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Load Frequency Control in Power System: A Short Review

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Abstract—LFC plays its significant role to keep expanded multi-source power generation systems in synchronism through adapting the real-time power outputs. In fact, the basic concept is to identify the frequency alterations or alterations from the power grid and also the adjustment of output of some distinct generator sets. This research work reviews 18 papers under LFC by considering certain parameters like methodology, performance measure, and best performance measure.

Keywords—Power System; LFC; Generating unit; Renewable resource;

Nomenclature

Acronym	Description
Distributed generations	DGs
Renewable Energy Sources	RESs
hybrid power system model	HPSM
Load frequency control	LFC
Optimal Load Frequency Control	OLFC
vanadium redox flow battery	VRFB
hybrid optimization model	HOM
proportional-integral-derivative	PID
multi-objective Fractional-Order Fuzzy proportional–integral–derivative	MOFOFPID
Microgrids	MGs
battery energy storage systems	BESS
vehicle-to-grid	V2G
modified black hole optimization algorithm	MBHA
hardware-in-the-loop	HIL
Photovoltaic	PV
quasi-Newton	QN
simultaneous perturbation stochastic approximation	SPSA
Neural Network	NN
fractional order proportional-integral-derivative	FOPID
thyristor controlled series capacitor	TCSC
Active disturbance rejection control	ADRC
hybrid power system model	HPSM
tidal power plant	TPP
quasi-oppositional harmony search algorithm	QOHSA
integral sliding mode control	ISMC
integral higher order sliding mode control	IHOSMC
sliding mode	SM
Electric Vehicles	EVs
Model Predictive Contro	MPC
Distributed Energy Resources	DERs
Automatic Generation Control	AGC
Direct Load Frequency Control	DLFC
adaptive event-triggering communication	AETC
Squared Errors	SSE
Mean Absolute Error	MAE
Mean Square Error	MSE

I. INTRODUCTION

The Electricity market deregulation has fascinated some new renewable forms of generation system, which is termed as DGs. RESs that is on the basis of power generating units are stochastic in terms of power output. Hence, the utilization of DGs with fossil fuel-fired that is on the basis of power generating units have generated a novel new HPSM. In fact, DGs are economical as well as environmentally appropriate. Nevertheless, the RESs' high penetration might affect the quality of power, stability as well as reliability of conventional electrical power system (that has existing generating units). In the recent power system dynamics, the generation control and frequency are the most significant problem in the operation of reliability. In this, LFC plays the significant role on keeping varied multi-source power generation systems [19] [20] [21] through the regulation of real power outputs. Basic concept is the identification of frequency change from power grid and for adjusting the output of some distinct generator sets as per the design rules so that the power grid frequency is restored for a distinct value. The key issue on for LFC the designing of rules, i.e. load frequency design problem.

Further, it is very much important to identify the change in frequency from power grid and for transmitting the needed adjustment for the respective generator set. The compilation of measurements, as well as controls transmission, requires the utilization of communication networks. Such open network could not realise a huge count of data accusation as well as data exchange in the broad range sense, however, it also raises certain issues like processing of information as well as transmission, data transmission in non-continuous way along with loss of packet that acquired through the congestion of network and further factors, and that affects the real-world data exchange, ensuing in huge as well as time-varying delay. The respective delays would unavoidably minimize the control impact of designed LFC without the consideration of time delay, which also leads to the breakdown of those controllers; this would seriously influence the power grid's safe operation. This paper makes a review on 18 papers under LFC by considering the facts like methodology, performance measure, and best attained measures. The rest of the paper is organized as follows: Section II reviews the literature work. Section III details the research works and challenges. Section IV concludes the paper.

II. LITERATURE REVIEW

A. Related Works

In 2016, Rinaldi *et al.* [1] have developed a model basis of Third Order Sliding Mode Observer for Optimal OLFC in power, and that was subdivided into control areas. They have modeled every area through the equivalent generator along with second-order turbine-governor. With the measuring assumption of little state variables, they have designed the mode of two-third order sliding on every control area for locally assessing the unmeasured aspects. They have also introduced a distributed 2nd sliding mode control approach that makes use of observer assessment and could attain both frequency regulation as well as generation costs reduction. Finally, the simulation outcomes have confirmed the validity of developed model.

