Application of PHEVs Influence on Frequency Regulation of a Two Area Power System

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***Abstract*—The stability of the power system has become an important factor in South Africa due to the lack of available capacity required to maintain system stability. With the integration of Plug-in-Hybrid Electric Vehicles (PHEVs), the power system can be injected with an additional load that is sourced from a PHEV aggregator. The inclusion of a Load Frequency Controller (LFC) further assists the power system to gain stability enhancement. This paper will showcase the modelling and analysis of a Two Area Power System, each area with a PHEV aggregator and interconnected with a tie-line. Various control structures are utilized and analysed to determine the best possible results to obtain swift steady-state conditions. In addition, a performance criterion is used to determine the unnecessary sustained oscillations in the system. The product of the study is then displayed using organized data figures and result values.**

Keywords – Load Frequency Control (LFC), Fractional Order PID (FOPID), Plug-in Hybrid Electric Vehicle (PHEV), Two Area System

I. INTRODUCTION

As the world moves towards a cleaner environment by reducing carbon emissions, clean energy is becoming more desirable with the usage of Renewable Energy Systems (RES), hydropower and electric vehicles. With the major demand for energy in developing countries, alternate solutions are required to help reduce the current system instability while moving towards a clean way of producing electricity. The maintenance of keeping South Africa's 50Hz frequency regulation to the end-user is of utmost importance. Therefore, the requirement of LFC becomes imperative for the regulation of frequency.

The depletion of fossil fuels is becoming of high importance and daily increases in pollutant emissions, which is influencing global countries to employ renewable energy solutions. Directives from world bodies have obliged members to achieve 20% shares of energy from renewable energy sources in the communities. Germany attempts to become fossil fuel-free by the 2030 horizon, similarly to Europe at the 2050 horizon. PHEV hits two birds with one stone by compensating for clean energy and having zero carbon emissions. This plays a major role in the production of electricity and transportation costs [1]. The inclusion of the PHEV system needs to be utilised in a way to achieve the benefits of frequency stability. The PHEVs can be utilised as a quick power source to support the frequency control loops for frequency response improvement of power systems and RES. PHEVs form an excellent option due to their fast-acting capability, distributed availability and slow discharge rate while in idle condition. To incorporate this, charging stations for electric vehicles are a very critical component for allowing the smooth functioning of an electric vehicle's state of charge patterns [2-7].

The services of ancillary using PHEV similar to battery systems are capable of frequency support in the power grid. PHEVs owner can be remunerated for the auxiliary services they can provide for the power grid. There have been shown in [8] to have effective balancing properties for load and demand with fast response time. However, there are uncertainties when bulk EVs are charging on the grid. Power management and SOC-based coordination are crucial for power at peak time and line loading. They are known to assist with shaving off additional power at peak load conditions which in return increases efficiency while reducing cost [9].

While incorporating PHEVs, secondary control action plays a pivotal role in achieving high-speed restoration of the system frequency to steady-state conditions. The power generation areas are capable of exchanging power with the help of an AC tie-line resulting in an interconnected network that is highly reliable and cost-effective which are commonly referred to as control areas. It is however recommended that each generation area meet its demand for power while controlling the power exchange between tie-lines [10]. The LFC regulators are implemented on the power system to manage the frequency deviations. Their role is to link the electrically generated power with the present load to minimize or set the Area Control Error (ACE) to zero value. LFC schemes based on optimal control provide the optimum performance by minimizing the certain performance index. Extensive research has been made on the LFC and many renewable-based power generation technologies capable to improve the LFC performance such as wind power and photovoltaic for the LFC of an electrical energy system [11-12].

