel to achieve large voltage. Unlike conventional sources, FCs can provide clean power. The lone drawback of the cell is that the constituent gas hydrogen used to generate power is expensive, when compared to conventional sources. A 200 kW FC is used in this study. The transfer function of cell [shown by $G_{ft}(s)$] implemented in microgrid, is represented by equation (5)

$$G_{fc}(s) = \frac{1}{1+sT_{fc}} \tag{5}$$

where T_{fc} (in sec) denotes the FC time constant.

f Aqua-electrolyser (as governable source)

The drawback of FC can be compensated by using an aqua electrolyser to generate hydrogen. The aqua electrolyser power is given by (P_{ae}). Hydrogen is produced by accomplishment of the electrolysis of water. A 100kW capacity aqua electrolyser is used in this work. The transfer function of aqua electrolyser (shown by $G_{ae}(s)$) is illustrated by equation (6)

$$G_{ae}(s) = \frac{1}{1+sT_{ae}} \tag{6}$$

where T_{ae} (in sec) denotes the aqua electrolyser time constant.

3 Frequency and power fluctuations

If the equilibrium conditions between the generation and load requirements is not preserved in an alternator based power system, then system frequency changes or fluctuates based on the demand and/or generation conditions. The discrepancy between the load demand (P_l) and power production (P_g) is defined as the power deviations. The mathematical modelling of the generator in terms of frequency deviation (Δf) may be illustrated by equation (7)

$$\Delta f = \frac{f_{sys}}{2Hs}\left(\Delta P_g - \Delta P_e\right) \tag{7}$$

where, Δf is system frequency deviations, ΔP_g is changes in generated power, is changes in composite electrical load conditions, f_{sys} is system frequency and H is inertia constant (in MWs/MVA).

The expression of P_g is shown by equation (8).

$$P_g = P_w + P_s + P_{dgt} + P_{fc} - P_{ae} \pm P_{bs} \pm P_{fw} \tag{8}$$

where P_{fw} is the flywheel power consumed/generated. Loads are often of different types, such as frequency sensitive and frequency variations independent. Henceforth the composite load characteristic in terms of speed load relationship is illustrated by equation (9).

$$\Delta P_e = \Delta P_l + D\Delta f \tag{9}$$

where D is frequency bias.

The first part in the above equation, i.e., (ΔP_l) represent the frequency independent component of load demand whilst, the second part, i.e., ($D\Delta_f$) represent the frequency dependency component of the load demand is expressed by equation (10).

$$\Delta P_g - \Delta P_l = \left(\frac{2H}{f_{sys}}s + D\right)\Delta f \tag{10}$$

As a result, the system frequency fluctuations to per unit system power variations is represented in the form of overall system transfer function (given by $G_{sys}(s)$) and illustrated by below equation (11).

$$G_{sys}(s) = \frac{\Delta f}{\Delta P_g - \Delta P_l} = \frac{1}{D + \frac{2Hs}{f_{sys}}} = \frac{K_{ps}}{1+sT_{ps}} \tag{11}$$

where K_{ps} (system gain) is given by $\frac{1}{D}$ and T_{ps} (system time constant) is given by $\frac{2Hs}{f_{sys}}$. Only when a synchronous machine is present in the microgrid, then the above relationship equation (7) is true.

4 Mathematical value method

The PID controls are based on feedback signals. The controller uses tuning of three constants (gains) of PID, i.e., P, I and D of these mathematical function, shown by equation (12). The controller helps in controlling many processes to a satisfactory amount.

$$U(s) = \left(K_p + K_d s + \frac{K_i}{s}\right) E(s) \tag{12}$$

where $U(s)$ is controller output, $E(s)$ is error signal, K_p is proportional gain coefficient, K_d is differential gain coefficient and K_I is the integral gain coefficient. The MATLAB model of the microgrid is shown by Figure 3.

