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Identification of an Appropriate Operating Strategy under ABT for Frequency Regulation in a Non-Linear Multisource Power System Linked Through a Hybrid AC/DC Tie-Line

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Abstract— *This research verifies Frequency-Linked Pricing (FLP)-based operating strategies under an availability-based tariff (ABT) for automatic generation control (AGC) of multisource power systems with nonlinearity and interconnections via AC/DC Tie-Lines. Through modeling and simulation in Matlab/Simulink, this study also identifies a comparatively superior and more appropriate FLP-based operating strategy for AGC under ABT. Different ABT operating techniques yield Generating Control Error (GCE) by combining unscheduled interchange (UI) charges corresponding to frequency deviation and the marginal cost of generation. Three FLP-based operating strategies are compared to standard operating strategies. In addition, several load pattern scenarios are analyzed to ensure a suitable FLP-based operational strategy. The economic accounting associated with UI pricing for FLP-based operational strategies has been analyzed. The outcomes demonstrate that the operational approach that compares actual UI charges and marginal expenses to their respective reference values excels relatively well.*

Keywords—Automatic generation control (AGC), availability based tariff (ABT), generation control error (GCE), tie-line, frequency linked pricing.

1. INTRODUCTION

The demand for electric power in different sectors like transportation, manufacturing, automation, and even small commercial or household applications is increasing with the expansion of the power system. The ways to produce power and a mixture of energy sources have also developed and evolved from single-source to multi-source. The interconnection of different areas through AC tie-link has also been developed to deliver bulk power generation from a variety of energy sources. Such multisource, interconnected power systems pose many challenges in the control and regulation of the frequency and tie-line power, followed by a mismatch between generation and demand.

AGC deals with issues relating to the regulation and control of frequency and tie-line power. It adjusts the output of the power-generating sources in response to the perturbation caused. It also plays an important role in regulating system frequency and the exchange of electric generation between control areas in the power system. The majority of the contribution to maintaining system frequency and tie-line power is from non-conventional sources. Therefore, designing AGC schemes for interconnected power systems is of utmost importance. In the past, many efforts [1–3] have been made to decide on suitable operating strategies for AGC in multisource, interconnected power systems. Although many of these studies have considered a single source of power plants in each corresponding control area, in practical circumstances, a control area may have combinations of various types of non-conventional energy sources, i.e., hydro, thermal, gas, etc. Also, in such studies, the modeling of the components involved does not consider non-linearities such as the generation rate constraint (GRC), the governor dead band (GDB), boiler dynamics (BD), etc. Further, the modern power system has interconnection through parallel AC and DC tie-links. All these aspects pose new challenges in deciding the operating strategy for AGC.

Few researchers [4–7] have investigated the operating strategy for AGC of power systems with diverse source generations in each system area. Researchers have focused their efforts in [8–12] on proposing the new structure of the controller, taking into account the impact of energy storage, introducing the application of optimization techniques, evaluating system stability, and similar concerns for standalone and/or interconnected multi-energy source systems.

Surveying all such relevant literature, it is observed and evident that generally, refinements of frequency control are carried out by introducing different types of conventional [13–17] or soft computing-based controllers [16–18] in the secondary frequency regulation. The objective of maintaining frequency through such controllers is to use optimization techniques to get zero frequency deviation for changes in load. But this mechanism does not ensure the economical operation of the grid, where neither the generators nor the users will lose money. So, an operating strategy was devised that serves the said purpose of maintaining the frequency and economic operation of the grid through the implementation of an ABT. This operating strategy offers the opportunity to all participants to exchange surplus energy as and when it becomes available at a price determined by prevailing frequency conditions [19]. Although the primary principle on which the UI mechanism of ABT operates is different from the typical load frequency control mechanism, it can still be viewed as a price-based secondary

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generation control operating strategy.

Thus, under the ABT framework, the frequency was linked to an unscheduled interchange charge. The combination of the UI charge corresponding to frequency deviation and the marginal cost of generating an operation determines GCE. This GCE governs the change in electric power generated to mitigate the frequency deviation.

Tyagi and Srivastava [20] have presented an operating strategy for AGC that is based on the UI price. It showed that the ABT works well when incorporated into the secondary control loop. S. Chanana [21] proposed the modification in producing GCE. The author shows that such a mechanism can improve the control of frequency and bring the UI price down. Few researchers adopted the modification that S. Chanana suggested in various literature on various types of power systems [22–26]. V. Murli and K. Sudha [27] further modified the way to produce the GCE signal. The authors suggested determining GCE after obtaining the difference between the prevailing and reference values of UI charges and the marginal cost of generation. Most of the previous works studied the implementation of such an operating strategy in an isolated area with several generators [27, 28].

The purpose of this paper is to determine the suitable operating strategy for frequency regulation by comparing various ABT-based operating strategies applied to a two-area multi-source power system interconnected via hybrid AC/DC tie-line. The schematic diagram of the same, i.e., the system under study is depicted in Fig. 1. In addition, the efficacy of ABT-based various operating strategies based on frequency-linked pricing mechanisms in frequency regulation is determined by simulating various scenarios in Matlab/Simulink version 2022a.

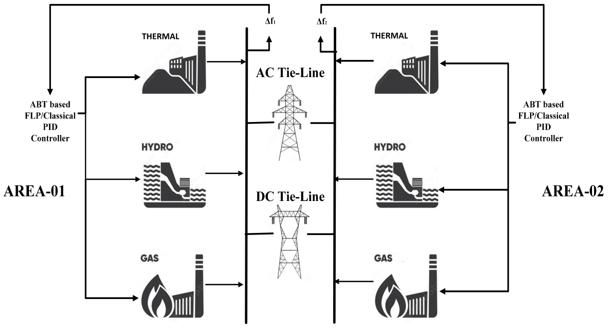


Fig. 1. The schematic diagram of the system under study.

As a result, the method suggested here modifies the secondary LFC loop. It can be seen from the literature that most research studies have taken into account the operating strategy suggested by Tyagi and Srivastava [20] in the secondary control loop of the LFC and is referred to as FLP type-01 operating strategy in further discussion in order to study the role of ABT-based FLP mechanism in frequency regulation. Over time, other researchers have suggested modifications to the ABT-based FLP mechanism in frequency regulation. For example, Chanana and Kumar [21] suggested modifying the frequency regulation system to control the generators solely based on reference UI prices (which is referred to as FLP type-02 operating strategy in the following discussion), while Murali and Sudha [27, 28] suggested further modifications based on considerations consideration of both reference marginal cost and reference UI price to generate control command for generators (and is mentioned as FLP type-03 operating strategy in the further discussions hereafter).

