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Load Frequency Control of Hybrid Power System with PIDD Controller in Presence of Electric Vehicles

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Abstract: - This paper provides the load frequency control (LFC) of an isolated hybrid power system (IHPS) with proportional-integral-double derivative (PIDD) controller to reduce the deviations in frequency profile. The IHPS consists of conventional and renewable power generating units along with storage devices. The power imbalances caused by load perturbations and solar generation are managed by conventional generating units and storage devices. Additionally, a large number of electric vehicles are incorporated into the system to study their impact in LFC studies. The PIDD controller is used in secondary LFC loop to fulfil the goals of LFC. The magneto tactic bacteria optimizer is used to tune the controllers gains of the IHPS with the help of new cost function which tracks the peak changes in the frequency deviations. Furthermore, the performance of the PIDD controller is compared with classical controllers to extract the benefits of the PIDD controller in LFC studies of IHPS in different perspectives.

Keywords: Load frequency control, PIDD, Hybrid power system, EV.

I. INTRODUCTION *(HEADING 1)*

The participation of renewable energy resources and electric vehicles (EV) increases rapidly in electrical sector. This integration holds the potential to revolutionize the energy landscape by addressing environmental concerns, enhancing energy security, and promoting a more efficient and reliable power grid. However, the intermittent nature of renewables poses a challenge to the power grid's stability. This issue is addressed and solved by proper LFC mechanism. The LFC facilitate the efficient integration of renewable energy sources by optimizing their use in support with conventional generating units and ensuring grid stability [1]. The integration of renewable resources and EVs can be mutually beneficial to create a more sustainable, reliable, and efficient energy ecosystem. Several studies are already available in literature to understand the impact of the renewable energy sources and EVs on frequency control of IHPS and interconnected systems [2].

In classical IHPS, diesel generators are primary units to generate the electrical power to the users for the continuous power supply [3]. Along with diesel generator, solar power is also considered in the test system available in [3] and fractional order-PID controller is suggested to minimize the frequency disturbances of the system during the power mismatch conditions. The optimal selection of the controller tuning values are identified by using particle swarm optimization (PSO). The FO-PID controller produced improved results compared to the classical controllers according to the outputs provided in [3]. Furthermore, tuning strategies are replaced with other optimization algorithms to enhance the frequency profile of such IHPS during the load and generation disturbances. In [4], classical controllers are used to reduce the deviations in frequency of the hybrid power system consisting of both renewable and nonrenewable power generation components along with the storage units. The performance of the system is improved with the secondary control mechanism where the controller gains are evaluated using the quasi-oppositional harmony search algorithm (QOHSA) instead of PSO. Intelligent controllers are also suitable to meet the objectives of the load frequency control of the IHPS particularly in presence of the generation uncertainties. In [5], fuzzy logic controller is suggested with scaling factor and the output of the FLC is used as input of classical controllers to minimize the frequency differences. The scaling and controller parameters are extracted from the large solution space using the QOHSA. In [6], sliding mode control (SMC) concept is adopted along with disturbance observer to effectively handle the intermittent characteristics of the wind and solar of IHPS. Compared to the classical SMC approaches, this disturbance observer-based SMC produced better dynamic response during the wind and solar power variations.

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Model predictive control (MPC) [7] is applied to improve the frequency characteristics of the power system integrated with wind generation. In [7], interconnected hybrid power system is opted to check the performance assessment of the MPC scheme to reach the AGC objectives. The outcomes of the SMC and MPC schemes are superior compared to the classical control schemes. Furthermore, cascade control schemes are designed to improve the frequency profile of the various diverse electrical power systems with fast response. These advanced control schemes provide better control action compared to the classical controllers [8]. The tuning procedures of the cascade controllers is similar to classical controllers and heuristic algorithms are helped to identify the optimal solution sets of the parameter gains of the cascade controllers. In [9], cascade structure of the PD and PID controller is suggested to fulfil the goals of the load frequency control of the diverse power systems. The merits of the cascade controllers over classical controllers attracted the attention of researchers towards the implementation of the new cascade control schemes [9].