Recently, the concepts of reduced-order modelling and internal model control have been showcased. However, there are limitations in certain environments that require improvement. An LFC application is FOPID which offers more freedom, flexibility and dynamic responses than traditional PI and PID controllers in terms of non-linearities and uncertainties which in return enhances the stability of the power system. FOPID is shown in [13] to provide positive effects with renewable energy systems that contribute to highly non-linear systems. PI controller has shown in previous research to have a significant disadvantage due to poor damping, thereby requiring refined tuning formula to improve performance. The PI controller with optimization called particle swarm optimization (PSO) is used to obtain optimum values for the coefficients [14]. This optimization comes from Artificial Intelligence strategies used by researchers for enhancing output results. The measurement of performance has commonly incorporated Integral of Time Absolute Error (ITAE) due to the recommendations and accuracy from researchers. FOPID has proven to be efficient in uncertain environments and PHEVs with frequency enhancements which are rarely seen in two area network research, therefore these components will be utilised in this paper for their benefits presented in the literature. [15-19]. From the discussion above, this study is structured to:

- Develop a two-area thermal power system used for frequency stability studies utilising the first-order linear transfer function approach.
- The power system thereafter is injected with PHEVs on each area of the thermal power plant and interconnected via an AC tie-line.
- Multiple secondary controllers are designed with their relevant gain values such as PD, PI, PID and FOPID.
- Manual tuning and system tuning were done to acquire the optimum value of gains for the controllers.
- Step load alterations are done on the power systems for behaviour patterns.
- Data are presented graphically for 1% load disturbance in Area 1. Then graphical results for both Area 1 and 2 with 1% and 2% respectively are shown for confirmation of output results. ITAE performance criteria are tabulated for 1% load change.
- Analysis of the results via comparison with the various controllers under the same conditions to show the discovery of the research done by achieving steady-state at the quickest time.

II. MODELLING OF POWER SYSTEM WITH PHEVS

A. *Two Area Power System*

The tie-line for two isolated power systems is interconnected to allow two-way power flow between the two areas. This is represented in Fig. 1 below. The model shown in Fig. 2 displays the transfer functions with the inclusion of the PHEV.

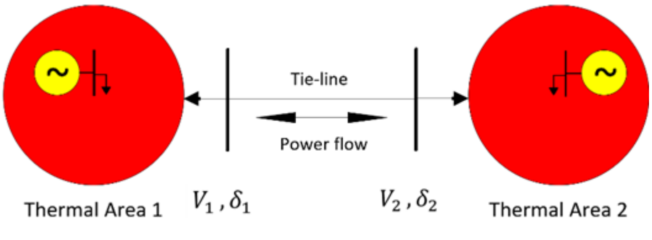


Fig. 1. Two-area power systems interconnected via tie-line.

The two area thermal power system is illustrated below showing the basic process of the generation of power using the primary equipment for analysis purposes such as the Governor, Turbine and Generator. The power system is integrated with a PHEV aggregator in each area to assist the system with supply and load demand scenarios at various patterns during the day. An LFC of various configurations and types are used in each area to control uncertainties and disturbances from the system. These controllers are used to compare the performances and behaviour of frequency which will bring the system back to steady-state conditions. In this research, the power systems for each area is identical with varying change in power demands.

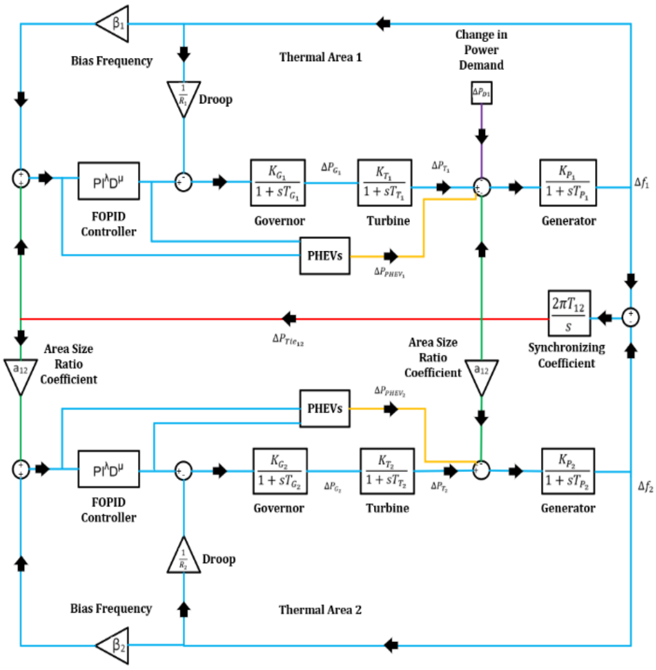


Fig. 2. Two-area system model with PHEVs.