But, FLP type-03 operating strategy has been adopted for a solitary control area that consist of only thermal generators in the earlier research. Therefore, the earlier research related to muilti-source power system with nonlinearity modelling and interconnected via hybrid AC/DC link has been chosen as the base and reference with the aim to further evaluate the performance and investigate the effectiveness of the FLP type-03 operating strategy for such interconnected control area that to with not only thermal generators but also having mixed generation. The system configuration and data mentioned in the article at the end in Appendix have been taken into consideration from various research literatures to create a base, and in order to maintain uniformity and conduct a fair comparison to demonstrate the improvement brought about by the proposed work, the ABT-based operating strategy through which the generation control error (GCE) is generated has been modified.

The majority of researchers have solely employed the conventional FLP type-01 technique to produce GCE commands for their studies. The FLP type-02 and FLP type-03 strategies, which outperform the type-01 approach in terms of performance, are also included in the current study in addition to the type-01 strategy. The effectiveness of the system is also assessed for varied disturbance sizes that are not equal in both areas, in addition to step load perturbations. Additionally, the current work assesses how well type-02 and type-03 regulation schemes function while simulating continuous random load variations that are close to real-time loads.

Additionally, the frequency to UI pricing conversion is modeled using CERC's UI vector guidelines. Signals for frequency-based pricing are promptly recognized by thermal generators. Both classical control and frequency-linked price-based regulation were looked at for secondary control. The investigation based on simulation was conducted using Matlab 2022a [29].

Thus, this paper attempts a further investigation of such frequency-linked pricing-based operating strategies under ABT used for AGC purposes. Hence, the contribution of this article is the identification of an appropriate operating strategy under ABT for frequency regulation in a non-linear multisource power system linked through a hybrid ac/dc tie-line, which uses an enhanced method of producing GCE signals.

This research sheds additional light on the ABT-based operating strategy by simply integrating unscheduled interchange charges and marginal generating costs with their respective reference values under nominal conditions. The proposed structure maintains the same number of decision variables in terms of problem dimensions as the traditional ABT-based operational strategy.

Interconnected hybrid power systems having thermal, hydroelectric, and gas-based generation in two control areas are considered. An integrated two-area power systems having thermal, hydroelectric, and gas-based generation interconnected via hybrid AC/DC tie-line is simulated in the Matlab/Simulink environment to verify the suggested technique. Each of the two sections, which are heterogeneous, has all three types of generation from thermal-hydroelectric and gas-based. Some parts of India are rich with monsoon-driven hydropower potential, while others have coal or gas reserves, etc. Therefore, the system adopted here is quite feasible and compatible with different scenarios. The non-linearities in the modeling of components involving frequency control have been introduced. Also, the emergence of interconnection via AC/DC parallel links and its impact have been assessed.

The effectiveness of the recommended operating strategy is compared to two other classic operating strategies, and their dynamic behaviours are assessed under various working conditions such as step load perturbation, continuous disturbance, and inconsistent disturbance magnitude. The introduced operating strategy's significant superiority in the face of varied disturbances and conditions is evidence of its effectiveness. In addition, this operating strategy is a desirable option for carrying out the LFC task due to its practical and uncomplicated design, as well as its strength and robustness in challenging working environments.

The core contribution of the paper can be deliberated as to justify a change in method is to demonstrate that the new approach is applicable to new or previously unexplored scenarios. For instance, if an existing method for LFC using ABT is limited to certain types of power systems or load scenarios, a new approach that can handle a broader range of scenarios would be justified on the basis of its potential impact in these new areas. Therefore, the contributions of this study are further fragmented and briefly summarized with supporting procedural steps of method involved are as follows:

1) By combining the unscheduled interchange charges and marginal generation cost with respect to their reference values at nominal conditions for interconnected power systems, a novel approach is presented that regulates the frequency and produces a potential minimal deviation of frequency and tie-line power.
2) In addition to the consideration of several challenging aspects and scenarios, the modeling aspects include consideration of non-linearities like generation rate constraints, governor dead bands, and boiler dynamics. Further, scenarios like step load perturbation, variable load perturbation, random load variation, and communication time delay have also been introduced to study the system response which were not considered typically for a study pertaining to frequency regulation under ABT regime. Thus, transfer function blocks are utilised in order to simulate each region's contribution, and the influence on frequency control is also taken into consideration. The degree of dependence on the capability of the recommended technique to establish system stability may be demonstrated by looking at the quality of the oscillations, the frequency nadir, and the settling length.
3) The performance was checked by comparing the results of different operating strategies under different use cases, such as with and without consideration of nonlinearities, with and without consideration of AC/DC parallel tie-links, and with and without consideration of different FLP-based operating strategies under ABT which are also not been part of study of frequency regulation under ABT based regime with conventional ways of producing GCE signal. So in nutshell, in order to compare the proposed operating strategy under different operating conditions, commonly used secondary control loops based on ACE with PI controllers and standard ABT-based secondary loops emphasising either UI or marginal cost as an individual are also simulated.
4) Comparisons under various working conditions are used to illustrate the superiority of the proposed operating strategy.
5) An attempt has been made to analyze the economic accounting associated with unscheduled interchange pricing. The comparison between different FLP-based operating strategies under ABT to determine the relatively better-operating strategy.

The rest of this article is organized into several sections that are presented as follows: The ABT-based operating strategies and corresponding aspects of frequency regulation are discussed in Section 2. The studied system topology, which considers the thermal, hydro, and gas-based multi-source power system with nonlinearity and interconnected via AC/DC tie-lines, is illustrated in Section 3. Section 4 discusses the application of proposed operating strategies for frequency control and the corresponding simulation results according to the different considerations and scenarios. Finally, Section 5 summarizes the conclusions and observations of the current work.

2. ABT BASED OPERATING STRATEGIES FOR FREQUENCY REGULATION

During the early development of the power system in India, the tariff structure included only two parts: Fixed charges and fuel charges. This mechanism inhibits the generation during off-peak periods to lower the generation or during peak load conditions to increase the generation. Due to such circumstances, the overall grid discipline was not upheld in terms of frequency deviations from the nominal. The ABT was introduced in 2003 to address issues related to the secure and stable operation of the power system. The three different components– capacity charge, energy charge, and unscheduled interchange charge– are the core parameters of consideration in ABT. The capacity charges are associated with the declared capacity of a particular plant in MW. The energy charges are being accounted for to compensate for fuel costs for the scheduled generation. UI charges are considered whenever a generator deviates from its scheduled generation at a rate according to the system marginal price at that time. The generators were also provided incentives in this mechanism for supporting the grid during the imbalance conditions of off-load and peak load situations. Thus, the operation of the grid under an ABT-based mechanism led to the advantages of more stable and secure grid operations, i.e., significant improvements in frequency and voltage, and consequently a reduction in equipment damage.

In India, unscheduled interchange charges are covered under the purview of the Central Electricity Regulatory Committee (CERC) and according to the Deviation Settlement Mechanism (DSM). The UI vector links frequency with pricing. The slope of the vector is declared, reviewed, and modified over time based on the study carried out and experiences gained by CERC periodically. One of such modifications in deciding the slope of the UI vector was carried out by CERC in 2018. According to this, the UI vector has a variable slope determined at various frequencies between 49.85 Hz and 50.05 Hz. The ceiling limit declared by CERC is 800 paisa per kWh.