The combination of the cascade controllers is also investigated in frequency control studies and successfully achieved improved results over classical controllers. In earlier studies, different types of IHPS models are selected to study the frequency control aspects. Recently, large number of electric vehicles (EV) are incorporated into such systems and control challenges need to address to minimize the power imbalances. In [10], PI-PD control strategy is used to minimize the frequency deviations of the IHPS consisting of solar, wind, micro turbine along with sufficient amount of EVs. Salp Swarm Optimization (SSO) algorithm is used in [10] to identify the optimal gain parameters of the cascade controller with integral square error (ISE) as objective function. Later, these cascade models are incorporated with MPC and SMC to further enhance the performance of the various IHPS [11]. Furthermore, cascade FO controllers are also proposed by the researchers to meet the goals of the stability of the power system during the generation and demand uncertainties. For example, tilt cascade fractional order control scheme is used in frequency control loop of the HPS with EV to minimize the disturbances of the frequency profile available in [12]. Later, different structural changes of cascade FO controllers are suggested in recent works assisted with various population search-based algorithms to improve the performance metrices of the outputs [13]-[14]. These works also provide wide range of investigations in system perspectives including storage units, EV etc. Instead of IHPS with conventional fossil fuel-based sources, total renewable energy-based micro grids are suggested in [15]-[16] to reduce the emissions. The aforementioned classical, intelligent and cascade controller schemes are investigated in these renewable micro grids and the optimal parameter gains of the controllers are examined by using the population search based algorithms. The process of the identification of new controller gains is achieved with the optimization algorithm assisted with performance measures as cost and fitness functions [6]-[7].

In this paper, a simple PIDD control scheme is suggested for an isolated hybrid power system to improve the frequency profile during the load and generation uncertainties. The optimal tuning values of the PIDD controller are achieved with the magneto tactic bacteria optimization (MBO) algorithm and comparisons are provided with the classical controllers to identify the merits of the work. These tuning values are extracted from MBO generated solution set using the new integral square error cost function. Additionally, EVs are incorporated in the system to check their contributions to minimize the frequency deviations of the system during the load perturbations. All the simulations are performed in MATLAB-SIMULINK software. The rest of the paper organizes as follows: Section 2 provides the details of the classical and PIDD control strategies, Section 3 provides the test system information, Section 4 provides the controller gains, Section 5 provides the simulation results, Section 6 provides the comparisons and finally conclusions are available in Section 7.

II. Classical and PIDD Controller

Most of the literature studies suggested cascade, advanced and intelligent controllers to reduce the frequency deviations of the power system. Apart from the response-based merits, the challenges are alive with the advanced control mechanisms. In terms of the optimal tuning procedure, the number of decision variables of the optimal parameter tuning problem are large compared to the classical controllers. Therefore, this paper suggested PIDD controller instead of classical controller to enhance the performance of the IHPS during the generation and demand uncertainties. With PIDD controller, the number of tuning parameter gains are less compared to available advanced cascade controllers. The block diagrams of the PID and PIDD controllers are provided in Figure 1.a & 1.b and control outputs of the PID and PIDD controllers are represented in equation (1.a) and equation (1.b) respectively.

$$u_{pid}(s) = \left(k_p + \frac{k_i}{s} + k_d s\right).r(s) \quad (1.a)$$

$$u_{pidd}(s) = \left(k_p + \frac{k_i}{s} + \frac{k_{d_1}s}{T_{f1}s+1} + \frac{k_{d_2}s}{T_{f2}s+1}\right).r(s) \quad (1.b)$$

In case of the PIDD controller, the number of the decision variables of the tuning problem are 4 without filter components and 3 for PID controller. The limits of these gains are pre-defined and population search-based algorithms are helpful to identify the best solutions of the controller gains with the help of the performance measures such as integral square error (ISE), integral absolute error (IAE), integral time square error (ITSE) and integral time absolute error (ITAE) etc. The application of the classical and PIDD controllers along with the tuning procedure is provided in section 3.