Figure 2 PID controller scheme

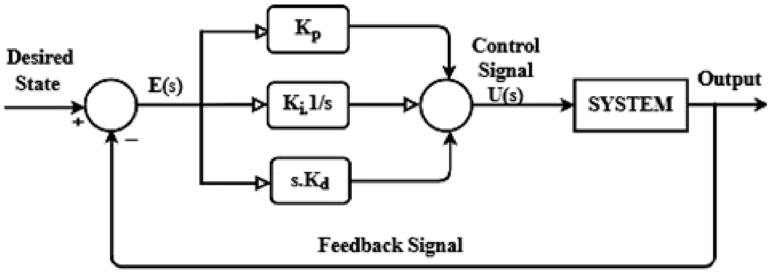
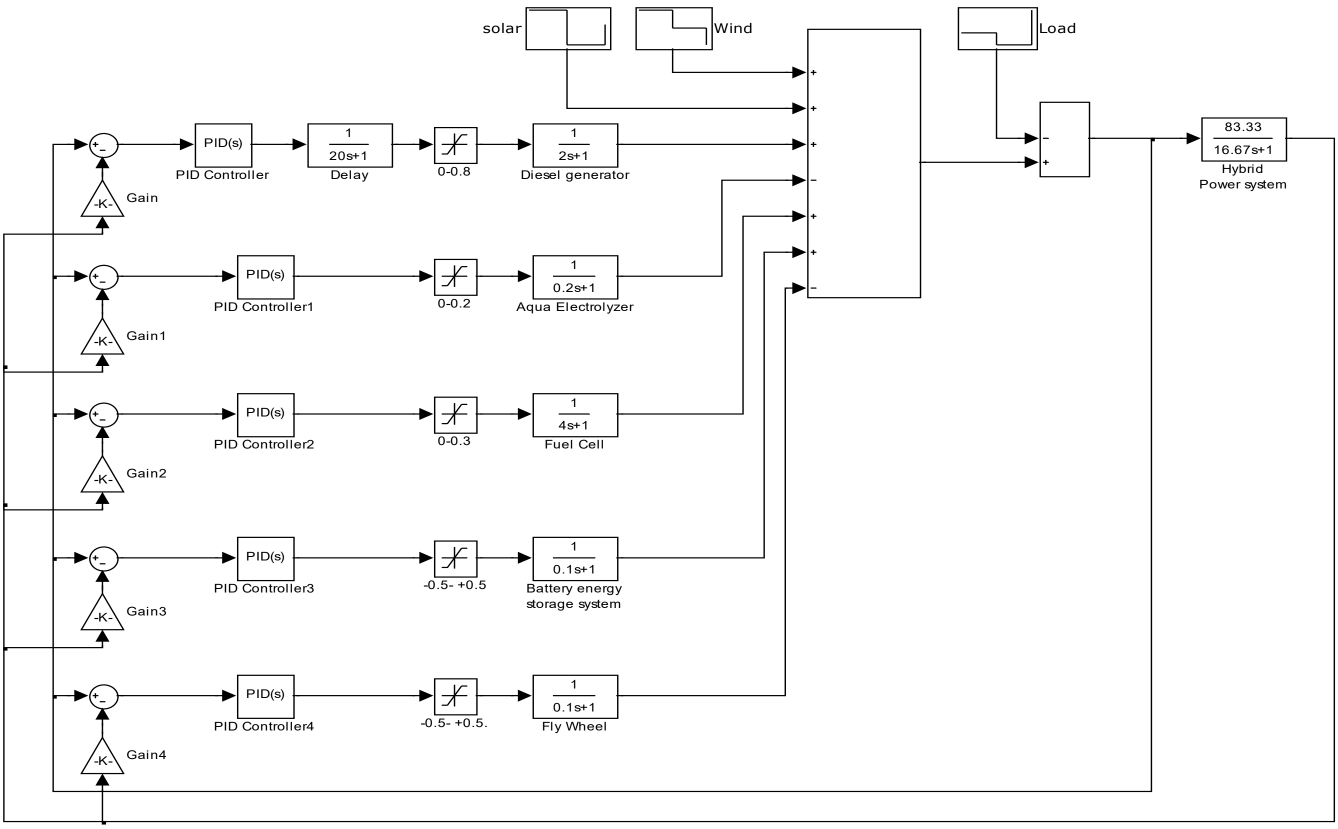