The detailed guidelines for determining variable UI vector slope are mentioned in the guidelines of the CERC under "Deviation Settlement Mechanism (DSM) and Related Matters" [30]. The sample UI vector is as depicted in Fig. 2:

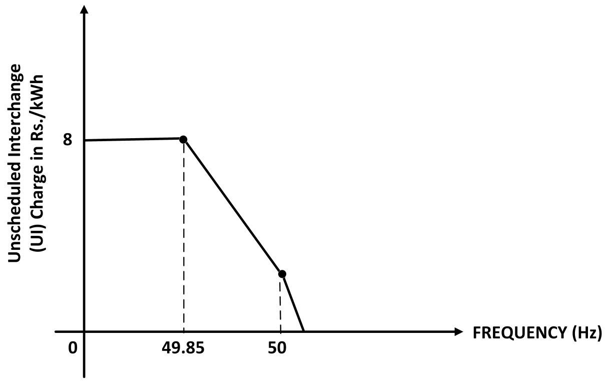


Fig. 2. Typical UI Vector.

The frequency of the system is linked with unscheduled interchange pricing based on area clearing prices as per CERC guidelines. The typical linkage between frequency and UI price can be represented as follows:

Following a perturbation, the new frequency of the system will be $\mathrm{f_{sys}} = \mathrm{f_o} + \Delta\mathrm{f}$.

If this $\mathrm{f_{sys}} > 50.05\,Hz$, in that case the UI price will be the minimum, i.e., zero Rs/kWh.

If $\mathrm{f_{sys}} \leq 49.85\,Hz$, the UI price will be the maximum, i.e., 8 Rs/kWh.

If $\mathrm{f_{sys}}$ ranges between 49.85 and 50 Hz or between 50 and 50.05 Hz in both cases, the UI price is calculated based on the linear relationship of slope between these corresponding boundary frequencies and the area clearing price of the day.

The generators will be accounted for in power draw and delivery to support the system frequency at 50 Hz. On continuing the support to maintain a nominal frequency of 50 Hz, the UI price will be equal to the average area clearing price (ACP) of the day. The "Area Clearing Price" means the price of a time block electricity contract established on the Power Exchange after considering all valid purchase and sale bids in particular area(s) after-market splitting, i.e., dividing the market across constrained transmission corridor(s) [30].

Various researchers have in due course proposed and investigated the various FLP-based operating strategies under ABT for UI-based LFC schemes. B. Tyagi and S. Srivastava [15] proposed an operating strategy for the LFC scheme based on a frequency-linked UI price. The proposed approach is depicted in Fig. 3 and mentioned as operating strategy FLP type-01 in further discussion. In this scheme, the primary control loop is similar to that of conventional frequency control, but the secondary control loop integrates the frequency-linked UI price signal. However, the disadvantage of the scheme was that even when the load was as per schedule, it resulted in undue unscheduled interchange between the generators at nominal frequency.

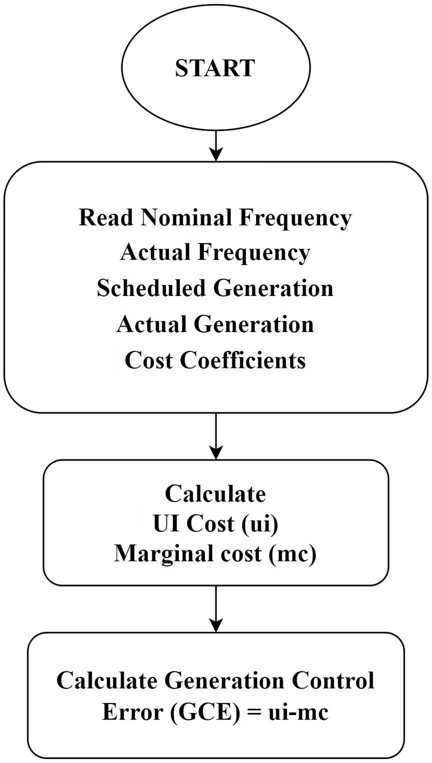


Fig. 3. Control approaches for frequency linked pricing (FLP) type-01 based regulation in power grid.

Later, S. Channa et al. [21] proposed another operating strategy for LFC through the modification of the secondary control decision based on UI price. The modified approach is illustrated in Fig. 4 and mentioned as operating strategy FLP type-02 in subsequent discussions. This modification resulted in overcoming the problem mentioned above. Further to this, V. Murli et al. [27, 28] observed that the secondary control loop regulates the reference power setting, which depends on GCE, i.e., the difference between the UI price and the marginal cost of a generator, for fine-tuning the frequency so that it settles at a reasonable value. A positive GCE increases the generation, and a negative GCE reduces the generation. So, GCE plays a vital role in controlling power generation. Hence, a further modification of the operating strategy for the LFC scheme based on UI pricing was proposed. The authors suggest the redefined GCE be as follows:

$GCE = \Delta \mathrm{UI\,price} - \Delta$ Marginal Cost,

Where ΔUI price is the change in UI price, which is defined as:

$\Delta \mathrm{UI\,price}$ = Actual UI price Reference UI price

Δ Marginal Cost is the change in the marginal cost of the individual generator, defined as:

Δ Marginal Cost = Actual Marginal Cost − Reference Marginal Cost

The GCE has been considered a combination of ΔUI price and Δ Marginal Cost. The reason for the same is that if GCE is defined as ΔUI price only, the controller can adjust the frequency but not the desired generation dispatch. At the same time, if GCE comprises Δ Marginal Cost only, the controller adjusts both frequency and desired dispatch but may take a longer duration to correct the frequency deviation. Hence, to have a compensated trade-off between frequency deviation and time to correct the same, GCE is defined as a combination of both signals. This method is shown in Fig. 5 and will be called operating strategy FLP type-03 in the rest of this article.

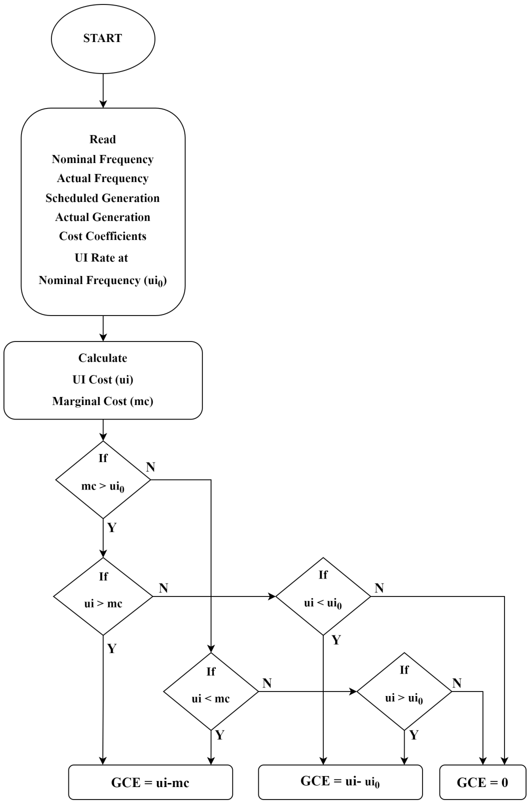


Fig. 4. Control approaches for frequency linked pricing (FLP) type-02 based regulation in power grid.