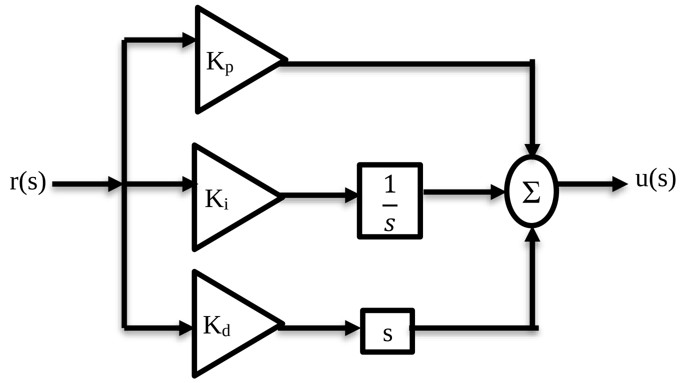

Fig. 1.a Classical PID controller block diagram

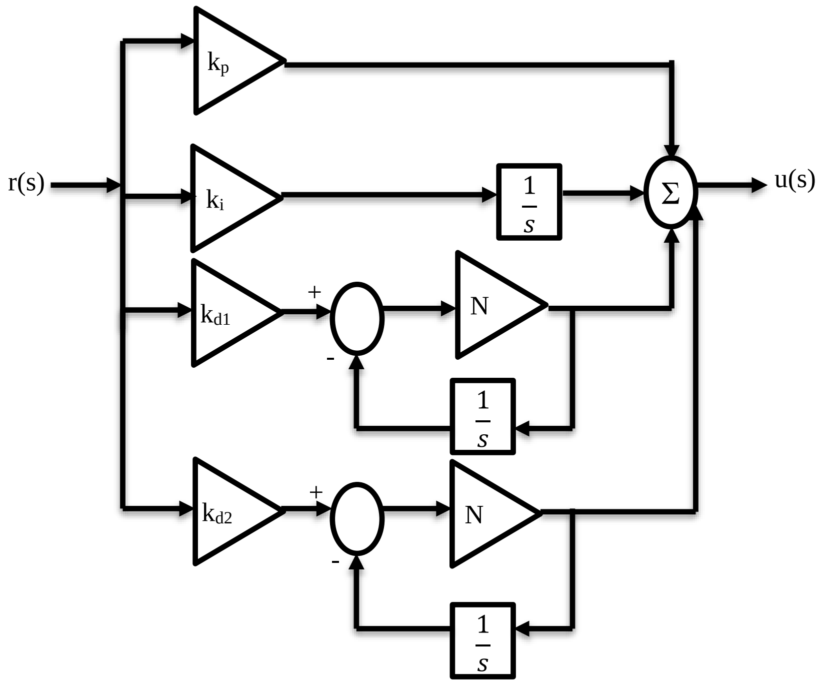

Fig. 1.b PIDD controller block diagram

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III. Test System Information

To investigate the impact of both renewable energy resources and EVs, an IHPS is considered and its block diagram is presented in Figure 2. The controller C(s) provides simultaneous control signal for both conventional generating unit and EVs. The load and power input of PV are responsible for the power mismatches and these unbalances are minimized by the conventional generating unit, storage components and EVs. The model is implemented in MATLAB-SIMULINK and all the parameters of the model are provided in appendix 1. To minimize the frequency deviations of the system, the optimal coefficients of the controllers need to be examined with the help of the cost functions by tracing the changes in the frequency information. In this paper, peak-based integral square error (PISE) concept is used as fitness function of the optimizer. The PISE is evaluated on change in frequency data using the expression (2).

$$PISE = ISE + \sum_{i=1}^{K} \Delta f(i)^2 \quad (2)$$

In equation (2), ISE is the regular integral square error estimated using all the samples of the change in frequency signal. Identification of the controller gains to minimize the PISE is an optimization problem and MBO is used in this work to solve this controller gains tuning problem. Similar to other search-based optimization techniques, MBO also examine large solutions with the steps known as initialization, power spectrum calculation, bacteria rotation, and replacement. The search process is initialized with random pattern and this is the common feature of the majority of the population search-based algorithms. Therefore, MBO also used randomly generated solutions for the initial search with the help of the Equation (3).

