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Conference paper

Load Frequency PID Controller Design Based on Pole Placement Method of an Islanded Microgrid

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ABSTRACT

This research paper addresses the issue of frequency deviation in MG, which has emerged as a significant challenge in the context of power supply to loads, particularly in the context of unpredictable and random climate shifts. The system was evaluated under two distinct scenarios: one lacking any control methodologies, relying on conventional techniques to guarantee uninterrupted power supply to the load, and the other utilizing a PID controller calibrated through the Pole Placement method. The uncontrolled system exhibited considerable frequency fluctuations, exceeding ±1.5 Hz, which undermined its stability and rendered it unsuitable for supplying power to loads that require precise frequency levels. Conversely, the introduction of the controller resulted in substantial enhancements, reducing frequency distortion and facilitating more rapid stabilization, with the frequency remaining within ±0.5 Hz shortly after system startup. These outcomes underscore the viability of this approach in ensuring stable frequency regulation in MG environments.

1. INTRODUCTION

The global population increase, in conjunction with technological advancement, has resulted in a notable increase in electricity consumption. Nevertheless, this exponential growth in energy consumption, coupled with apprehensions about the finite nature of fossil fuel resources and the threat of climate change, has given rise to a burgeoning interest in alternative energy solutions. MG, which integrate RES and storage with conventional sources such as FC and DEG, are emerging as crucial solutions to meet this growing energy demand.

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The principal appeal of renewable energy-based MG is their capacity to reduce greenhouse gas emissions. In comparison to conventional electrical grids, MG present the possibility of reducing these emissions. In consequence of the energy crisis and environmental concerns, a considerable number of stakeholders, including those from the research and governmental sectors, have made investments in MG projects. Recently, the majority of research has been focused on the development of MG systems with a primary objective of enhancing energy stability and ensuring uninterrupted load supply. Furthermore, some electrical companies have also been implementing these studies.

MG are defined as localised electrical grids that are capable of operating independently or in conjunction with the main grid. They predominantly harness energy from RES, such as solar or wind, integrating storage systems, such as batteries, to ensure a consistent and sustainable power supply to local communities or facilities. In light of the paramount importance of control and optimisation in RES, MG are frequently deployed in rural or remote areas with limited access to the main grid, thereby ensuring a stable energy supply. Furthermore, they function as dependable backup power sources during instances of grid failure, with the objective of optimising the utilisation of RES, minimising energy costs and reducing carbon emissions.

Nevertheless, hybrid electrical systems, which combine different energy sources, require the implementation of robust control strategies to ensure equilibrium between electricity production and demand. The generation of RES is inherently stochastic and intermittent, rendering them susceptible to fluctuations in weather patterns. This can potentially give rise to imbalances between supply and demand. The utilisation of storage devices, such as batteries and flywheels, provides an effective solution to enhance the performance and stability of MG. The objective is to attain equilibrium in the energy produced by RES, enhance the reliability of the power supply, and mitigate fluctuations in frequency.

The continued advancement of MG is contingent upon their resilience and their capacity to furnish a reliable and sustainable power supply. While wind, solar, fuel cell, and diesel generators represent the primary distributed generation resources in MG, supplemented by storage systems like batteries and flywheels, they encounter challenges associated with frequency fluctuations, which impact stability and reliability. Therefore, the objective of this study is to mitigate MG fluctuations through the implementation of a PID controller, a solution that has gained significant acceptance within the industry due to its simplicity, robustness, and reliability. Furthermore, the research introduces alternative methods for secondary frequency control loops, with the objective of alleviating frequency fluctuations.

The structure of the article is outlined as follows:

- The initial section offers the theoretical foundation of the proposed approach.
- Following that, the second segment illustrates a small signal model of the chosen configuration.
- The subsequent section delineates the steps entailed in designing the PID controller.
- The fourth segment encompasses the examination of the acquired results.
- Lastly, the conclusions are outlined

2. PROPOSED MICROGRID CONCEPT

Fig. 1 depicts the structural composition of the MG system, which integrates a variety of energy sources, including solar and wind power, in conjunction with diesel generators. The energy is transformed through the utilization of current converters (AC-DC), and the system incorporates storage units to guarantee uninterrupted power supply to the loads *(Regad et al. 2020)*.

