Power system frequency control: an updated review of current solutions and new challenges

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ABSTRACT

Frequency control of power grids has become a relevant research topic due to the increasing penetration of renewable energy sources, changing system structure and the integration of new storage systems, controllable loads and power electronics technologies. The advances in control, communication and computation technologies also contribute to the development of novel techniques and solutions. This paper provides an updated review on most important frequency stability concerns, modern control strategies, and challenges for the integration of renewable energy sources, current trends, recent achievements, and new research directions.

Keywords: Frequency control, renewable energy, virtual inertia, synchronous generator, demand response, microgrid

(Word count: 9238)

List of abbreviations:

ACE	Area Control Error
AGC	Automatic Generation Control
DR	Demand Response
DG	Distributed Generation
ESS	Energy Storage System
EV	Electric Vehicles
GRC	Generation Rate Constraint
HV	High Voltage
HVDC	High Voltage DC
LFC	Load-Frequency Control
MG	Microgrid
MGCC	Microgrid Central Control
RES	Renewable Energy Source
SG	Synchronous Generator
SOC	State of Charge
VSG	Virtual Synchronous Generator
WT	Wind Turbine

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1. Introduction

Frequency stability is the ability of an electric network to regulate its frequency within the permitted/nominal operating range. Frequency instability is often a result of a serious imbalance between the grid total generation and load. It is usually combined with a poor coordination of protection devices and control systems, as well as insufficient system responses and power reserves [1].

Since the frequency of a power grid is proportional to the rotation speed of the synchronous generators (SGs), the frequency stability issue can be directly connected to the rotor speed regulation of the power grid generating units. This problem is basically solved by adding a system, i.e., governor which feedbacks the generator speed, and tunes the input actuator to change the output power to follow the load variation and finally to control the system frequency close to the specified nominal value.

Preliminary efforts in the field of power grid frequency regulation are reported in [2]. Subsequently, the IEEE working group prepared some standard definitions of significant terms and concepts on power system frequency control [3]. The first optimal controller synthesis for megawatt frequency regulation in multi-area power grids including of two identical generating units of non-reheat thermal turbines was reported in [4, 5]. A comprehensive survey and exhaustive bibliography on frequency control up to 2014 is given in [1, 6].

Frequency stability and control in today`s power systems faces some new challenges arising from the growing integration of power electronics based distributed generators (DGs) and loads. Key challenges are because of the reduction of overall system rotational inertia, as power electronics based DGs and renewable energy sources (RESs) are gradually replacing the SGs [7]. Reducing inertia in a power system can negatively affect the grid frequency response, voltage and control systems, and may degrade the conventional frequency control capability and performance. This may lead to significant frequency changes, load shedding, and even frequency instability [8, 9]. Decreasing power grid inertia due to high penetration of power electronic interfaced DGs makes system balancing power and frequency control extremely challenging. Emerging variable renewable power production significantly magnifies this problem [10].

Emulation of inertia and proper shaping of injected active power from controlled power sources are known promising solutions. Furthermore, increasing integration of power electronic interfaced DGs/RESs motivates the necessity of proposing additional regulation power and new ancillary services to compensate frequency deviations [11]. The regulation power reserve provided by microsources/DGs and Microgrids (MGs) may support the system robustness against various disturbances and reduce frequency fluctuations. Due to the fast response of power electronic interfaces, this regulation power can be injected into the grid in relatively short time [12].

Demand response (DR), i.e. the idea of controlling loads and flexible demand side units, also provides a promising scheme for power grids frequency regulation [13]. The switching-based control ability of equipment on the load side enables the demand to respond faster to system disturbances, in comparison of conventional bulk SGs. This function together with the recent advances in monitoring, computing and communication technologies introduce the load-side units as ideal candidates for the grid frequency control.

Increasingly, the important of information and cyber part in a modern power grid as a complex cyber physical system has highlighted the frequency control from the attack scheme perspective [14, 15]. Although rapid progress in cyber part offers many advantages in frequency regulation issues, it may also increase the attack risks of cyber intrusion and unreliability problems.