The control area consists of generators that maintain the relative power angles either by increasing or decreasing their speed. The LFC maintains a turbine speed governing system for steady-state conditions due to load demand changes. This system of a steam turbine has four components which are:

- Fly ball speed governor that senses the change in speed/frequency;
- Hydraulic amplifier that has a pilot valve and main piston that opens or closes the steam valve against the pressure steam;
- Linkage mechanism that provides movement to control valve in proportion to change in speed and feedback from the steam valve movement;
- And a Speed Changer which provides steady-state power output setting of the turbine.

The model of a speed governing system and derivation of the transfer function considers the system initially operating at a steady-state with the linkage mechanism unvarying, pilot valve closed, opened position of steam valve by a magnitude, constant speed of turbine while balancing the generator load due to turbine output power. A linear incremental model is determined using the conditions mentioned. By making assumptions about the behaviour of the turbine speed governing system, a Laplace transformation of the equations is generated. From here, the speed regulation of the governor, the gain of the speed governor and the time constant of the speed governor are derived.

The steam turbine model considered is a non-reheat turbine which will consist of a single equivalent time constant for ease of analysis. The turbine time constant and gain can be seen in Table 1.

The generator load model is derived using the incremental turbine power output where generator losses are assumed to be negligible, the rate of change of kinetic energy in the generator rotor and the rate of change of load due to frequency changes. The generator power system gain and power system time constant is thereafter derived. For an interconnected two area power system, the tie-line connects the two areas where power is transported in and out of the areas. The equation for tie-line power is:

$$P_{tie,12} = \frac{|V_1||V_2|}{X_{12}} \sin(\delta_1^o - \delta_2^o) \qquad (1)$$

By using the incremental changes of frequency and Laplace transformation, the synchronizing coefficient equation is used as part of the simulation. The area control error is redefined as a linear combination of incremental frequency and tie-line power which is:

$$ACE = \Delta P_{tie}(s) + b_1 \Delta f_1(s) \qquad (2)$$

Where frequency bias is included in equation 2 and the determination of area size ratio coefficient is determined from the change of power tie-line in area 1 and area 2. The speed changer set to give a scheduled frequency of 100% at full load at steady-state load frequency characteristics shows a linear relationship between frequency and load for free governor operation is represented in the droop.

TABLE I. SYSTEM PARAMETERS FOR THERMAL POWER SYSTEM

Parameters	**Values**
Governor Time constant	0.4 sec
Turbine Time constant	0.5 sec
Generator Time constant	20 sec
Governor/Turbine Gain	1
Generator Gain	100
Speed Regulation	3
Area size ration coefficient	0.425
$2\pi T_{12}$	0.05

B. *PHEV Aggregator*

The PHEV aggregator behaviours as a centralised communication centre between electric vehicles and the power grid. This system manages the charge and discharge of electric vehicles. The aggregator consists of a Primary Frequency Control (PFC), LFC signal from Area 1 or 2 controllers and a battery charger model. The participation factor has also been included as part of the model due to considering PHEV's state of charge (SOC) which varies during the day according to the PHEV operating modes. The modes consist of disconnected mode, charging mode and idle mode. Each mode affects the SOC and participation factor. An estimated participation average has been utilised for this study. The LFC controller signal is transferred to the PHEV aggregator to manage the frequency oscillations and improve the stability results. The model of the aggregator can be seen in Fig. 3. Parameters used for the purposed of this model were obtained from [1] and can be seen in Table 2. Components of the aggregator are explained for the requirement and operation of EV connected to the grid.