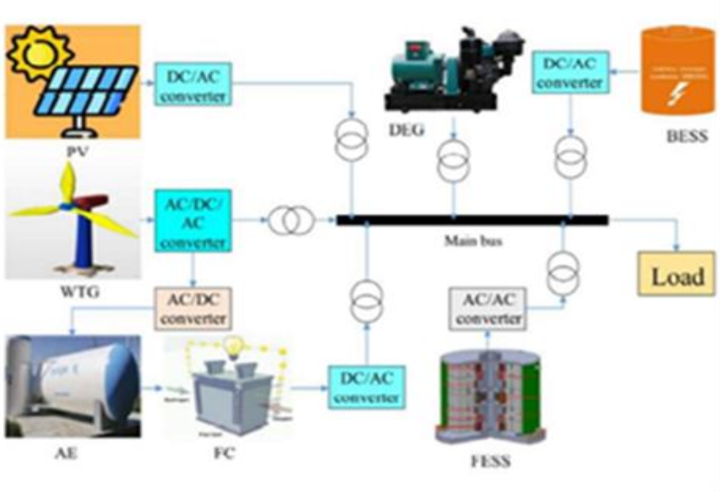

Fig1: The simplified schematic model of the proposed MG.

3. MODELING OF MG SYSTEM

In order to gain an understanding of the mathematical model of a MG, it is necessary to analyse the behaviour of RES and storage systems in terms of solar radiation, wind speed and the variation in load within the MG. The mathematical representation of each source is as follows:

3.1 Renewable energy systems model (RES)

The proposed MG incorporates a series of RES, including a configuration of solar panels and wind turbines. The solar panels are designed to convert sunlight into DC electricity. However, the output of these panels is dependent on a number of factors, including temperature and solar irradiance. The response of solar power is represented by a first-order function, as illustrated in the following diagram *(Regad et al. 2020; Thomas-Rodriguez & Banks, 2004; Moghayadniya & Razavi, 2019; Gupta et al. 2024)*:

$$G_{STPG}(s)=\frac{\Delta P_{STPG}}{\Delta P_{SOL}}=\frac{K_S.K_T}{(1+T_S.S).(1+T_T.S)} \tag{1}$$

The operation of wind turbines entails the conversion of kinetic energy into electrical energy. The performance of these devices is contingent upon the torque generated by the rotation of turbine blades, as well as the design of the blades themselves. This is represented mathematically as follows *(Moghayadniya & Razavi, 2019; Gupta et al. 2024)*:

$$G_{WTG}(s)=\frac{\Delta P_{WTG}}{\Delta P_W}=\frac{K_{WTG}}{1+T_{WTG}.s} \tag{2}$$

3.2 Diesel generator modelling

DEG are a non-renewable and polluting energy source, but their addition to the MG is essential to ensure the continuity of power supply when the load increases, especially during a shortage from all other sources. The diesel generator consists of a diesel engine and an electric generator, and these engines require speed control and voltage regulation of the generator. They are represented by a first-order transfer function as follows *(Regad et al. 2020; Thomas-Rodriguez & Banks, 2004; Moghayadniya & Razavi, 2019; Gupta et al. 2024)*:

$$G_{DED}(s) = \frac{\Delta P_{DEG}}{\Delta u} = \frac{K_{DEG}}{1+T_{DEG}.s} \quad (3)$$