This paper reviews and updates the status of power system frequency control and identifies a number of future research directions that required to be addressed in the synthesis and control of future power grids. Research needs and major challenges for the integrated assessment of new generation sources with enhanced frequency control capabilities are also discussed. Existing challenges and new control possibilities are explained. Following a brief updated review in Section II, frequency response characteristics are described in Section III. Various frequency control loops and new control possibilities are discussed in Section IV. The conclusions and future work are emphasized in Section V.

2. Frequency control: A brief updated review

Frequency response as a means to stabilize grid frequency after a disturbance/fault is assessed with respect to frequency nadir, steady state deviation, a dynamic rolling window and rate of change of frequency. Power system non-linearities, including speed governor dead-band impacts, system generation rate constraint (GRC), and communication delays may affect the frequency dynamics of interest. The available studies on the power grid frequency regulation in areas of analysis and synthesis are graphically summarized in Fig. 1.

Frequency control synthesis covers the frequency control designs in different control levels, i.e., droop-based or primary control, secondary control that is also known as load-frequency control (LFC), tertiary control, emergency control, demand control, and new control supports. LFC and tertiary control loops must be considered with the system security control, automatic generation control (AGC), and economic dispatching. Control supports contain the regulation supports coming from energy storage systems (ESSs), DGs/MGs, virtual synchronous generators (VSGs), and the required coordinators. Emergency control covers all control and protection schemes that are necessary in contingencies and emergency conditions.

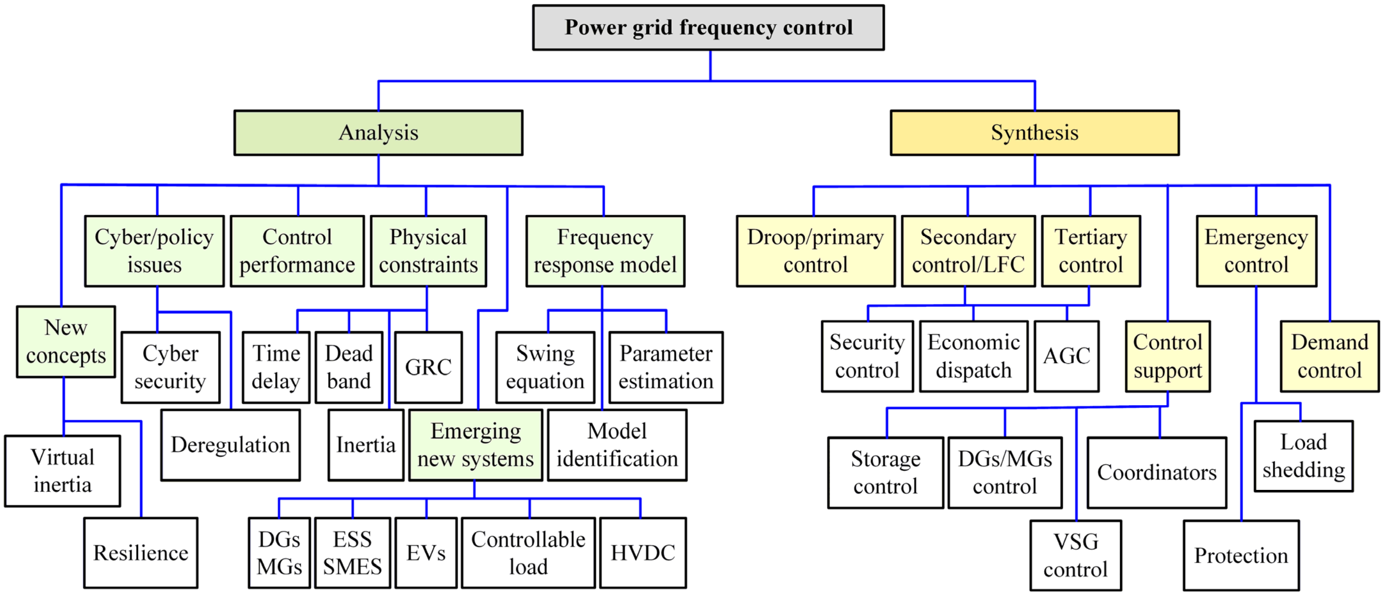

Fig. 1. Analysis and synthesis studies of power grid frequency control.