In 2017, Marcelo *et al*. [2] have developed a new model for VRFB optimal sizing, which has aiming at granting the LFC of power system along renewable generation of power including wind generation. The corresponding model has utilized a novel optimization issue, in which the VRFB's optimal size was an endogenous outcome from the approach of optimization issue. In order to solve the novel optimization issue, the authors have employed a HOM for evaluating the optimal assessment of VRFB (optimal size) during the consideration of both power system impact and its quality. By the stochastic optimization, the developed HOM has allowed the evaluation of the cost of variable operating and the investment cost of VRFB with the consideration of uncertainties related to PS. This respective stochastic optimization has used a novel quasi-stationary simulations that demands the lower computing effort. For this purpose, this research work has proposed a new modeling approach of VRFB as well as PS operation. Further, they have proposed statistical indexes as the novel factor and has utilized in LFC operating reserve sizing. Finally, the outcomes have shown that the proposed model could permit the assessment with stochastic characteristics precision of PS.

In 2017, Guha *et al.* [3] have made a maiden attempt for deriving an optimal as well as efficient outcome of LFC by a new algorithm namely multi-verse optimization. In order to prove the efficiency, they have investigated a 4-area hydrothermal power plant and subsequently, they have studied the 5-area thermal power plant. In order to improve the dynamic stability, the authors have designed an appropriate PID plus double derivative controller (PID + DD), and that was comprised in the control fields. They have proven the superiority of developed model over other conventional algorithms via the transient analysis approach.

In 2017, Khooban *et al.* [4] have proposed an adaptive MOFOFPID controller for the LFC of islanded MGs. Even though the utilization of BESS could resolve the unbalance impacts among load as well as isolated MG supply, their great cost on degradation were the factors that demand the utility of the some other power balancing options. Nowadays, the concept of BESSs utilization that was also called as V2G has gotten greatest attention. For permitting the V2G controller for optimal operation, the authors have developed a novel multi-objective fractional-order control approach for the EVs under V2G fields. Further, as the controller performance purely based on their respective parameters, its optimization could play a vital role in generating the resultant

performance of LFC control; thus, a MBHA was used to do the adaptive tuning of PID controller coefficients (non-integer fuzzy). Finally, the developed LFC performance was formulated through real-time world wind data as well as data related to solar radiation. Finally, the extensive investigation, as well as HIL simulations works, were described for proving that the developed controller tracks frequency that has reduced variation and fluctuation was very effective when compared to other conventional controllers.

In 2017, Khooban *et al.* [5] have stated that because of the rapid renewable systems' enhancement and the severe restriction done by Marine Pollution Protocol, the wind turbines usage, utility of solar generation, as well as energy storage systems have gotten greatly attracted been. Thus, the marine vessel power system along with PV, SWE, WT as well as ESS could be concerned as the distinct mobile islanded microgrid. Subsequently, this research work has designed a novel optimal Fractional Order. As the controller's performance is purely based on its parameters, the optimization plays its vital role in granting the output LFC control performance. As per, MBHA was used to get adaptive coefficients tuning of non-integer fuzzy PD+I controller. Finally, the assessment of shipboard microgrid was done under the real time environ thgrough solar radiation data, and the final results have proven the superiority of proposed model over other methods.

In 2018, S. Mohsen Azizi and S. Ali Khajehoddin [6] have designed a decentralized controller in an optimal manner to control the LF of a multiarea islanded grid along different synchronous generation systems. Further, the decentralized controller comprises of different PI controllers were developed and had also optimized through classical descent-direction QN-based model. Finally, the simulation outcomes have confirmed the superiority of developed decentralized PI control model..