3. MULTISOURCE POWER SYSTEM UNDER INVESTIGATION

The power system considered for investigation consists of two areas interconnected power system model depicted in Fig. 6. Each area contains thermal, hydroelectric, and gas power plants. The initial study did not include any non-linearities in the modeling of the components involved in frequency control. Also, initially, only the AC tie line is considered between the two areas. The system parameters are given in the appendix, and the areas are discussed by Hakimuddin N. et al. [31]. In a later study, non-linearities such as generation rate, governor dead bend, boiler dynamics, and time delay were introduced. The generation rate constraint for thermal is considered to be ±0.0017 pu MW/sec; for hydro, +0.045 pu MW/min and -0.06 pu MW/min; and for the governor dead band, it is considered to be 0.06% as suggested by various researchers in [32–35]. The communication time delay in the signal of 0.1 seconds has also been considered, as suggested by Saha A. and Saikia L. [36]. The parameters and modeling of boiler dynamics are referred to in the various literatures [37–39]. The efforts have been extended by considering an AC/DC parallel tie-link as well.

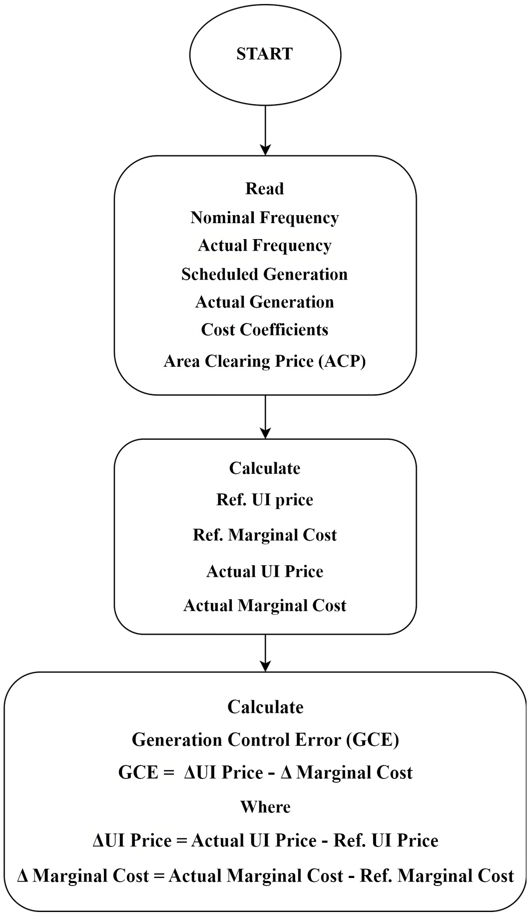


Fig. 5. Control approaches for frequency linked pricing (FLP) type-03 based regulation in power grid.

The modeling and parameters of the DC tie-line are as mentioned in the literature by Barisal and Somanath Mishra in [32]. The results obtained through simulation work are presented in the subsequent section.

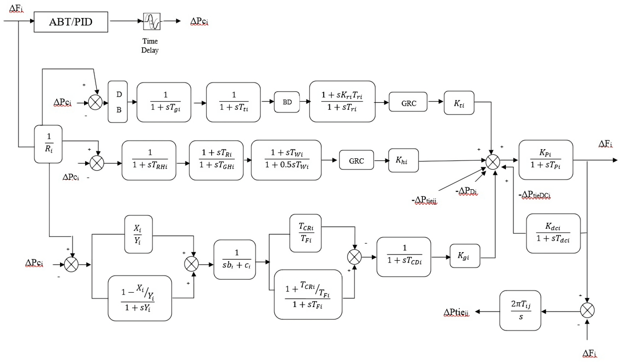


Fig. 6. Generalized multi-area power system, only grid area i shown.

4. DISCUSSIONS OF SIMULATION STUDY AND RESULTS

The present work is focused on investigating operating strategies for frequency control in multisource, interconnected power systems. The simulation study in a Matlab/Simulink environment has been performed. The 1% step load perturbation is applied in Area 1. The parameters of the controllers are tuned automatically through an in-built method in Matlab. The initial controller parameter settings are obtained using the automated PID tuner in Matlab/Simulink. This application interface permits user-defined constraints for linear plant model construction using system data. Background information determines the system's response to stimuli. PID Tuner takes into account every unit between the controller output and input. The PID modulator adjusts the steady-state error, overshoot, and settling time with precision. This metric evaluates controller performance and recommends adjustments. Thus, the initial controller structure strikes a balance between efficiency and stability. The user interface of PID Tuner allows you to modify the controller's rising time, settling time, and overshoot. After the PID controller has been automatically tuned using Simulink, the values within the specified ranges are iterated through the various controller parameter combinations to fine-tune the response. Simulink evaluates the objective function and simulates the system response for every parameter combination as a exhaustive search method manually. If the objective function improves, the parameter values are continually modified. This practice is continued until sufficient combinations have been evaluated. This has assisted in determining the suitable controller parameter values required for desired system performance. Additional simulations or testing scenarios replicating real-world conditions validate the performance of the tuned controller. Thus, the efficacy of the controller is evaluated. For the scenario without FLP the ranges of parameters are selected as $-7 \leq K_p \leq 0$, $-5 \leq K_i \leq 0$ and $-3 \leq K_d \leq 0$ where as in case of consideration of FLP based operating strategies the initial value of ACP is considered as 190.5 paise/kWh and the range of proportional gain is selected as $-1 \leq K_p \leq 1$ Further, to identify the effectiveness of various operating strategies, various scenarios about the techno-economic perspectives of frequency regulation have been considered. The scenarios considered are as follows:

1) Multisource power system controlled by classical controllers without consideration of non-linearities and interconnected via AC tie-link only
2) Multisource power system controlled by classical controllers with consideration of non-linearities and interconnected via AC tie-link only
3) Multisource power system controlled by classical controllers that take nonlinearities into account and linked by AC/DC hybrid tie-link
4) Multisource power systems controlled by different frequency-linked pricing-based operating strategies (type-01, type-02, and type-03) under ABT with consideration of non-linearities and interconnected via AC/DC hybrid tie-link
5) Assessing the impact of ACP on the frequency response of all three frequency-linked pricing-based operating strategies under ABT with consideration of non-linearities and interconnection via AC/DC hybrid tie-link
6) Assessing the impact of variable step load perturbation and random continuous load variation on the frequency response of type-03 frequency-linked pricing-based operating strategies under ABT with consideration of non-linearities and interconnected via AC/DC hybrid tie-link