3.3 Models representing various storage systems

The storage systems proposed for the MG in this paper include FC, AE and UC. The aforementioned storage systems employ energy in instances of surplus energy derived from RES, and are represented by a first-order transfer function *(Regad et al. 2020; Thomas-Rodriguez & Banks, 2004; Moghayadniya & Razavi, 2019; Gupta et al. 2024)*:

$$G_{FC1,2}(s) = \frac{\Delta P_{FC1,2}}{\Delta P_{AE}} = \frac{K_{FC}}{1+T_{FC}.s} \quad (4)$$

$$G_{AE}(s) = \frac{K_{AE}}{1+T_{AE}.s} = \frac{\Delta P_{AE}}{\Delta P_{WTG}+\Delta P_{STPG}).(1-K_n)} \quad (5)$$

$$G_{UC}(s) = \frac{\Delta P_{UC}}{\Delta f} = \frac{K_{UC}}{1+T_{UC}.s} \quad (6)$$

3.4 Frequency deviation model

In order to maintain frequency deviation stability in a MG, it is essential to achieve a precise equilibrium between the consumption of electrical energy and the amount of electricity produced. Two distinct types of RES have been integrated, along with an array of storage batteries. These batteries serve to store surplus energy, which can then be drawn upon in the event of a deficiency in RES supply. In the event that both sources are unable to meet the required output, a DEG is activated. Accordingly, the control of frequency deviation, defined as the discrepancy between the actual frequency and the reference value, can be expressed by a first-order transfer function as follows *(Gupta et al. 2010)*:

$$G_{sys} = \frac{\Delta f}{\Delta P_e} = \frac{1}{D+M.s} \quad (7)$$

In this context, the inertia constant, M, and the equivalent damping constant, D, are of particular significance. This model encapsulates the fundamental components of the synchronous machine, and the associated parameters are presented in the following Table 1 *(Gupta et al. 2010; Regad et al. 2019).*

Table .1 Values of Parameters Used in the MG Frequency Model.

MG	Gain (K)	Time constant (T)
WTG	K_{WTG} =1	T_{WTG} = 1.5
PV	K_{SPV} = 1	T_{pv} = 1.8
FC	K_{FC} =0.01	T_{FC} = 1
DEG	K_{DEG} = - 0.003	T_{DEG} = 2
BESS	K_{BESS} = - 0.01	T_{BESS} = 0.1
AE	K_{AE} = 0.002 K_n = 0.6	T_{AE} = 0.5
FESS	K_{FESS} = -0.01	T_{FESS} = 0.1

The small-signal model illustrated in Figure 4 is used to analyse the frequency stability of the SM as a function of weather conditions and parametric variations *(Regad et al. 2019; Pan et al. 2012):*

$$PP_e = P_{PV} + P_{FC} + P_{DEG} + P_{FESS} + P_{UC} \quad (8)$$

$$\Delta P_e = P_{PV} + P_{FC} + P_{DEG} + P_{BESS} + P_{UC} \tag{9}$$

$$\Delta f = \frac{1}{D+MS}(P_{PV} + P_{FC} + P_{DEG} + P_{BESS} + P_{UC}) \tag{10}$$

4. PID CONTROLLER STRUCTURE

The role of the controller in a closed-loop system is to ensure that the system's response exhibits appropriate dynamic and stable characteristics. The controller can be evaluated based on the following criteria *(Helaimi et al. 2023)*:

- ✓ Ensuring the maintenance of the controlled variable at its setpoint.
- ✓ Guaranteeing the asymptotic stability of the closed-loop system and satisfactory performance over a wide range of frequencies.
- ✓ Minimizing the impact of disturbances on the system.
- ✓ Ensuring fast and smooth responses to setpoint variations

It is crucial to avoid excessive control action, meaning that the control variable u (t) is not overly accentuate

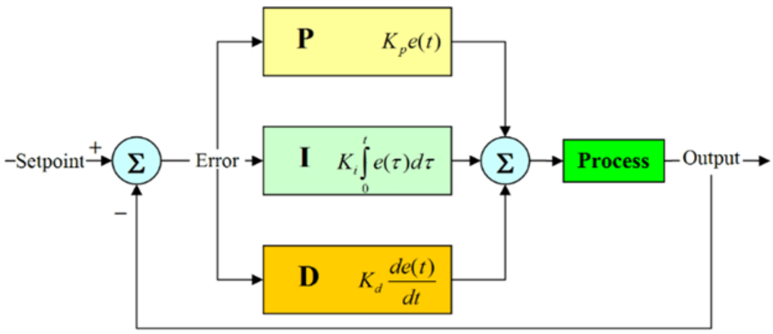

Fig. 2 PID controller models.