In 2018, Dong *et al.* [7] have stated that for meeting the demands of the new power system, they have developed a new data-driven control model, which could resolve the problem of LFC along complete analysis of convergence rate. The respective model was designed on the basis of SPSA approach and the ensemble of NN. They have developed the data-based controller, and that was fixed under NN. Being the control parameters, at every iteration, the NN's connection weights get updated. To enhance the overall controlling accuracy rate and also for getting more stable controlling performance, the authors have developed the concept of NN ensemble for the designing of data-based controller structure. The developed data-based controller includes the previous as well as the present system data as the input informtion and has produced the control signal, which could affect the performance of future system, and while doing the total process, it was nor required in building the the mathematical approach for the controlled plant. They have also introduced the one-area LFC issue with the uncertainties of system parametric along with the typical two-area LFC for the purpose of simulation tests, and the posibility, as well as superiority of novel developed data-based LFC approach, was also revealed.

In 2017, Javad *et al.* [8] have compared the fractional order phase lead-lag controller, FOPID, along with damping controller that was on the basis of tilt-integral-derivative controllers as TCSC for improving the performance of LFC. In order to prepare the effective ancillary service, the authors have presented an optimal evaluation for TCSC participation in tie-line power flow exchange, and that was compared to the previous Taylor-based approximated approach. They have adjusted the controller parameters through the employment of various evolutionary algorithms. In order to attain realistic outcomes on the competitive environ, they have considered various-GENCOs. They have demonstrated that the non-linear time-domain simulations could suppress the area frequency as well as oscillations of tie-line power. Furthermore, examinations were done for uncontracted higher order step for confirming the betterment of developed fractional order controllers-based TCSC–LFC over other methods.

In 2018, Fu and Wen [9] have studied the decentralised LFC for multi-area power systems along delays in communication. They have adopted the ADRC approach for handling the delays in communication. Initially, the existing ADRC was tuned through the bandwidth approach, which was shown that the delayed systems' achievable performance was not so effective than the PID controllers. Then, the authors have discussed about the altered ADRC structure , which was reviewed that the performance was restricted by the bandwidth of controller. To enhance the performance, an approach for tuning the ADRC parameters was developed through the internal model control approach. Finally, the simulation outcomes have shown that the developed approach was simpler in applying as well as could attain better damping performance.

In 2017, Xin *et al.* [10] have stated that the time delay that because of communication network would influence the power system's LFC that comprising of multi-microgrids. The multi-area power system that includes more standard microgrids connection along tie lines was developed. Then, they have constructed the LFC equivalent, which was on the basis of time delay consideration. Consequently, they have designed a coordinated controller that was on the basis of predictive algorithm for dealing with the disturbances of load and the wind power fluctuation along the delays in communication. Finally, they have conducted the case studies and has demonstrated superiority of developed model over other existing controllers.

In 2018, Kumar and Gauri [11] have explored the performance analysis of autonomous HPSM's LFC that includes the TPP as well as diesel power plant. They have also adopted the concept of deloaded TPP for utilizing the suitable reserve power. Further, the examination approach has incorporated the frequency regulation via damping control as well as inertia, supplementary control modalities. The respective control

approaches were realized via existing controllers, in which the values of gain were optimized by QOHSA. The proposed QOHSA efficiency was demonstrated through the comparison of proposed and existing algorithms.

In 2018, Kanti *et al*. [12] have aimed for designing a higher order sliding mode control for the issue of LFC by decentralised control model. Then the developed controller ensures the alterations in frequency in total areas due to the coverage of load disturbance to zero in finite time. Finally, the outcomes were compared to the attained performances by ISMC as well as IHOSMC. Subsequently, the developed controller aids in attaining the finite time convergence of frequency change because of load disturbances were compared with the attained one by ISMC and IHOSMC. The controller performance was tested for the concerned plant with non-linearities exists in power system including conditions of generation rate and governor deadband. Moreover, the validation of developed controller over random load disturbances was done and proven the superiority of proposed system.