Frequency control analysis mainly addresses frequency response modeling, physical constraints, control performance standards, cyber security and deregulation policy issues, applications of new concepts such as virtual inertia and resilience, and emerging of new systems, e.g., DGs/MGs, ESSs and superconductivity magnetic energy storages (SMESs), electric vehicles (EVs), high voltage DC (HVDC) systems and controllable loads. Communication channels time delay, governor dead band, GRC, and rotating mass inertia are the most important physical constraints in frequency control and modeling analysis. The well-known load-generation swing equation, measurement-based parameter estimation and data-driven model identification are useful methods for proposing power grid frequency response models. With reference to the mentioned classification (Fig. 1), a brief updated review is given in the rest of this section.

Considering the physical constraints and to cope with the advances in technologies and the changed system environment, dynamic modelling developments, security constraints, and communication delays, as well as modifications on the frequency control definitions have been discussed over the years [16-20]. The study on system GRC was initially started in 1983 [21]; then, numerous research works were conducted on system nonlinearity dynamics behaviors like governor dead band and GRC [22-25]. Accordingly, a system GRC of 3% $MW_{p.u.}/min$ was used to limit rate of change of thermal generating units output power, while the GRCs of 270%, 360% $MW_{p.u.}/min$ were applied for hydro generating units, respectively [21].

Some research considered load characteristics/dynamics [26-29] and the relationship between the frequency/active-power and voltage/reactive-power controllers [30-32] in the frequency controllers synthesis process. Moreover, frequency control analysis, frequency response modelling, nonlinearity and uncertainty presentation, specific applications, frequency bias calculation, control performance standards and parameters identification are presented in several documents [8, 19, 33-43].

The usage of communication channels, even dedicated channels or open communication networks, addresses time-delay in frequency control design frameworks. Communication time delays may render frequency dynamics faster, and even cause system instability. While dedicated communication channels introduce constant delays which could be neglected according to their smaller value in comparison to the slow frequency dynamics, open infrastructure introduces time-varying and random delays and hence should be tackled into the stability problem formulation. Considerable research on the time-delayed system is contained in [1, 20, 38]. Some frequency response models and control design methodologies are presented to adapt well-known conventional secondary control or LFC systems to the changing of grid operation under various deregulation policies [44-55]. The effects of deregulation on the LFC system and some different operation scenarios for deregulated power grids are extensively explained in these reports.

A comprehensive research is performed on the applications of advanced optimal/intelligent control methodologies to synthesis more flexible and effective secondary frequency control loops [56]. The attempts were done to use modern intelligent control methodologies for designing of powerful LFC systems. These efforts have finally led to optimize a cost function subjected to some constraints to full satisfy all defined secondary frequency control goals by optimal control Methodologies. In addition to these synthesis techniques, several self-tuning and adaptive control strategies are widely applied for power grid LFC system synthesis over the years [31, 57-60].

Considering parametric uncertainty, which is also known as structured uncertainty, is a significant topic in power system frequency control synthesis, and thus the robust control theorems are widely used in the design of power grid LFC systems in the past three decades. Providing robust stability and performance for the frequency control system under parameters perturbations and disturbances was the main design objective. In this direction, several robust control methodologies with associated powerful software toolboxes like H_∞, H_2, mixed H_2/ H_∞, structured singular value theory (μ), Riccati-equation approaches, Lyapunov stability theory, linear matrix inequalities, Kharitonov's theorem, quantitative feedback theory, eigenvalues placement method, model predictive control (MPC) and Q-parameterization are used [1, 61-69].

However few publications consider the application of specific systems and components like SMES, voltage source converter (VSC)-based multi-terminal HVDC systems and solid-state phase shifter [59, 70-72]. Some research works on the frequency control considering the HVDC links are given in [71-79]. Dynamic impacts of intermittent DGs, and high penetration of RESs on power grids frequency response is discussed in [8, 53, 80-84]. A number of recent works have suggested the application of inverter-based virtual inertia emulators to improve frequency stability and frequency response performance [72, 76, 85-92]. Furthermore, numerous research works have been recently focused on the use of DGs, RESs, MGs, electric vehicles, and storage devices to provide frequency control supports in the power grids [93-101].

Following the concerns for the cyber part in a modern power network as a bulk complex cyber physical system and the rapid progress in information technology, design of preventive control schemes and detection process for the possible cyber-attacks in frequency regulation process are emphasized in several works [14, 15, 18-20, 67]. At the same time, load shedding, special protection plans and emergency control schemes have attracted more attention [1, 88, 102-105].