The control law is formulated as follows:

$$C(S) = K_p e(S) + K_i \frac{e(S)}{p} + k_d . p . e(S) \tag{11}$$

5. POLE PLACEMENT METHODS

Pole placement, also referred to as zero placement, represents a technique employed in the domain of control system design, whereby the desired response of the system is specified. The poles are defined as the eigenvalues of the system, and it is their value that determines the dynamic behavior of the system. Pole placement can be performed using a variety of techniques, including mathematical analysis, graphical methods, numerical optimization, and advanced control design techniques *(Thomas-Rodriguez & Banks, 2004; Ray et al. 2012)*.

This method was used graphically with the help of the "Matlab" environment.

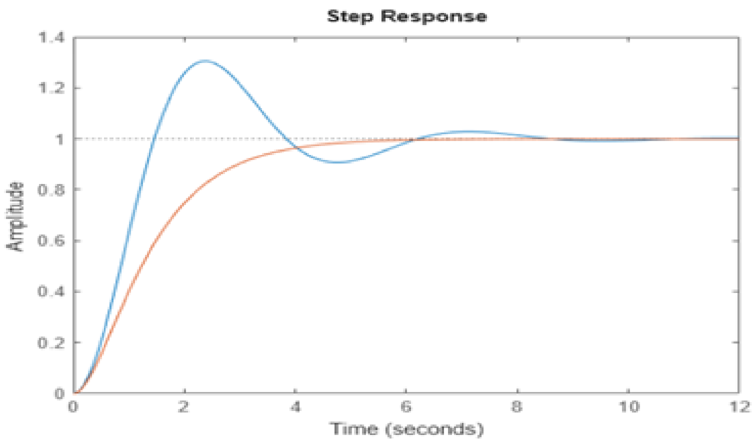

Fig. 3. Methods pole placement method graphically using the 'Matlab".

6. SIMULATION RESULTS AND DISCUSSION

The proposed configuration of the MG is simulated under nominal conditions for 120 seconds using the Matlab/Simulink-2023 environment

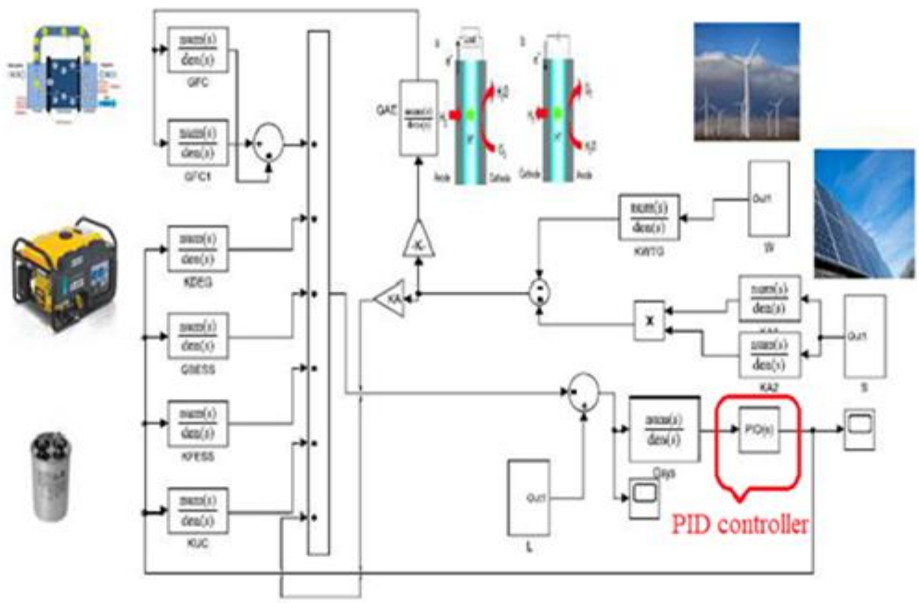

Fig. 4. The small signal model of the proposed MG

Fig. 5 represents the power outputs in a microgrid system from different sources. The colored curves show the changes in power output over time. The red curve illustrates the changes in the power load, while the yellow and green curves represent the power generated from PV panels and WTG, respectively.