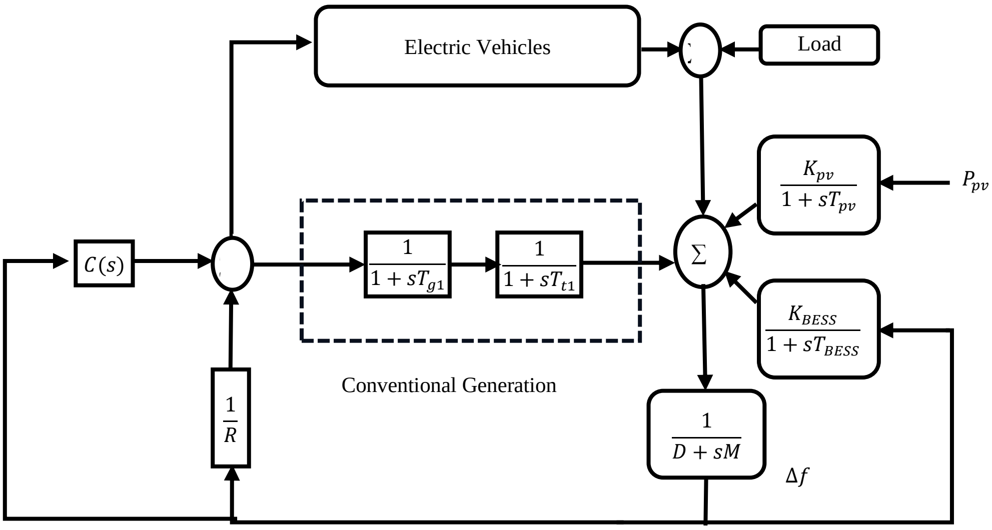

Fig. 2 Architecture of the test system to study the frequency control in presence of EV

$$x_{i,j} = x_{min,j} + rand * (x_{max,j} - x_{min,j}) \quad (3)$$

In Equation (3), x (max, j) is the maximum value and x (min, j) is the minimum value of the x multiplied by the random number to keep the position of the particle inside the solution region. The difference of two selected solutions is used to generate the new solution according to the Equation (4).

$$L_{r1,r2}^{t} = x_{r1,j}^{t} - x_{r2,j}^{t}$$
(4)

In Equation (4), t is iteration number. Further, the power spectrum of a single bacteria S_i is identified with Equation (5) to update the solution for the next iteration using Equation (6)

$$S_{i,j}^{t} = \frac{2\tau_{p,q}^{t}}{1+(2\pi f\tau_{i,j}^{t})^2}) \quad (5)$$

$$x_{i,q}^{t+1} = x_{p,q}^{t} + S_{i,j}^{t} \quad (6)$$

After rotation, the bacteria swim as follows:

$$x_i^{t+1} = x_{best}^{t} + rand * (x_{best} - x_i^{t}), if\ rand > 0.5\ x_i^{t} + rand * (x_{best} - x_i^{t}),\ otherwise\ \} \quad (7)$$

For more convergent outputs, few worst solutions are replaced by using Equation (8)

$$x_i^{t+1} = S_{p,q}^{t} * ((rand(1,n) - 1) * rand(1,n)) \quad (8)$$

The MBO's update technique involves repeating power spectrum calculation, bacteria rotation, and replacement computing procedures to develop new solutions until the maximum number of iterations is reached. In MBO, each bacterium particle represents a controller parameter gain, and optimal gains are obtained at the end of the MBO iterations.