Figs 7 and 8 depict the change in frequency in Areas 1 and 2, respectively. Nonlinearities like GDB, GRC, boiler dynamics, and time delay have a noteworthy impact on dynamic performance. The responses of frequency and tie-line power indicate significant oscillations after considering such nonlinearities in the modeling of various components involved in frequency control. With the use of the AC/DC parallel tie-link, this effect can be effectively reduced. In scenarios 1 and 2, the frequency nadir deepens to 49.96 Hz and 49.97 Hz, respectively, however in scenario 3, the frequency nadir only descends to 49.99 Hz. Additionally, it can be seen from comparing the settling times that scenario 1 and scenario 2 require settling times of 21 and 16 seconds, respectively, while scenario 3 requires settling times of only 8 seconds. In comparison to scenarios 1 and 2, the settling time thus improves by roughly 350% and 100%, respectively. The system with traditional AC tie-link has only produced a reasonable performance and results in steady state deviation in scheduled power flow of -0.005 pu. However, the DC tie-link operating in tandem with the AC tie-link has produced a response that is much better and has a speedy return to normal behavior when disturbed. When comparing a power system with an AC/DC tie line link to a power system with an AC tie line solely, the peak deviations with the frequency of insignificant oscillations are smaller in the case of the AC/DC tie line link power system. As demonstrated in Fig. 9, power systems with AC/DC parallel lines have been found to have smaller tie-line power deviations than power systems with only AC tie lines.

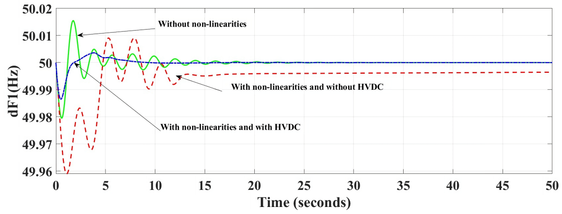


Fig. 7. Change in area-1 frequency with consideration of nonlinearities and DC tie link.

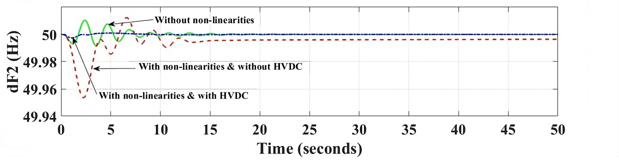


Fig. 8. Change in area-2 frequency with consideration of nonlinearities and DC tie link.

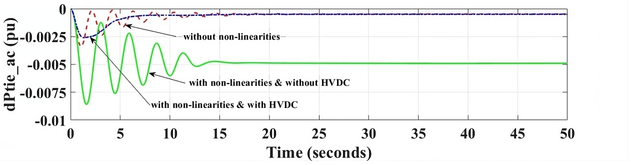


Fig. 9. Change in AC tie-line power with consideration of nonlinearities and DC tie link.

An attempt has been made to compare the frequency response of a system controlled without FLP to that of a system controlled using different FLP-based operating strategies under ABT. The steady-state frequency following a disturbance can be observed in the absence of FLP and with various types of FLP strategies as 50Hz; however, the steady-state frequency for FLP type-01 is 50.02Hz. As far as frequency nadir is concerned, the cases with FLP type-02 & 03 and without FLP are able to limit the deep to 49.99 Hz, whereas the frequency deepens to 49.98 Hz for FLP type-01. Also, the settling time remains within 8 seconds in all cases. FLP type-02 frequency settles in 4 seconds, FLP type-03 settles in 5 sec, whereas FLP type-01 frequency settles in 6 seconds. Thus, FLP type-02 outperforms by a 100% improvement in frequency settling time compared to FLP type-03 and FLP-based strategies without implication. Consequently, it is evident from Fig. 10 that, among all operating strategies, FLP type-01 performs the best, albeit with a comparatively degraded frequency response. The FLP type-02 operating strategy, on the other hand, results in relatively low nadirs, oscillations, and a reasonable settling period with no overshoot. FLP-type-02 has a modest overshoot and oscillations, but a faster settling time than without an FLP-based operating strategy.

The Table 1 indicates the comparison of settling time, steady state settling value, nadir value and error indicator ITAE (Integral of Time-weighted Absolute Error) for without FLP and under different types of operating strategies consideration. In the context of load frequency control for inter-connected power systems, the ITAE error function is a frequently used performance index. The ITAE error function quantifies the control system's capacity to keep the frequency and tie-line power flows within allowable bounds, allowing for the evaluation and improvement of the performance of the controllers. This is accomplished by measuring the integral of the absolute frequency or tie-line power error, with each error value being weighted by time. Typically, the ITAE error function is written as:

$$ITAE = \int_0^t (|\Delta f_1| + |\Delta f_2| + |\Delta P_{tie12}|) * t\, dt.$$

This ITAE function is advantageous in many aspects such as it is relatively simple to implement and calculate, it also ensures that both positive and negative errors contribute to the performance index and further, the time-weighting factor (t) gives more importance to errors that occur at later times. This reflects the idea that errors occurring for a longer duration are generally considered more significant and problematic in power system control. Therefore, by giving more weight to errors at later times, the ITAE error function aims to minimize the integral of the absolute error over time. Hence such function has been considered as one of the prime parameters to be analysed.

From the Table 1, it can be observed that the FLP based operating strategies, typically type-02 and type-03 operating strategies are fairly competent with performance without FLP and control by traditional secondary control loop with classical controller. This confirms and encourages the validated augmentation of secondary control loop for frequency regulation through FLP based operating strategies i.e., either by type-02 or type-03.

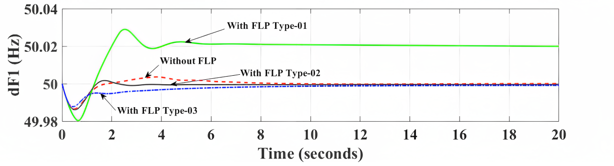


Fig. 10. Change in area-1 frequency with consideration of various frequency linked pricing based operating strategies under ABT.

To have better insight in identification of an appropriate operating strategy under ABT for frequency regulation in a non-linear multisource power system linked through a hybrid AC/DC tie-line, the impact of variation in ACP has been assessed as far as various FLP-based operating strategies are concerned. The three different values of ACP have been considered for the simulation study: 190.5 paise/kWh, 300 paise/kWh, and 800 paise/kWh. The impact of variation in ACP on the frequency response of type-01, type-02, and type-03 operating strategies is presented in Figs. 11, 12, and 13, respectively. From Figure 11, it is clear that the FLP-type-01-based operating strategy is significantly affected by variation in ACP, and a rise in ACP may lead to unstable operation as well. From Figs. 12 and 13, one can observe that the effect of variation in ACP on frequency response is not so substantial. The lower ACP in both the cases of FLP type-02 and type-03 results in small oscillations, but type-02 may result in an overshoot too in comparison to type-03-based operating strategy. It is also further observed that the frequency nadir reduces and the settling time increases slightly as ACP increases in both cases.