In 2017, Yang *et al.* [13] have developed a novel model for the issue of stability, one-area and multi-area LFC model along time delays. They have derived the new stability criteria along delay dependency with respect to inequalities of linear matrix for LFC systems through the augmented Lyapunov–Krasovski functional. The design of LFC takes the interval time-deviating communication delays, and they have also modeled the load disturbance as the non-linear function (normbounded). Further, the examination has suggested a novel class of inequality by the intermediate auxiliary functions, and that could grant high tighter bounds. Finally, certain case studies have taken place for illustrating the efficiency of developed design model.

In 2017, Mi *et al*. [14] have stated that the interconnected power system (time-delay) has turned into the vital issue for the open communication network. Further, because of output power fluctuation, power system's LFC with variable loads as well as sources have become highly challenging. The authors have developed a new decentralised SM- LFC approach for the power system (Multi-area time-delay) with vital penetration of wind power. They have also chosen the suitable switching surface gain for ensuring the power system's stability with mismatched uncertainties. Here, the construction of SM was done for satisfying the hitting constraints. Finally, the superiority of proposed work was verified using some real world experimentation (digital simulators) with various time delay case, wind penetration, as well as operating point. Then, the developed SM LFC could minimize the deviations of frequency and tie-line power fluctuation.

In 2017, Khooban [15] have used a novel novel optimal model-free controller that was on the basis of sliding mode approach for making the balance among load demands as well as power generations in MG system along EVs. A novel modified optimization algorithm, namely Black Hole algorithm was determined for tuning the developed model-free technique's coefficients. At last, for validating the possibility of suggested model under load disturbances, the authors have done the detailed simulation work and the results have also proven.

In 2017, Kayalvizhi and Vinod [16] have presented a fuzzy adaptive model predictive model for LFC of isolated micro grid. They have also derived the isolated micro grid that has controllable as well as uncontrollable power sources. This was for predicting the future output as well as control inputs to the control of micro grid frequency. Along with this, they have also implemented a MPC along single input system model that was on the basis of controllable DERs. Finally, the efficiency of utilizing developed fuzzy MPC was validated thereof.

In 2017, Alexander *et al.* [17] have developed a fast as well as tuningless frequency control model, which tackles the limitations of LFC in terms of new grid monitoring as well as communications infrastructures. Initially, the supply's direct observation along with the demand reviews rapid power balancing from the total system dynamics. Next, to this, the primary resources were actively evolved in frequency restoration through the systematic adjustment. Contrarily to the usual AGC, the developed DLFC could not need the integrator to do the frequency controlling under partial grid observability. They have also performed an examination of AGC under 3 area power system in a real-time laboratory grid.

In 2017, Peng, *et al.* [18] have investigated an adaptive event-triggering H1 LFC approach for the systems. The authors have developed the AETC approach, in which the event-triggering threshold could be adjusted dynamically for saving more restricted network resources during the preservation of needed control emulation-based approach that the controller might known a priori, they have derived the stability as well as stabilization criteria, which has granted the tradeoff for balancing the needed resources like communication and the desired control performance. The efficiency of developed approach was also validated through two numerical instances.

B. Algorithmic Analysis

Fig 1 depicts the algorithmic analysis that the contributions used. Here, various LFC controlling schemes have been used. Particularly, Third Order Sliding Mode Observer-based approach is used in [1]. In [2], the authors have used HOM, multi-verse optimization is the method used in [3]. The authors of [4] used MOFOFPID controller. A new optimal Fractional Order Fuzzy PD+I LFC is the model of [5]. Descent-direction QN is in [6]. SPSA is the model in [7]. In [8], TCSC based dampling controller is developed. ADRC method is proposed in [9]. In [10], multi-area power system is developed. autonomous HPSM is the model used in [11]. the authors of [12] have used ISMC for LFC. Lyapunov–Krasovski functional [13] a new model used for LFC.

In [14], novel decentralised SM LFC approach is developed. Optimal model-free controller is developed by [15]. In [16], the authors have developed centralized (MPC. DLFC is developed in [17]. Adaptive event-triggering H-infinity LFC scheme is in [18].