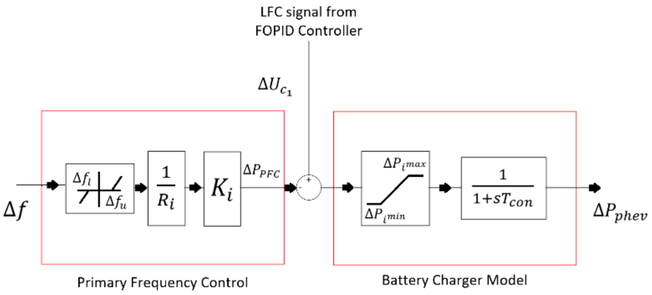


Fig. 3. PHEVs aggregator model including average participation factor.

The dead band function is utilised by all generating units involving Primary Frequency Control (PFC) with the upper Δf_u and lower Δf_l limits. This is used to avoid uninvited small frequency perturbations that may cause excessive wear and tear in the turbine, which in turn increases maintenance costs. The frequency droop coefficient R_i controls the output active power according to the input frequency deviations. This controls the increases in the PHEV power by ΔP_{PFC} for the frequency drop of Δf. PFC loop integrates participation factor k_i. The participation is determined by the PHEV's operating modes. This value varies from zero to one, which is dependent on varying SOC. The average power for a PHEV is within the primary reserves of the upper limit $\Delta P_i{}^{max}$ and lower limit $\Delta P_i{}^{min}$. This represents the number of reserves which can be consumed over the frequency nominal value and the reserves that can be injected back into the grid when the frequency drops below the nominal value. The transfer function is modelled as a first-order with a small-scale time constant. Fast dynamics such as Pulse-width modulation (PWM) have been neglected in this model. If the time constant has a higher value, the frequency response could be affected, which influences the PFC response.

TABLE II. SYSTEM PARAMETERS FOR PHEV AGGREGATOR

Parameters	**Values**
Dead Band	±10mHz
1/R	100
SOC_{av}	76%
K_{av}	0.9
$T_{conv,av}$	50ms
ΔI_{av}^{max}	10A
ΔI_{av}^{min}	-11A
$V_{d,av}$	391.2V

III. MODELLING OF FOPID CONTROLLER AND PERFORMANCE CRITERION

A. *FOPID Controller*

The FOPID has been widely used for methods in control theory and improved expiation of results. Similarly, the controller has the same benefits as the conventional PID controllers utilizing proportional control to provide an immediate action to control error, integral control to use the constant error by driving it near to zero and derivation control which acts upon the change of the error. The PID controller has advantages of reducing steady-state error to zero, moderate peak overshoot, moderate stability and can be used for fast/slow process variables. The FOPID has similar characteristics, with the inclusion of integral and differential order λ and μ. This provides two additional adjustable parameters compared to the traditional PID controller. The controller becomes more flexible in a control structure and can obtain a better control effect. The various control structures encompass gains for KP, KI and KD which were obtained using trial & error and tuning app PID on MATLAB for the experimental study of the research. Multiple iterations of the controller were done to discover optimal gain values. The arrangement of this controller can be seen in Fig. 4.

$$K_c(s) = K_P + \frac{K_I}{S^\lambda} + K_D s^\mu, \ \ \lambda, \mu > 0 \qquad (3)$$

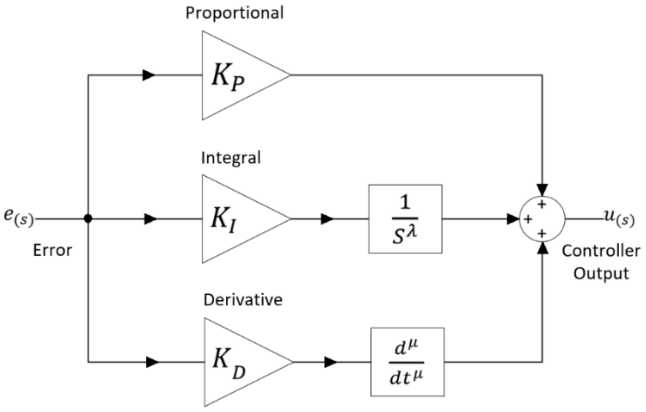


Fig. 4. Arrangement and structure of FOPID controller.