Figs. 14 and 15 indicate the change in frequency of Areas 1 and 2, respectively. These give further insights to evaluate the performance under consideration with and without an FLP-based operating strategy. It seems from these results that FLP type-02 and

Table 1. Comparison of settling time, steady state settling value and nadir value for different types of operating strategies.

Operating Strategy	**Settling time of frequency in area 1 (sec)**	**Steady State settling Value of frequency in area 1 in Hz**	**Nadir Value of frequency in area 1 in Hz**	**ITAE**
Without FLP	7	50	49.99	0.232
With type-01	6	50.02	49.98	11.66
With type-02	4	50	49.99	0.8607
With type-03	5	50	49.99	1.907

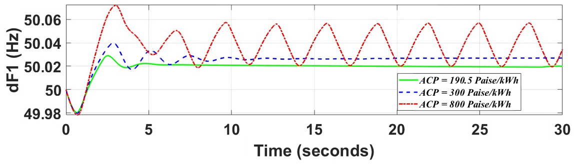


Fig. 11. Effect of variation in ACP on change in area-1 frequency with consideration of FLP type-01 operating strategy under ABT.

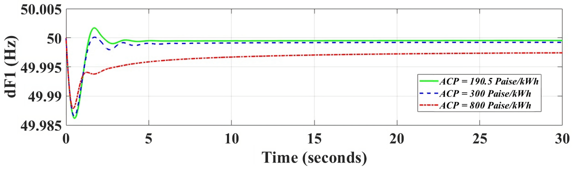


Fig. 12. Effect of variation in ACP on change in area-1 frequency with consideration of FLP type-02 operating strategy under ABT.

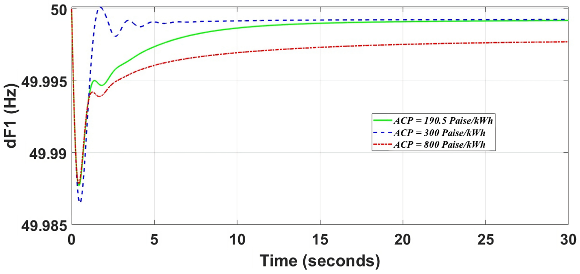


Fig. 13. Effect of variation in ACP on change in area-1 frequency with consideration of FLP type-03 operating strategy under ABT.

FLP type-03-based operating strategies are relative to those without FLP based operating strategies in terms of settling time, overshoot, and frequency nadir. Out of FLP type-02 and type-03-based operating strategies, FLP type-02 outperforms relatively, with the least nadir, the fewest oscillations, and a fair settling time.

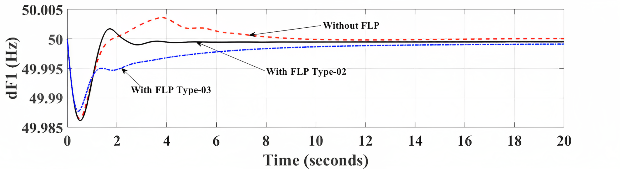


Fig. 14. Change in area-1 frequency with consideration of with and without FLP based operating strategy under ABT.

Looking at AC and DC tie-line power in Figs. 16 and 17, the deviation in AC tie line power is -0.0005 pu where as in case of FLP type-02 & 03 it deviates and settles to -0.0014 pu. Thus, the deviation in AC tie-line power in the case of FLP-based strategies is also fair and within an acceptable range. In the case of DC tie-line power deviations, FLP-based operating strategies are the same as each other and give better performance than strategies that don't use FLP. The system without implying FLP based strategy and controlled classically settles the deviation in dc-link power by 10 seconds, while the FLP based operating strategies able to restore scheduled dc-link power by 5 seconds and thus indicates an improvement by 100%.

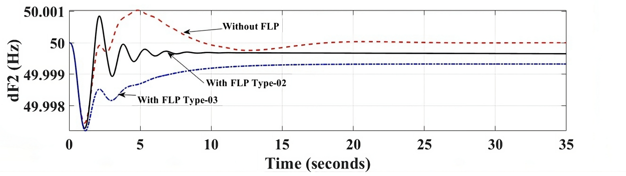


Fig. 15. Change in Area-2 frequency with consideration of with and without FLP based operating strategy under ABT.

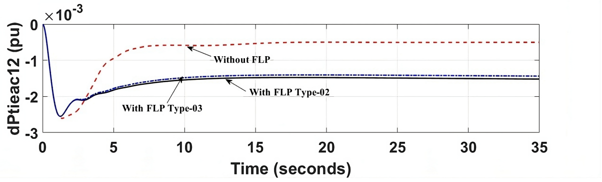


Fig. 16. Change in AC tie line power with consideration of with and without FLP based operating strategy under ABT.

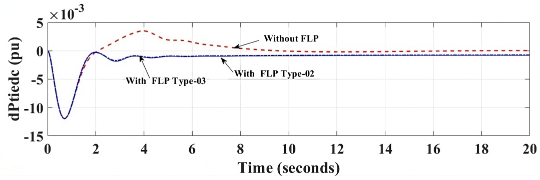


Fig. 17. Change in DC tie line power with consideration of with and without FLP based operating strategy under ABT.

The ITAE criterion is typically used to quantify the system's capacity to regulate its response to perturbation/changes. It considers both the magnitude and duration of the system's response to these alterations. In the context of frequency regulation, the ITAE is computed for the various scenarios considered so far and are depicted illustratively in the Fig. 18 and Fig. 19.

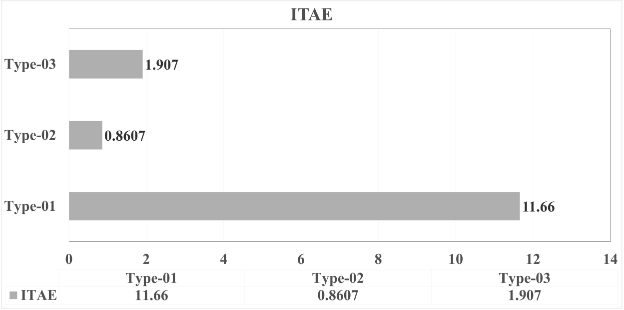
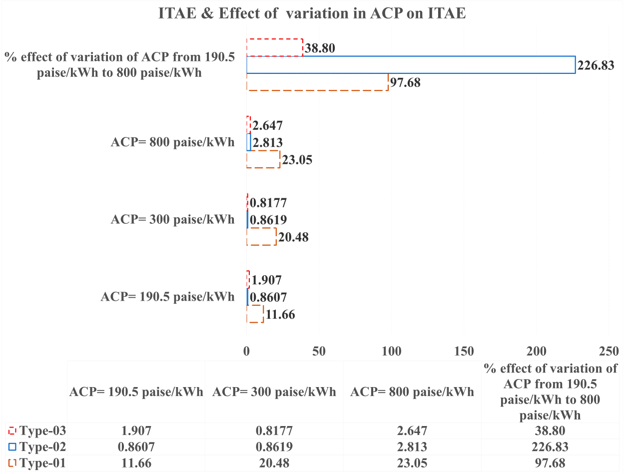


Fig. 18. Comparison of ITAE for the FLP based type-01, 02 & 03 operating strategies.