Figure 3 Illustration of microgrid in MATLAB



Also, it is a challenging task to perfectly tune the gains of a PID controller. The most simplest and fast technique is using the proportional method. The combination of gain along with evaluated error will get resulted in the form of proportionate factor. As a result, the proportional factor produces more output when the proportional gain or error is greater. When the proportional gain is fixed for a very high value, the controller will regularly outstrip the set point and results in oscillation in the output. The error term is compounded up over time using the integral component. As a consequence, even a little error causes the integral part to steadily increase. Unless the error is zero, the integral controller response will continue to rise over time and results in the zero steady state error. If the variable is fast growing, the derivative component forces the output to decline. The derivative action is directly proportional to the rate of change of the process variable. Because the derivative result is particularly sensitive to disturbances in the process signal (variable), hence the most efficient control systems generally exploit a fairly short derivative time. The loop output is insignificant when the proportional gain is set to a very low value. The Zeigler-Nichols approach of setting differential gain and the integral gain initially to zero and then raising proportional gain is employed. Such that the output starts to oscillate is a way to counteract this steady-state incorrectness.

Procedure adopted for obtaining the values of PID gains utilising the proposed MVM is as follows (illustrated for flywheel only)

Step 1 Multiply the transfer functions of the flywheel with the transfer function of hybrid power system, given by expression of

$$G_{dg} = \frac{1}{0.1s+1} * \frac{83.3}{16.67s+1}$$

This gives

$$G_{dg} = \frac{83.3}{1.667s^2 + 16.7s + 1}$$

Step2 From the value obtained in step 1, an expression for compensator is obtained using the SISO tool in MATLAB

$$C = 0.00221 * \left(\frac{1+9.2s}{s}\right)$$

where c is the proposed tuning function.

Step 3 The value obtained from compensator is compared with standard PID formulation given as below

$$K_p + \frac{K_i}{s} + K_d s = 0.00221 * \left(\frac{1+9.2s}{s}\right)$$

The values of K_p, K_i and K_d obtained for flywheel are

$$K_i = 0.00221$$
$$K_p = 0.02026$$
$$K_d = 0$$

In the same say the values of K_p, K_i and K_d are calculated for the diesel generator, FC, battery and aqua-electrolyser.

5 Result and discussion

Different performance parameters utilised in this study are settling time, steady state error and maximum overshoot. Settling time is termed as the time taken for the output to become stable. It is the time that is consumed for an output to reach and stay within a predetermined range (error) between 2% to 5% of set value. The discrepancy between actual and targeted output over a time range is known as steady state error. The largest peak value in the result calculated from the set values is known as maximum overshoot.

A fixed wind power output of 0.25 p.u., along with the solar fixed output power of 0.25 p.u. and satisfying the load requirements of 0.50 p.u., are considered. An increment of load power of 0.05 p.u. is considered in the system, after simulation duration of 8 seconds. Further to this next load values (step change) are 0.55 p.u., after time duration of 8 seconds. For this the wind as well as solar outputs is considered constant at the previous values. In this case of load variation after 8 seconds, microgrid components (i.e., governable sources) reflect their dynamic actions. Battery/ storage energy module along with fly wheel supplies/ exchanges the outputs. If one of them is supplying, the other one is getting charged and when the charged storage is supplying the first one is storing the energy.

To reduce supply demand inaccuracy and frequency deviation, the output powers of the microgrid elements are automatically adjusted to the appropriate values. In continuation to this, system FC supplies around 0.03 p.u. of power and diesel generator contribute 0.02 p.u. of power in the steady state conditions. Hence, the change of load conditions is met by these governable sources. In the same process the contribution of electrolyser (aqua) is simply in hydrogen generation for FC.