IV. Controller Gains

To find the optimal controller gains of the IHPS using the MBO algorithm, PISE is used as cost function instead of regular performance metrices such as ISE, ITSE, IAE and ITAE. The tuning mechanism, control and common parameters of the MBO algorithm are same for both classical and PIDD controllers. The final optimal values of the controllers are reported in Table 1.

Table 1. IHPS controllers gains by MBO algorithm.

Controller	Parameter Gains			
	k_p	k_i	k_{d1}	k_{d2}
Integral	**---**	**0.83639**	**---**	**---**
PI	**0.99519**	**0.9641**	**---**	**---**
PID	**0.92815**	**0.97231**	**0.32452**	**---**
PIDD	**0.97515**	**0.9924**	**0.23343**	**0.090318**

V. Simulation Results

The performance of the PIDD controller is validated on the test system under different conditions of the load and generation changes and comparisons are provided with the classical controllers. Later, the presence of storage units, EV and other factors are discussed to study their impact on the frequency control of the test system. Furthermore, the merits of the performance measure and tuning procedures are also discussed and comparisons are showcased.

A. Load changes at constant operating conditions of the PV

The electrical demand variation is balanced by the electrical generation by triggering the action of the frequency control via primary and secondary control schemes. To study the variation of frequency under such load changes, a simple step disturbance of 5% is created in test system and the frequency variations are presented in Figure 2. In Figure 2, the response of the PIDD controller is compared with the classical controllers to show the improvements in the frequency profile of the test system in presence of electrical vehicles and storage units. Furthermore, the power sharing of different components of the test system is presented in Figure 3 for the case study of the PIDD controller. As the investigated case opted constant PV power output, the change in PV power shows 0 after the load disturbance. However, the power balanced condition is achieved with conventional unit, EV and storage devices.

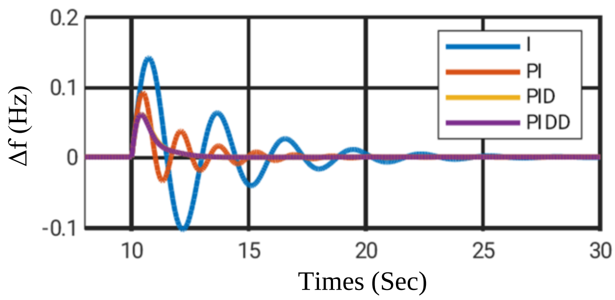

Fig. 3. Frequency deviations during load perturbations

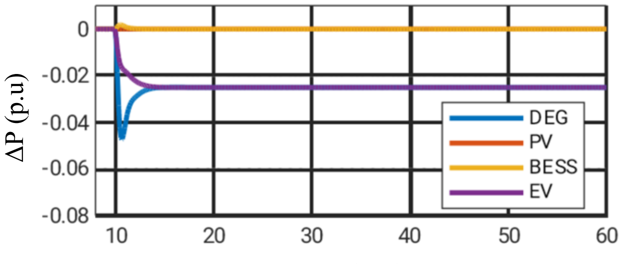

Fig. 4. Power deviations during load perturbations

B. PV output perturbations

The irradiation of the PV system is also responsible for the power mismatches in the given test system and the impact of the variations of the PV output is investigated on both classical and PIDD controllers. For simulations, the PV input is modelled with the step functions as shown in Figure 4. The variations are initiated at 0 and 40 sec in the PV side by keeping the system as load perturbations free. Under the PV power uncertainties, the frequency profile response of the test system is presented in Figure 5 for classical and PIDD controllers. The improvement in frequency profile is identified with PIDD controller compared to other classical controllers which is provided in Figure 5 since the power deviations are quickly balanced by the conventional, EV and storage units of the test system due to the control action of the PIDD scheme. The information of the power shared by each unit is presented in Figure 6 for the PIDD controller case.