Fig. 18 shows that in an ABT-based environment, the error values are significantly impacted by the choice of operating strategy for frequency management. The error value drops from 11.66 for a type-01 operating strategy to 0.8607 for a type-02 strategy and 1.907 for a type-03 strategy. As a result, it's evident that the operating strategies of types -02 and -03 are superior to type-01 in terms of performance. In addition, the effect of variation in ACP on frequency regulation has also been evaluated in the current study, as mentioned previously. A comparative evaluation of the effect of variation in ACP on the ITAE has also been undertaken in this context. Fig. 19 depicts the variation in ITAE corresponding to variation in ACP when a typical FLP-based operating strategy is considered. The FLP type-1 is affected by 97.68% when comparing the value of ITAE with ACP of Rs 800 paise/kWh to the value of ITAE with ACP of 190.5 paise/kWh, as shown in fig. 19. In addition, the FLP type-02 is substantially impacted by 226,83% when comparing the value of ITAE with ACP of Rs 800 per kWh to the value of ITAE with ACP of 190.5 per kWh. Comparing the value of ITAE with ACP of Rs 800 paise/kWh to the value of ITAE with ACP of Rs 190.5 paise/kWh, the FLP type-03 is least affected by 38.80%.



	ACP= 190.5 paise/kWh	ACP= 300 paise/kWh	ACP= 800 paise/kWh	% effect of variation of ACP from 190.5 paise/kWh to 800 paise/kWh
Type-03	1.907	0.8177	2.647	38.80
Type-02	0.8607	0.8619	2.813	226.83
Type-01	11.66	20.48	23.05	97.68

Fig. 19. Impact of variation in ITAE corresponds to variation in ACP under consideration of typical FLP based operating strategy.

To check its robustness, the system is subjected to random load perturbations in Area 1. The response of the system to the frequency of area-1 is shown in Fig. 20. Fig. 20 reveals that satisfactory system response is obtained with an FLP type-03-based approach following random load perturbation. So, it can be concluded that the FLP type-03-based operating strategy is relatively robust. When the disturbance is sudden and large, the FLP type-02 operating strategy makes the system settle down more quickly.

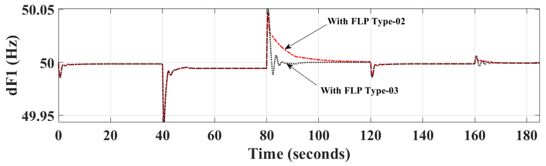


Fig. 20. Change in area-1 frequency with consideration of variable loading and FLP type-03 operating strategy under ABT.

Typically, the nature of real load variation is high-frequency and random. To further confirm the performance and evaluate the stability of the controlled system operated by the type-03 strategy, a high-frequency load change is introduced in area-1 of the multisource power system with nonlinearities and interconnected via AC/DC parallel tie-links. The change in frequency is shown in Fig. Fig. 21. The amplitude of most random loads is in the range of -0.04 pu to 0.04 pu. The result shows that under the control of the type-03 operating strategy, the two-area system still has a good resistance to high-frequency disturbances. The deviation of the frequency lies between the range of ±0.01 Hz i.e. $49.99\,Hz \leq F_1 \leq 50.01\,Hz$.

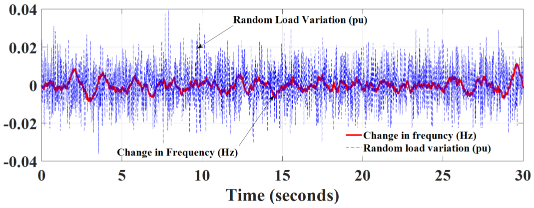
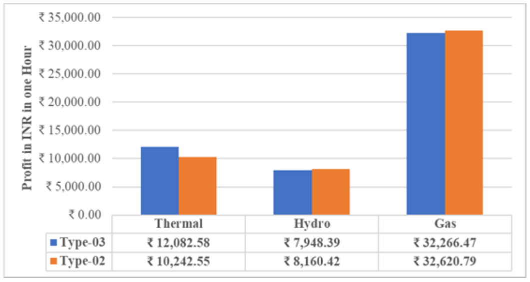


Fig. 21. Change in area-1 frequency with consideration of random loading and FLP type-03 operating strategy under ABT.

The performance of FLP-based operating strategies type-02 and type-03 has been evaluated from the different perspectives of accounting and economics associated with them as well. The UI Charges corresponding to the frequency deviation for one hour in four blocks of 15 minutes have been considered for accounting charges. The corresponding generation by each generator in Area-01 has also been considered in a similar way. Thus, Table 2 and Table 3 depicts the values of accounting for the individual generators operated under FLP type-02 and 03 operating strategies respectively. Based on these, the as-per-net accounting carried out for each generator in INR during one hour is shown in Fig. 22. The net sum aggregated by area 1 in one hour is depicted in Table 4. This has been computed based on a comparison carried out for the profit earned by each generator in the case of operating under type-02 and type-03-based strategies. Comparison reveals that around Rs. 1,273.68 more profit can be achieved aggregately by Area-01 in one hour if generators are operated by the FLP type-03 operating strategy, as depicted in the table below:



	Thermal	Hydro	Gas
Type-03	₹ 12,082.58	₹ 7,948.39	₹ 32,266.47
Type-02	₹ 10,242.55	₹ 8,160.42	₹ 32,620.79

Fig. 22. Profit incurred in one hour by various generators of area-1 with consideration of FLP type-02 and type-03 operating strategy under ABT.

5. CONCLUSIONS, OBSERVATIONS & FUTURE SCOPE

This paper includes the main concluding points and observations as mentioned below:

1) A multisource power system with nonlinearity and interconnected via AC/DC tie-lines that includes several traditional units (i.e., thermal, hydro, and gas) has been presented in this work to assess the effectiveness of the operating control strategies combining system frequency and unscheduled interchange charges under ABT.
2) Several scenarios have been represented in this work to study the effectiveness of the suggested operating strategies in tackling the problem of LFC, such as the consideration of nonlinear parameters in the modeling of the components involved in LFC, the consideration of AC/DC parallel tie-links, and the application of different load variation types: step load perturbation, variable loading, and random loading.
3) The robustness of the different types of FLP-based operating strategies under ABT for LFC has been confirmed by a fair

Table 2. For generators operated by FLP type-02 strategy.