Settling time is reduced from 170 seconds (classical method) to 40 seconds in MVM. As compared to the classical PID method, low value of overshoot is obtained using the proposed MVM method. Also, the values of PID gains obtained through the classical and proposed MVM is given by Tables 1 and 2, respectively.

Also, the optimal regulations values are shown in the Table 3.

Table 1 PID gains tuning using classical method

Microgrid components	*Proportional gain (K_p)*	*Integral gain (K_i)*	*Differential gain (K_d)*
Diesel generator	0.0410	0.0634	2.9701
Fuel cell	0.1190	0.1971	2.9710
Fly wheel	0.3405	0.01701	0.009
Battery	0.3907	0.02001	0.009
Aqua-electrolyser	0.41	0.029	0.067

Table 2 PID gains tuning using proposed MVM method

Microgrid components	*Results of mathematical value based method*		
	Proportional gain (K_p)	*Integral gain (K_i)*	*Differential gain (K_d)*
Diesel generator	0.02523	0.01984	0.17049
Fuel cell	0.02025	0.00212	0.00010
Fly wheel	0.02026	0.00221	0
Battery	0.02026	0.00212	0
Aqua-electrolyser	0.01628	0.00189	0

Table 3 Microgrid components frequency regulations for the two methods

Microgrid components	*Regulation (frequency)*	
	Classical method	*MVM method*
Diesel generator	3.7	9.3
Fuel cell	1.8	4.5
Fly wheel	0.09	0.05
Battery	0.09	0.05
Aqua-electrolyser	0.1	0.01

The variations in the system frequency owing to the abrupt variation in demand (0.05 p.u.) and the management of the same using the two methods are illustrated through the Figures 4 and 5. The figures show the variations in the system frequency with respect to time. As, the load demand changes to 0.55 p.u., change in system frequency is shown by the Figure 4. There is decline of approx. 0.005 Hz in the frequency at the instant of variation in load demand after simulation duration of 8 seconds. Subsequently, due the PID controller operation the system frequency returns to its normal value (50 Hz) after 170 seconds. Also, in the same case a second dip of frequency changes is observed at 50 seconds due to some PID gains mismatching.

As per the Figure 5, this frequency variations results clearly show that the steady state error in frequency is reduced to zero in 40 seconds utilising the proposed method as compared to the classical method (170 seconds). The maximum overshoot value of change in frequency using classical PID is 0.007 and the same utilising MVM is 0.0375. Also, the root locus and magnitude- phase plots for the different microgrid elements (sources) are illustrated by the Figures 6(a)–6(e).

Figure 4 Frequency variations using classical method (see online version for colours)

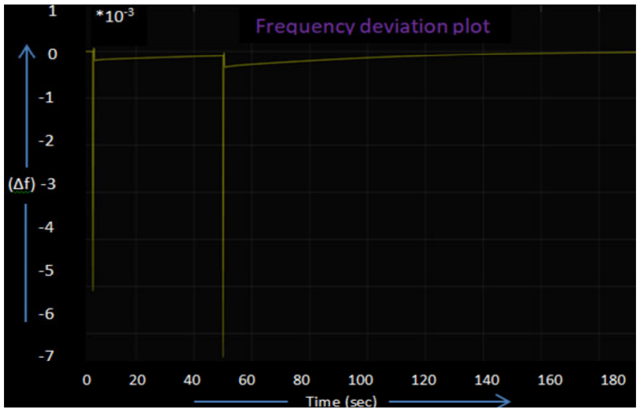


Figure 5 Frequency variations using proposed MVM method (see online version for colours)