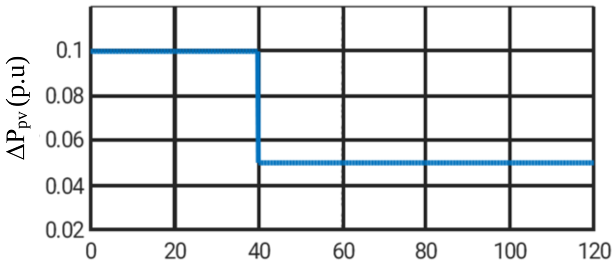

Fig. 5. PV system input pattern

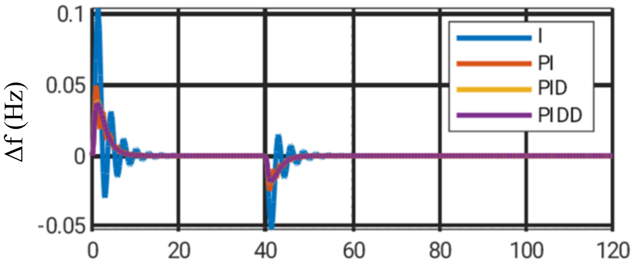

Fig. 6. Frequency deviations of the test system during PV perturbations

C. Random load and generation changes

It is essential to consider the stochastic variations of the generation and demand of the electrical power system to study the frequency control. As the frequency deviations are triggered with these power imbalances, the control mechanisms are designed to handle the continuous variations of both generation and load changes. To simulate the system, the load and generation input change patterns are modelled with step functions in MATLAB and provided in Figure 7.

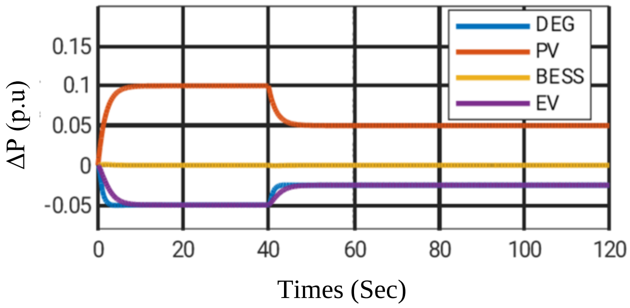

Fig. 7. Power deviations of the test system during PV perturbations

Under such load and generation changes, the frequency deviations of the test system are presented in Figure 8 in presence of I, PI, PID and PIDD controllers. The power sharing of all components of the test system in presence of PIDD controller are presented in Figure 9. In all scenarios, the power oscillations are minimized with the PIDD controller during the load perturbations and generation uncertainties.

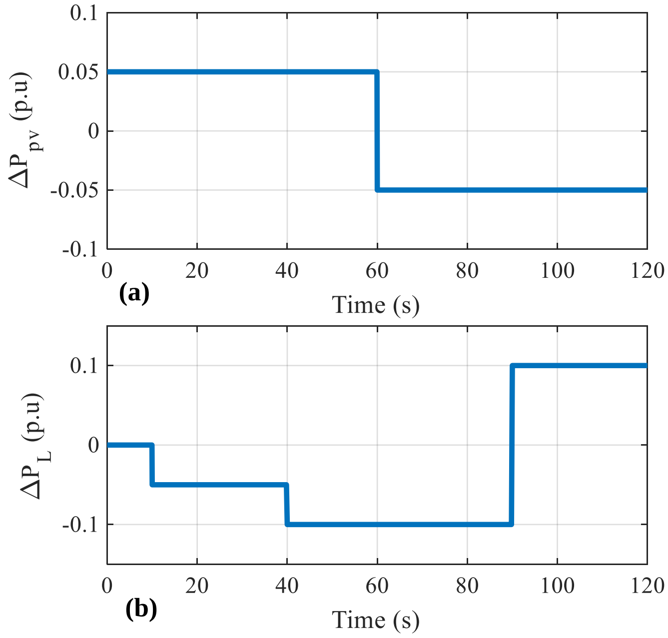

Fig. 8. Represents the change in power (a). PV generation, (b). Random load pattern