Time in sec	**UI Charge Rs/MWh**	**Generation in MW**			**Accounting in INR (Profit)**		
		Thermal	**Hydro**	**Gas**	**Thermal**	**Hydro**	**Gas**
0 to 900	₹ 3,446	4.753	5.617	8.983	₹ 4,094.71	₹ 4,839.05	₹ 7,738.85
901 to 1800	₹ 3,027	2.708	1.463	10.96	₹ 2,049.28	₹ 1,107.13	₹ 8,293.98
1801 to 2700	₹ 3,027	2.708	1.463	10.96	₹ 2,049.28	₹ 1,107.13	₹ 8,293.98
2701 to 3600	₹ 3,027	2.708	1.463	10.96	₹ 2,049.28	₹ 1,107.13	₹ 8,293.98
	Total				**₹ 10,242.55**	**₹ 8,160.42**	**₹ 32,620.79**

Table 3. For generators operated by FLP type-03 strategy.

Time in sec	**UI Charge Rs/MWh**	**Avg. Change in Generation in MW**			**Accounting in INR (Profit)**		
		Thermal	**Hydro**	**Gas**	**Thermal**	**Hydro**	**Gas**
0 to 900	₹ 3,450.00	4.915	5.658	8.966	₹ 4,239.19	₹ 4,880.03	₹ 7,733.18
901 to 1800	₹ 3,026.00	3.456	1.352	10.81	₹ 2,614.46	₹ 1,022.79	₹ 8,177.77
1801 to 2700	₹ 3,026.00	3.456	1.352	10.81	₹ 2,614.46	₹ 1,022.79	₹ 8,177.77
2701 to 3600	₹ 3,026.00	3.456	1.352	10.81	₹ 2,614.46	₹ 1,022.79	₹ 8,177.77
					₹ 12,082.58	**₹ 7,948.39**	**₹ 32,266.47**

Table 4. Comparision of type-02 & type-03 FLP based operating strategies.

Type of Generator of Area-1	**Accounting in INR for type-03**	**Accounting in INR for type-02**	**Relative Accounting (INR) in one hour**
Thermal	₹ 12,082.58	₹ 10,242.55	₹ 1,840.03
Hydro	₹ 7,948.39	₹ 8,160.42	-₹ 212.03
Gas	₹ 32,266.47	₹ 32,620.79	-₹ 354.32
Total Profit in INR	**₹ 52,297.44**	**₹ 51,023.76**	**₹ 1,273.68**

comparison between their performance and the performance of other traditional strategies based on the area control error from the literature.

4) The performance of FLP type-01-based operating strategies (exactly practiced) under the ABT regime is highly affected by variations in area clearing prices (ACP). The performance gets degraded with the rise in ACP. whereas FLP type-02 and type-03-based operating strategies (with applied modification) remain almost intact even under variations of ACP in a wide range.
5) The FLP type-02 and type-03-based operating strategies outperform in comparison to FLP type-01 operating strategy and are found suitable in a relative comparison carried out on the technical aspects of assessing frequency regulation, i.e., settling time, frequency nadir, and overshoot.
6) The FLP Tye-03-based operating strategy is identified as relatively better under various challenging scenarios considered amongst all the applied strategies based on both types of considerations: technical as well as economical accounting.
7) The FLP-based operating strategies encourage efforts by generating players to maintain and support system frequency by incentivizing their participation in LFC.
8) The FLP-based operating strategies also fairly manage tie-line power deviations.

The work can be extended further by introducing renewable energy sources and energy storage components that participate in frequency regulation.

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APPENDIX

Thermal turbine with reheater:

- Governor & Turbine time constants in sec $-T_{g1} = 0.08$; $T_{g2} = 0.08$; $T_{t1} = 0.3$; $T_{t2} = 0.3$;
- Coefficient of reheater steam turbine and its time constant $-K_{r1} = 0.3$; $K_{r2} = 0.3$; $T_{r1} = 10$; $T_{r2} = 10$;

Hydro turbine:

- Hydro turbine speed governor transient droop Time constant $-T_{RH1} = 28.75$; $T_{RH2} = 28.75$; Hydro turbine speed governor main servo time constant $-T_{GH1} = 0.2$; $T_{GH2} = 0.2$;
- Hydro turbine speed governor reset time $-T_{R1} = 5$; $T_{R2} = 5$;
- Nominal starting time of water in penstock $-T_{W1} = 1$; $T_{W2} = 1$;

Gas Turbine:

- Gas turbine speed governor lead time constant $-X_1 = 0.6$; $X_2 = 0.6$;
- Gas turbine speed governor lag time constant $-Y_1 = 1$; $Y_2 = 1$;
- Gas turbine constant of valve positioner $-b_1 = 0.05$; $b_2 = 0.05$; $C_1 = 1$; $C_2 = 1$;
- Gas turbine combustion reaction time delay $-T_{CR1} = 0.3$; $T_{CR2} = 0.3$; $C_1 = 1$; $C_2 = 1$; Gas turbine fuel time constant $-T_{F1} = 0.23$; $T_{F2} = 0.23$;
- Gas turbine compressor discharge volume time Constant $-T_{CD1} = 0.2$; $T_{CD2} = 0.2$;

System Data:

- Power rating of each control area = 2000 MW;
- Droop in $Hz/pu\,MW - R_{t1} = 2.4$; $R_{t2} = 2.4$; $R_{h1} = 2.4$; $R_{h_2} = 2.4$; $R_{g1} = 2.4$; $R_{g2} = 2.4$;
- Thermal power generation contribution $-K_{t1} = 0.6$; $K_{t2} = 0.6$;
- Hydro power generation contribution $-K_{h1} = 0.3$; $K_{h2} = 0.3$;
- Gas Power generation contribution $-K_{g1} = 0.1$; $K_{g2} = 0.1$;
- Area size ratio = -1;
- Tie line power coefficient $-T_{12} = 0.0433$;
- Bias Constants $-B_1 = 0.425$; $B_2 = 0.425$;
- Inertia constant $-H_1 = 5$; $H_2 = 5$;
- Gain constant of power system $-K_{P1} = 120$; $K_{P2} = 120$;
- Time constant of power system $-T_{P1} = 20$; $T_{P2} = 20$;
- Power rating of each control area $\breve{}\,2000MW$;

- Controller gains $-k_{d1} = -1.2716$; $k_{P1} = -6.3749$; $k_{i1} = -4.1687$; $k_{d2} = -1.1735$; $k_{p2} = -5.9635$; $k_{i2} = -2.8757$;

Boiler dynamics

- k1; k2; k3 = 0.85, 0.095 and 0.92 respectively;
- CB = Storage constant of the boiler = 200;
- TD; TF = Fuel system time constant = 20 s, 40 s;
- KIB = Gain of the pressure control = 0.030;
- TIB; TRB = Time constant of pressure control = 26 s, 69 s; Generation Rate Constraint for Thermal is ±0.0017 pu MW/sec; for Hydro +0.045 pu MW/min and -0.06 pu MW/min and Governor Dead Band=0.06%.