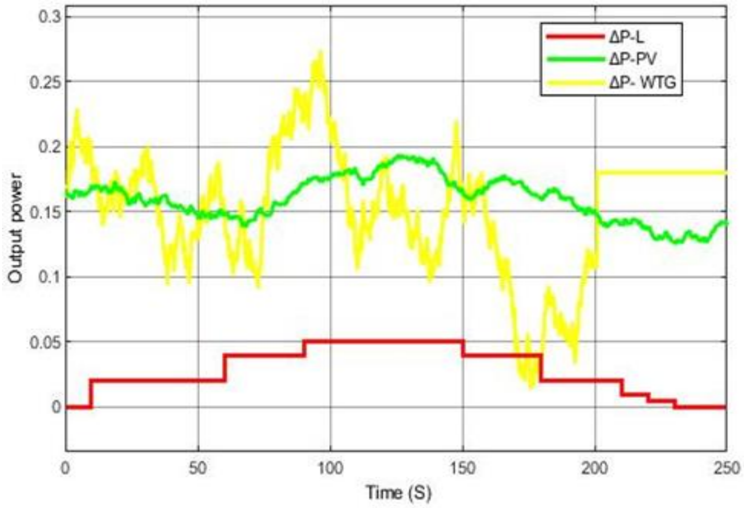

Fig. 5. Power Output Dynamics in a MG from Various Energy Sources

A PID controller is implemented to mitigate frequency resulting from the integration of RES like PV. The simulation results are presented in Table 2.

Table 2. Frequency deviation

PID	Kp	Ki	Kd
pole placement	4.934	2.429	2.501

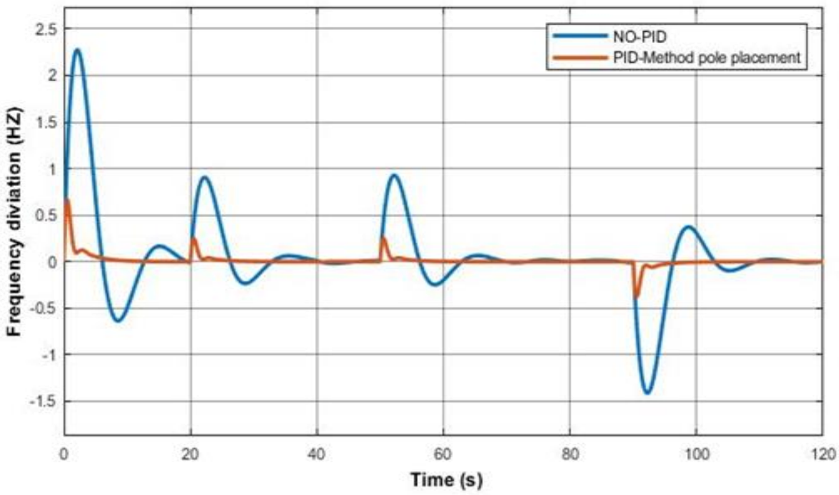

Fig. 6 The difference between the Prior to Enhancement and the pole placement method

Fig. 6 illustrates a comparison between two frequency deviation control systems. The accompanying analysis demonstrates the discrepancy between the two systems, with particular consideration of the acceptable deviation of ±0.5 Hz. The system without a PID controller is illustrated by the blue line. The system commences with a considerable deviation of up to 2.5 Hz at time point (0), which is markedly larger than the permissible value (0.5 Hz). During the initial time periods, the system exhibits pronounced oscillations, with deviations reaching 1.5 Hz and -1.5 Hz, indicative of a clear instability. Even after 120s, the system continues to exhibit oscillatory behavior that exceeds the acceptable limit (0.5 Hz), indicating that the system is unable to achieve the desired performance.