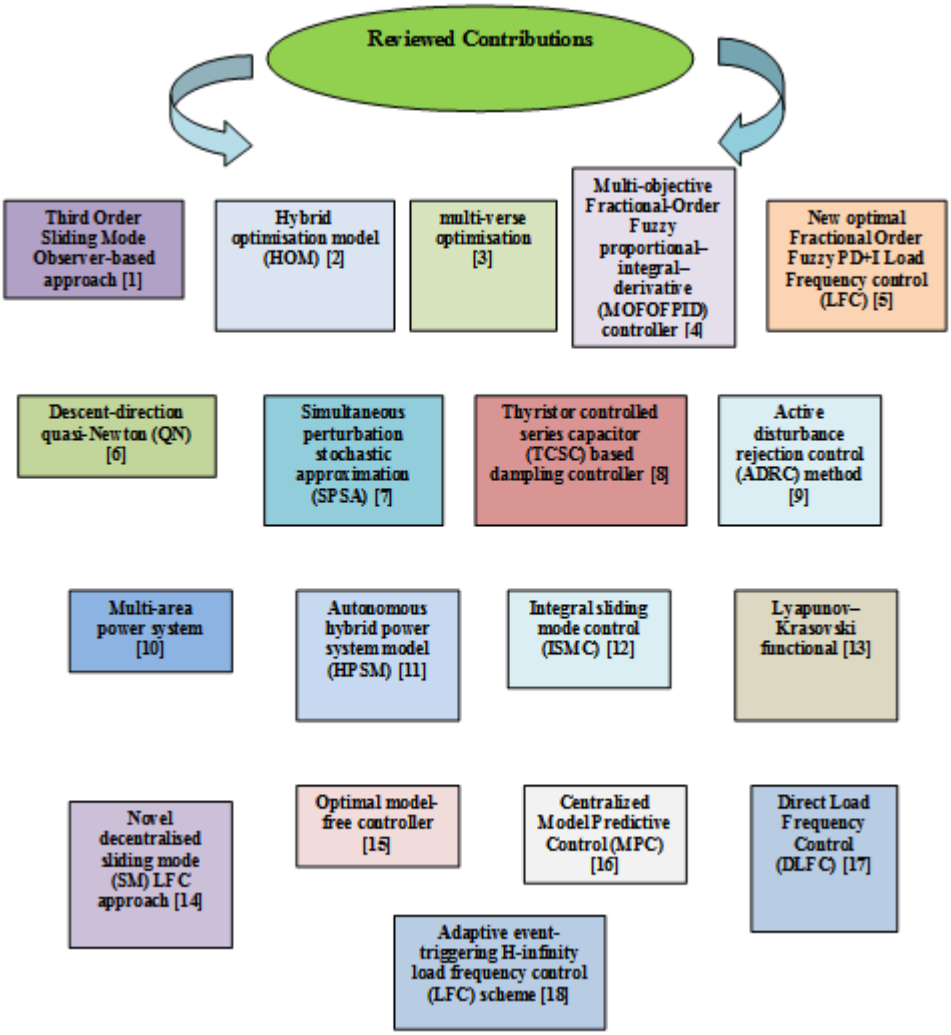

Fig. 1: Algorithmic Analysis

C. Performance Measure

Table I summarizes the performance measures that used in reviewed contribution works. In this, 66.66% of contributions have used the turbine power variation for load frequency control. Then, 60% of contributions have used the measure like frequency domain. The Annual investment cost is used by 6.66% of reviewed works. Then the ENS cost is utilized by 13.33% of contributions. 13.33% of contributions have used the load deviation measure and tie-line power measure to analyze the performance of LFC model. Similarly, the frequency error is a measure that used by only 6.66% of contributions. Then, the measures like SSE, MSE, and MSE are used by 6.66% of reviewed works.