B. *ITAE Performance Index*

The ITAE performance index has been widely used for control system design. This method integrates the absolute error multiplied by time over time. ITAE weights errors that exist after a long time much more heavily than those at the start of the response. The settling time has been shown to be faster than Integral Square Error (ISE) and Integral Absolute Error (IAE). The ITAE is put to use in this study as a comparative figure and optimize the parameters of the model. The formula for ITAE is shown below:

$$ITAE = \int_0^\infty t \left| e(t) \right| dt \qquad (4)$$

IV. STUDY ANALYSIS AND SIMULATION RESULTS

The study work focal point is to determine the analysis of the different controllers been used and the effect of PHEVs on the thermal power systems which are interconnected via a tie-line to satisfy the demand of the control areas. The model is used for evaluation for the demand change of 1% in Area 1 within the two-area interconnected system. This is compared with the various PD, PI, PID, FOPID and finally FOPID controller with PHEVs. The simulated results showcasing the frequency variations in Area 1, Area 2 and Tie-line are displayed in Fig. 5 (a-c). For further comparison and results, a change in demand for both Area 1 and Area 2 with 1% and 2% respectively were modelled for study, which is graphically displayed in Fig. 6 (a-c). This has been done to understand the behaviour of the controllers and the performance influence of the PHEVs in both areas.

TABLE III. ITAE RESULTS OBTAINED FOR VARIOUS CONTROLLERS FOR DEMAND CHANGE OF 1% IN AREA 1

Controllers	**Two Area Power System**		
	Area 1	**Area 2**	**Tie-line**
PD	16.68	16.25	6.17
PI	0.6433	1.656	0.7546
PID	1.104	0.5053	0.07105
FOPID	0.2165	0.1392	0.06173
FOPID with PHEV	0.1042	0.07045	0.02994

From the data tabulated above, the results are easily displayed that there is a scaled-down value of ITAE for FOPID with PHEV compared to the other controllers for differentiation and performance of the LFC. The FOPID Tie-line (0.06173) is shown to have a low value compared to PI (0.7546) and PD (6.17).

The PD controller has a huge ITAE and the results are clearly shown that the error still exists in the system response which is not suitable for consideration. PI has displayed multiple oscillations for frequency, which is not recommended. The ITAE for PID in Area 1 (1.104) is very high compared to the few other controllers due to the overshoot.