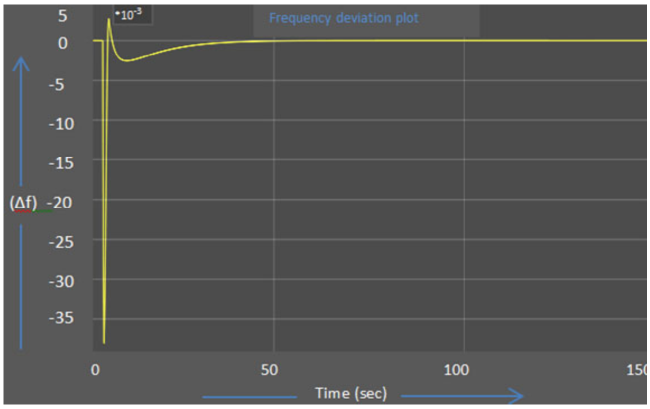
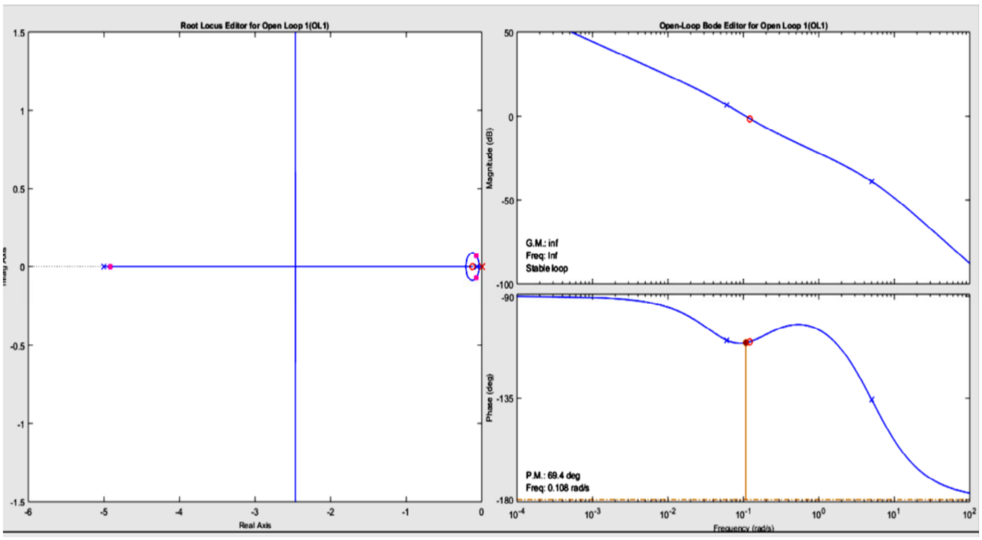
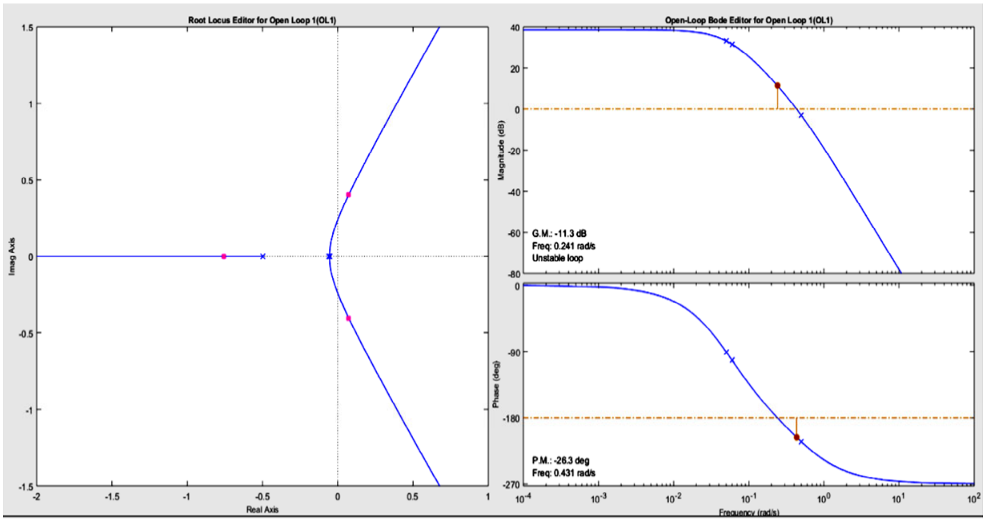