TABLE I. PERFORMANCE MEASURES OF DIFFERENT CONTRIBUTIONS

Citation	Turbine power variation	Frequency deviation	Annual investment cost	ENS cost	Load deviation	Tie-line power error	Frequency error	SSE	MAE	MSE
[1]	□	□								
[2]			□	□						
[3]		□								

[4]		□			□					
[5]		□			□					
[6]						□	□			
[7]		□								
[8]		□				□				
[9]										
[10]		□								
[11]										
[12]										
[13]		□								
[14]		□								
[15]								□	□	□
[16]		□								
[17]				□						

D. Maximum Achieved Measures

The achieved best measure is given in Table II. Here, it is observed that the power variation in [1] is $16*10^{-3}$ p.u. The generation cost of [2] is 2006$/h. In [4] and [5], the authors have used the load deviation, and the attained best value is -0.05pu. Almost in all papers, the measure like frequency deviation is used, and the best value of this measure is 0.001Hz. [6] and [8] has used the Tie-line power error, and the best attained value is 0.019p.u. The best random load is 0.02. The error rate SSE is attained as 0.7301, MAE is 0.0020 and Average time is 1.9355h.

TABLE I. NED BEST MEASURE

Measures	Best Value	Citation
Power variation	$16*10^{-3}$ p.u	[1]
Generation cost	2006$/h	[2]
Load deviation	-0.05pu	[4] [5]
Frequency deviation	0.001Hz	[1] [3] [4] [5] [7] [8] [10] [13] [14]
Tie-line power error	0.019p.u	[6] [8]
Random load	0.02	[8]
SSE	0.7301	[15]
MAE	0.0020	[15]
Average time	1.9355h	[18]

E. Renewable Energy Source

This section explains the contribution of renewable energy sources in the LFC models (Fig 2). From this, it is observed that the wind renewable energy source has given 61.11% of contribution from the total works and the remaining 46.66% of contributions have worked on other renewable resources.

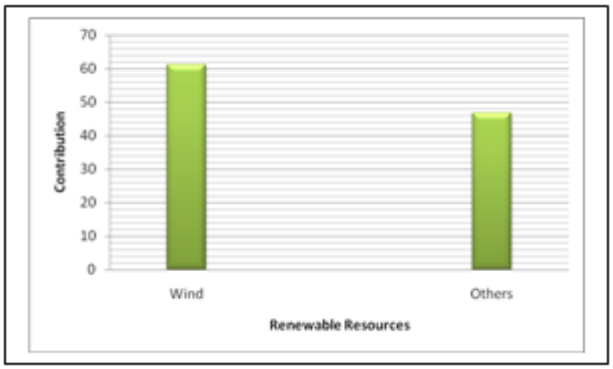

Fig. 2: Contribution of Renewable Energy source

III. RESEARCH WORKS AND CHALLENGES

Even though the LFC modalities show their effective performance, some barriers are still exist that needs further further study on solving it. As the performance is purely depends on its parameter, some other advanced optimization algorithmic programs are need to do the optimization, and the performance evaluation is also a major core. An important challenge in LFC is frequency deviations and alterations in line power. Hence, certain controllers must be utilized in future for managing the deviations and alterations. Additionally, system implementation can be done in multi-area, and the performance evaluation should be studied more properly. The LFC that interconnects control areas is the most challenging issue, and the same is unsure if the present implementations are enough for dealing the demanding share of renewable energy sources. The reserve power raises the cost of generation as, on a single side, it poses the requirement of dispatching a huge generating units and, meanwhile, the generating units, which do the supply of reserve should be dispatched at reduced effective operating points. Further, the challenge that is to be rectified is minimization of load disconnection probability. Moreover, the reserve assigned for LFC would affect the quality of power and the power system's operation as well, which is very much required to take into account and needs some additional optimization model.

IV. CONCLUSION

This research work has reviewed 18 LFC contributions, which has analyzed in terms of diagrammatic representation and tables. The methodologies were represented, and the performance measures that used in all contributions were signified in tables and the best values attained were also described. Finally, the most important research gaps and challenges regarding the LFC were also clearly described.

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