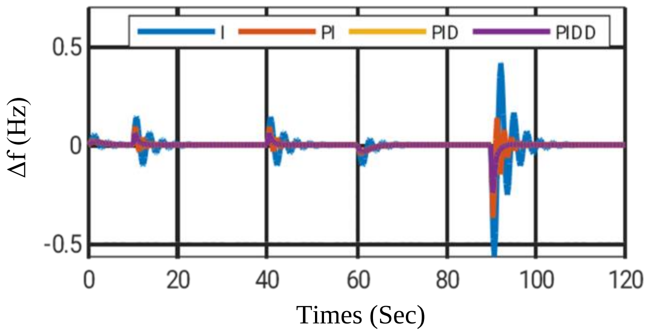

Fig. 9. Frequency deviations during load and generation changes

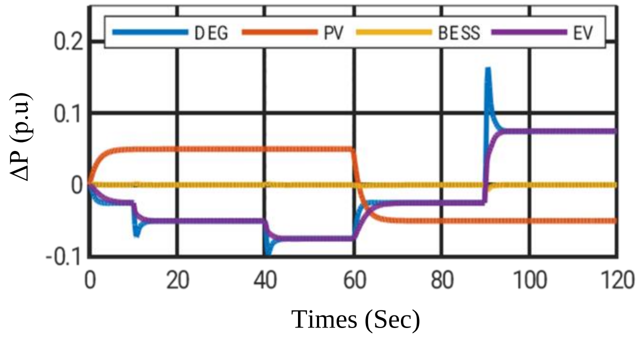

Fig. 10. Power deviations during load and generation changes

D. Impact of EV

The test system is integrated with the sufficient amount of EV and controlled by the secondary control action of the generation. The impact of the EV on the system frequency profile is validated at random load perturbations and the results are presented in Figure 10. The presence of EV reduces the peak overshoots of the frequency deviations of the system during the load perturbations compared to the system without EV.

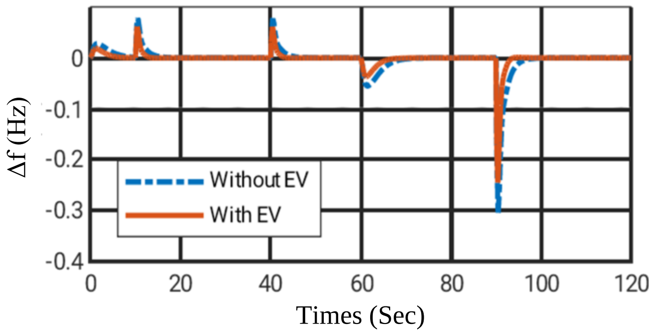

Fig. 11. Frequency deviations with and without EV during load uncertainties.

E. Impact of storage units

The frequency profile of the test system with and without storage units is presented in Figure 11 during the simple load perturbations. The enhancement in the frequency profile is observed in Figure 11 due to the storage units which reduces the peak deviations of the signal. Furthermore, the stability of the system enhances with the storage units since the additional generation of the renewable units is stored and utilized to maintain the power balance condition of the system.

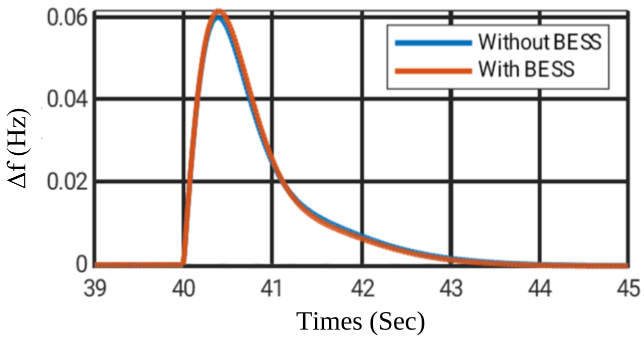

Fig. 12. Frequency deviations with and without BESS during load uncertainties.