Figure 6(a) shows the root locus and magnitude-phase plots for diesel generator. As per the diagrams it is observed that the diesel generator system is working as a stable system and having a phase margin of 69.4 degree. Figure 6(b) shows the root locus and magnitude-phase plots for aqua electrolyser. Figure 6(c) shows the root locus and magnitude-phase plots for FC. From the figures it is observed that the phase margin is 73.9 degree, which is quite a good value of system stable performance. Figure 6(d) shows the root locus and magnitude-phase plots for battery system. Again a phase margin of 73.9 is achieved for the battery system. Also, as per the root locus plot, a good margin is there. It is also showing a steady performance as per the proposed MVM method. Figure 6(e) shows the root locus and magnitude-phase plots for the fly-wheel system. At crossover frequency value of 0.122 radians, the value of phase margin is around 73.9, which also shows a steady and faithful operation of the fly-wheel system utilising the suggested MVM algorithm.

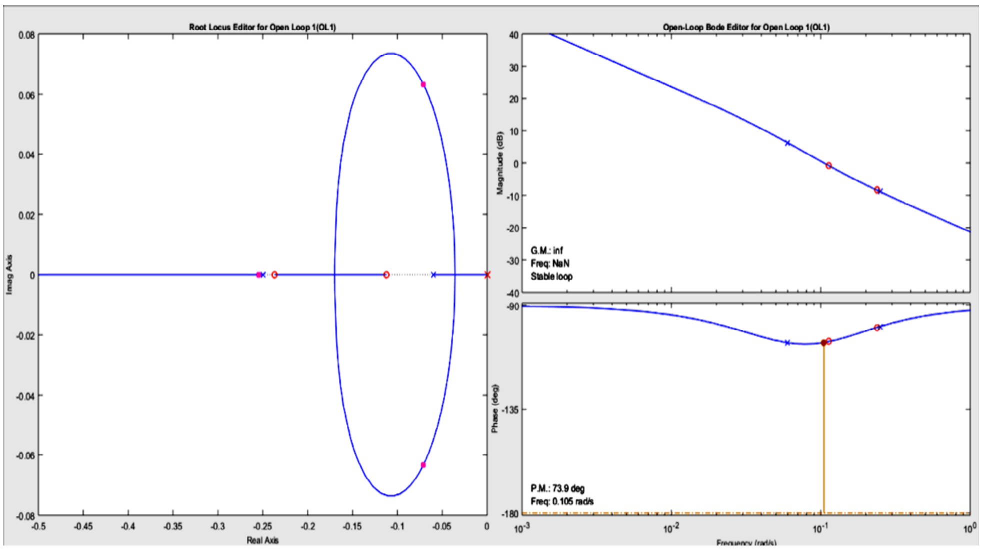
Figure 6 Root locus and magnitude-phase plots of using MVM of (a) diesel generator (b) aqua electrolyser (c) fuel cell and (d) battery (e) fly-wheel (see online version for colours)



(a)