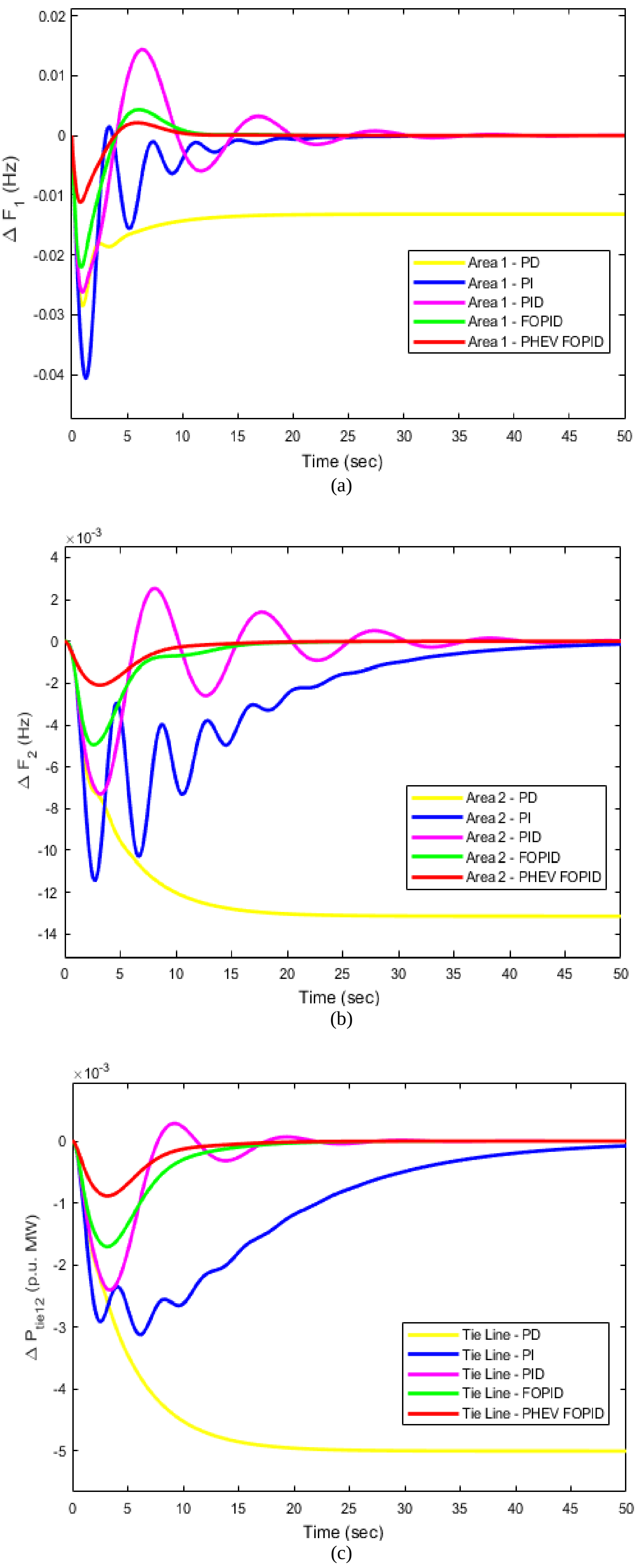
As shown by researchers, FOPID has proven to have the fastest response time, the least overshoot and best stability performance. From graphs in Fig. 5 (a-c), the responses are coming back to the steady-state value observed between 10 and 15 seconds, which is not shown by the other controllers.

The frequency doesn’t exceed (±0.02) Hz in both areas. The output has also shown that the FOPID with PHEVs is free from oscillations for frequency and tie-line power, which is favourable for the power quality of the system. The PHEVs has been shown to assist the frequency positively for both areas and tie-line by reducing the overshoot and steady-state error at a moderate value.

Similarly shown in Fig. 6 (a-c) the behaviour of the controllers is shown to act in the same way. The PI controller for Areas 1 and 2 frequency oscillations still exist but with a longer wavelength. The PID controller comes to a steady-state between 25 – 35 seconds for the two areas. The controller has been shown to have a longer settling time than the FOPID. The peak overshoot has also increased with controllers from the load demand of 2% in Area 2 which affects frequency in Area 1. The FOPID with PHEVs still triumphs in this case.

With minimum overshoot and speedy settling time between 5 – 15 seconds. The PHEVs still shows an enhancement of stability for both areas with load disturbances on single or both power systems. The controllers have been shown to have different overshoot peak.

It is difficult to see a change of frequency with PHEVs in Fig. 6 (c) for the tie-line due to the slight positive enhancement. PD controller has still shown to be out of bounds and not achieving a steady-state, therefore this controller is proven from [10] to be unsuitable. The controller selected has shown to be superior to other controllers in its performance while introducing load alteration in both areas.