F. Effect of the different loadings

The irradiance of the PV plant, the demand of the power system are volatile in nature and different patterns of those variations are assessed on the test system to check the performance of the test system. In Figure 13, the frequency deviations of the test system are reported with classical and PIDD controllers during the random load disturbances in presence of the stochastic load noise. The improvements are observed with PIDD controller compared to the classical controllers in presence of the stochastic load variations. Furthermore, the sinusoidal load variation is simulated and inserted into the system and the response is presented in Figure 14. In Figure 14, the frequency deviations of the test system during the continuous time varying disturbances are provided with classical and PIDD controllers. The frequency changes are minimum in case of PIDD controller compared to the classical controller at same loading condition of the test system.

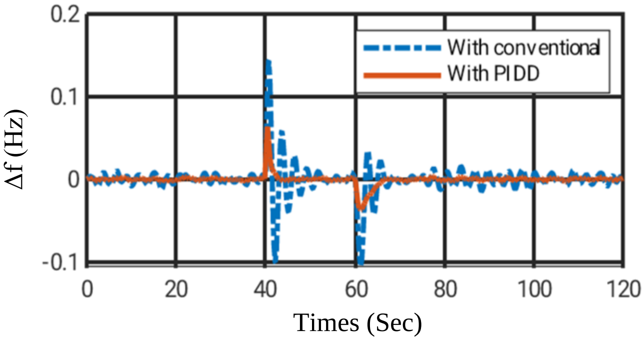

Fig. 13. Frequency deviations during noisy load condition.

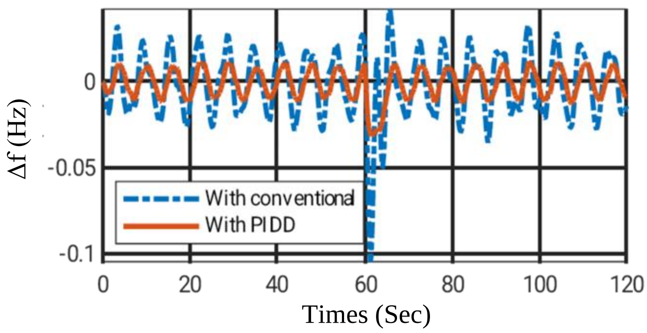

Fig. 14. Frequency deviations during sinusoidal load condition.

VI. Comparisons

The PIDD controller provided enhanced frequency profile for the test system during the load and generation perturbations compared to the classical controllers. The case studies investigated in the results section shows these improvements. Furthermore, the PISE values are provided in Figure 15 shows the simulation evidence of the improvement in the cost function which is directly interconnected with the frequency disturbance record. The PISE value of the PIDD controller relatively small compared to classical controllers and therefore superior response is guaranteed.

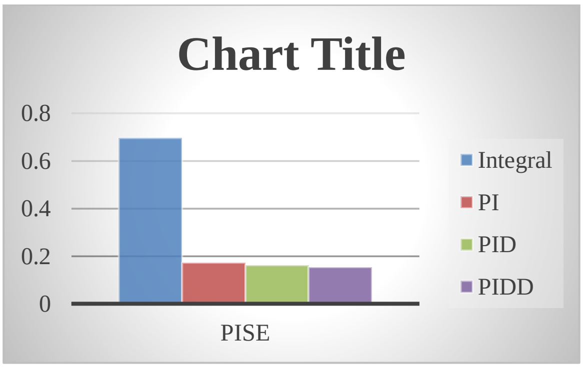

Fig. 15. PISE values for various controllers.

VII. Conclusion

This paper suggested PIDD controller to minimize the frequency disturbances of the IHPS during the load and generation uncertainties without increasing the complexity of the controller structure, tuning procedure and the number of the decision variables of the optimization process. The new peak-based ISE measure is used as cost function to identify the optimal gains of the controller with the help of MBO algorithm. With the PISE-assisted

PIDD controller, improved frequency profile is achieved during power mismatches. Furthermore, the impact of EV and BESS on system frequency control was studied in presence of PIDD controller to validate its suitability.

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