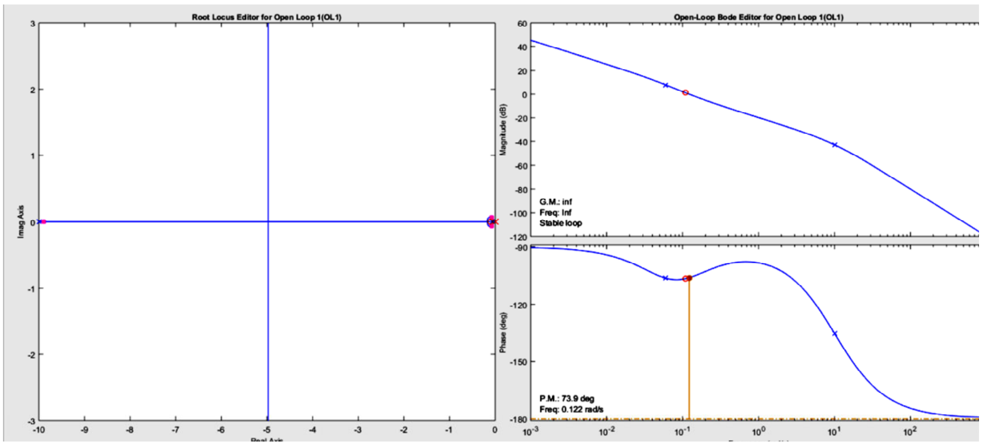


(b)

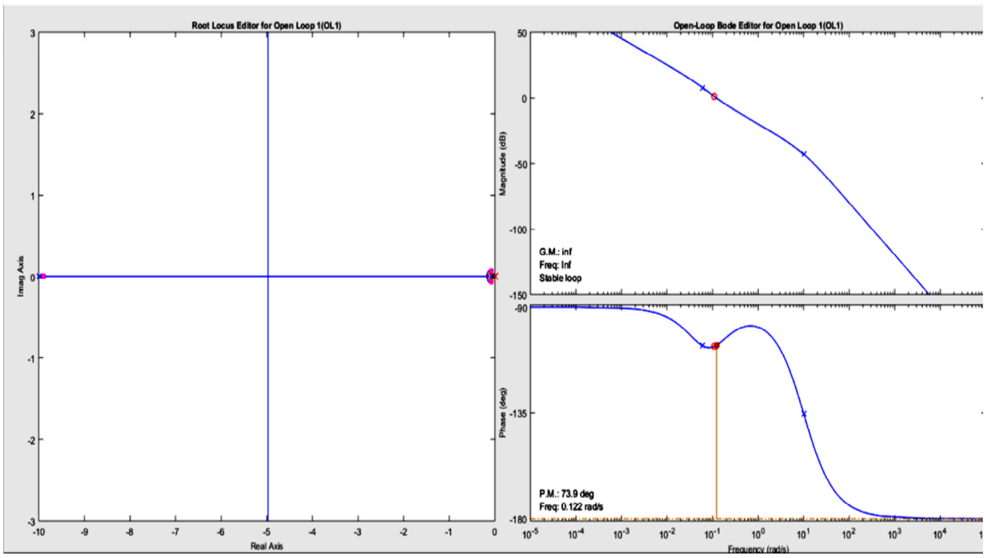


(c)

Figure 6 Root locus and magnitude-phase plots of using MVM of (a) diesel generator (b) aqua electrolyser (c) fuel cell and (d) battery (e) fly-wheel (continued) (see online version for colours)



(d)



(e)

6 Conclusions

The article presents optimal tuning of proportional, differential and integral gain coefficients for zero frequency variations in the steady state operations. Microgrid energy elements include diesel generator, wind turbine, solar PV, batteries, FCs, FW, and AE. The functional abnormalities regarding the change in system frequency occur in the system as a result of generation and load mismatches. In this proposed work, tuning of the PID controller utilising MVM is implemented. Also, using the MATLAB simulation, results of the proposed method is compared with classical PID based method. Results shows that the proposed mathematical method has better capability of tracking the fluctuations in load to have zero steady state error. The settling time and frequency deviation are also reduced to a large extent using this method. Settling time reduced from 170 seconds (classical PID tuning) to 40 seconds. The utility of the proposed work is due to the higher penetration of renewables in the microgrid now-a-days. Hence, the increased complexity of the system can be tackled efficiently regarding the frequency stabilisation and control operations. Also, the hybrid optimisation and artificial intelligence methods can also be implemented in future for frequency regulations in microgrid.

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