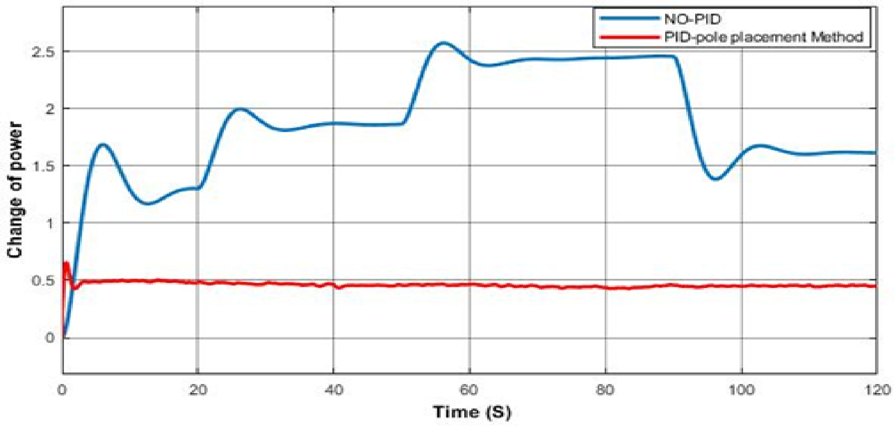

Fig. 7. Comparison of System Response Without PID and With PID Using Pole Placement Method for Power Variation.

Fig. 7 demonstrates the correlation between frequency deviation and power instability in both systems with clarity. Given the relationship between power variation and frequency deviation, fluctuations in frequency directly result in fluctuations in power, thereby increasing the instability of the system. The system without PID (depicted by the blue line) demonstrates that elevated frequency deviation precipitates pronounced fluctuations in power variation, with fluctuations exceeding a 2.5-fold increase. As the frequency deviation increases, the oscillations become more pronounced and persist over time, indicating that the system is unable to achieve stability. The system with PID (red line) exhibits a near-constant response, with minimal power fluctuations. This illustrates the impact of PID control in reducing frequency deviation, thereby ensuring stable power and preventing significant fluctuations. In other words, a reduction in frequency deviation will result in an increase in power stability.

The graph demonstrates that frequency deviation in the system without PID is directly responsible for increased power instability. Conversely, the PID system helps achieve stability by reducing frequency deviation. The PID control demonstrates a more stable response from the outset, with the deviation starting at less than 0.5 Hz in the initial moments of operation. After approximately 20 seconds, the oscillations decrease significantly, remaining within the acceptable limits (±0.5 Hz). At 40 seconds, the oscillations become almost non-existent, and the frequency deviation remains well below 0.5 Hz, indicating that the system is stable and meets the performance requirements.

7. CONCLUSION

In this research paper, we controlled the frequency deviation, which has become a major obstacle due to unpredictable random climate changes. We operated the system in two scenarios: the first without any enhancements or controllers, and the second with the PID controller whose parameters were adjusted using Pole Placement Method. The results showed that the system without the PID controller suffered from significant frequency oscillations, exceeding ±1.5 Hz, making it unstable and unsuitable for supplying power to loads, especially for devices that require complete frequency stability and accuracy.

In contrast, the performance of the MG was much better, with a noticeable reduction in distortion levels and faster settling time. The frequency stabilized within the acceptable limits of ±0.5 Hz shortly after startup, making this proposed approach applicable for achieving stability in the MG. Based on the results and analyses reached in this research paper, it is possible to reliably improve frequency deviation using the PID controller with its parameters determined by Pole Placement Method.

NOMENCLATURE

AE	Aqua electrolyzer	FC	fuel cells
BESS	Battery energy storage systems	UC	Ultra Capacitors
RES	Renewable Energy Sources	MG	Microgrid
DC	Direct Current	PV	photovoltaic
DEG	Diesel Engine Generator	WTG	Wind turbine generators

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