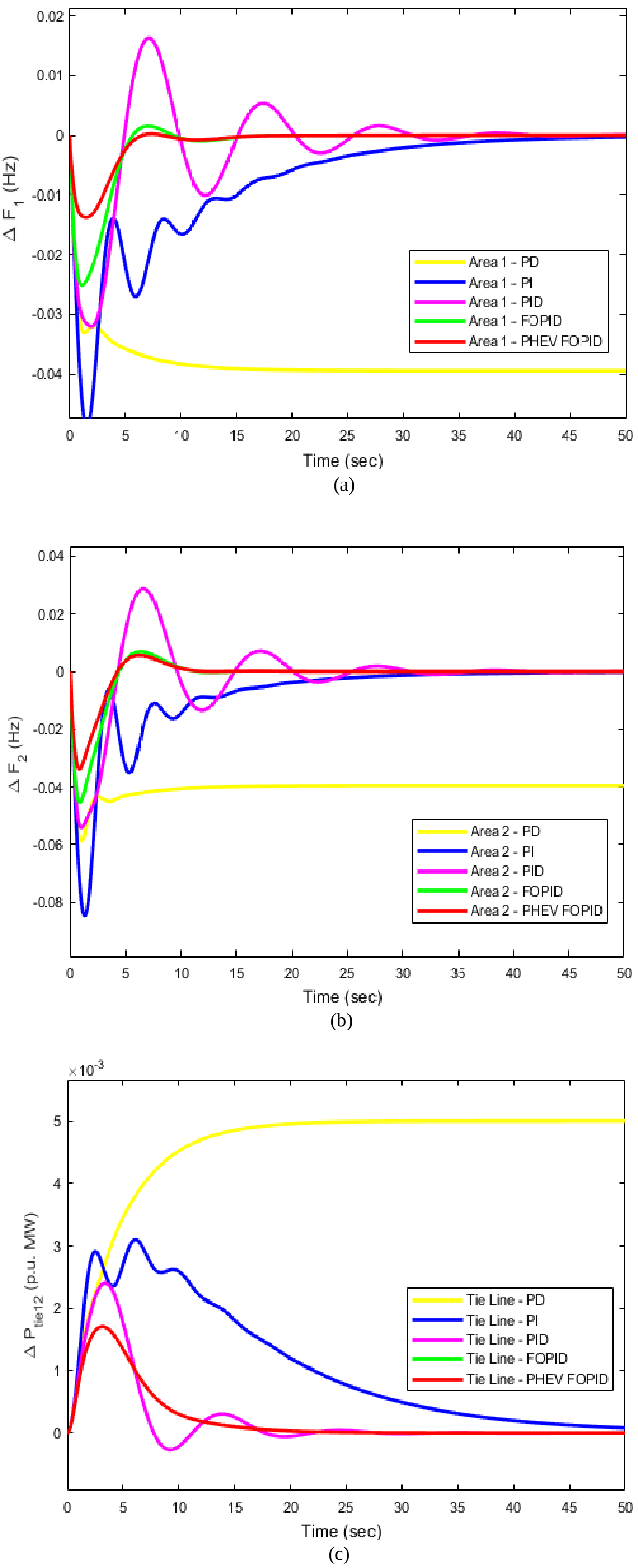


(a)

(b)

(c)

Fig. 5. (a-c) System frequency results for 1% load disturbance in Area 1 using various controllers.



(a)

(b)

(c)

Fig. 6. (a-c) System frequency results for 1% load disturbance in Area 1 and 2% load disturbance in Area 2 using various controllers.

V. CONCLUSIONS

This paper shows the inclusion of PHEVs into a conventional thermal power plant that is interconnected through an AC tie-line and controlled with FOPID. In order to match the varying load demand in one or both areas with the generated power, multiple controllers such as proportional, integral, derivative controls were used to establish the results of the interconnected power system. Frequency studies have been done to verify the best controller design option and its performance. FOPID with PHEVs has shown to positively affect the control zones by stability enhancement, the least overshoot and also provide oscillation free for frequency and tie-line power deviations in LFC responses. Furthermore, PHEVs has enhanced the capacity of LFC which can act as a load or storage bank. This shows the need to incorporate them is possible through a centralised control system and an LFC to be utilised efficiently into the power grid as and when required.

The expansion of this study can be utilised from this paper with the incorporation of fuzzy logic systems and optimization techniques, the results produced can be refined and further investigated for assorted working conditions of the system with integration through PHEVs.

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