Providing frequency control support via controllable loads and smart load technologies using the concepts of DR are discussed in [13, 28, 29, 106-110, 123, 124]. The ability of on-off switching electronic components in the demand side load blocks enables the loads to provide a faster response to system events and dynamic perturbations, compared to the most synchronous generating units. This feature along with recent advances in measuring, computing and communication technologies, makes load-side resources as ideal alternative for frequency control issue.

Investigation of the dynamic impact of MGs on power grid frequency stability and performance is another new attractive research direction. MG dynamics equivalent model derivation is an emerging research area in the field, which tries to include inherent and control characteristics of MGs in a unique equivalent model from upward point of view. This, in turn, facilitates dealing with bulk system dynamic assessment and control in presence of MGs. While, [112] exclusively reviews methods and challenges of equivalencing in conventional power systems, [113-116] introduce some new approaches in the field of MG equivalencing. Developing a robust equivalent model that appropriately tackles uncertain behaviour of MGs into model formulation remains an open issue. Two recent works in this area are [117, 118], where the authors discuss the impact of a high integration of MGs on the frequency control of power systems and propose a decentralized stochastic frequency control of MGs based on addictive increase multiplicative decrease, a method that has been already successfully utilized in heavy-loaded internet communication and traffic congestions.

Current research activities in the field of power grid stability and control rely on quasi steady state assumption where constant frequency (nominal frequency) is used for determining of all phasors and component reactances. However, due to the development of new technologies such as DGs/RESs and larger load changes caused in DR programs, frequency dynamic response is becoming more changeable. Consequently, crude definition of phasors and component reactances may affect operation of power grid relaying, power quality management and monitoring, and functions of digital technologies-based components. In addition, the capability of power system to accommodate MGs is limited by regional frequencies impediments. To this end, local frequency estimation plays an important role in modern power grids. Recently, some research works deal with local frequencies estimation in modern power systems [69, 119-122]. Some new works have considered the concept of resilience in the frequency control issue [125, 126]. These attempts are done to increase the resilient of frequency control systems against attacks and the resulting manipulations. Several papers also take benefit of the additional virtual inertia created by reactive power sources for improving the primary frequency control loop [127, 128]. Design optimal frequency control for the generating units with unknown input functional observer has been recently addressed in some reports [131. 132].

3. Conventional frequency control

Sustained off-normal frequency variations for a long time may negatively affect power grid operation, stability, security and performance. This event may also damage equipment, and degrade operation of relays and protection systems. Depending on the size and time period of frequency variation, different types of frequency controllers are needed to be activated to stabilize and restore the power grid frequency [1].

3.1 Primary control

Under normal operation, small frequency changes can be naturally compensated by *primary control* loop of the existing SGs. Following a disturbance, the mentioned regulation loops of all SGs respond during a few seconds. However, due to proportional characteristic of SGs *droops,* the grid frequency will be settled in different value from the nominal frequency. Accordingly, the tie-line power flows between interconnected control areas may reach to values different from the scheduled ones.

3.2 Secondary control

During off-normal operation, depending on the accessible amount of regulation power, *secondary control* loop or LFC system will be activated to compensate the power grid frequency and return it to the nominal value. The LFC is the main component of AGC. The secondary control can attenuate the frequency and active power changes from tenth of seconds to few minutes. This control system restores the nominal frequency and the scheduled tie-line power by allocation of available power reserve.

3.3 Tertiary and emergency controls

A serious fault/disturbance can cause a significant load-generation imbalance and rapid frequency deviations that may not be sufficiently compensated by the secondary frequency control system. In this case, to reduce the possibility of cascade faults and instability, additional control action, called *tertiary control*, using the standby power sources is required. This control system uses the available support power reserve, connects (disconnects) some generating units, reschedules the frequency control participants, and controls grid demand to manage the circumstance and retuning back the grid frequency and interchange tie-line power to the nominal and scheduled values. In worst cases, protection *and emergency control* systems like under-frequency load shedding (UFLS) must be activated [111].

3.4 Conventional frequency response model

Generally, in a real bulk multi-area power grid, all above mentioned frequency control loops are working. Figure 2 depicts a simplified frequency response model including primary control, secondary control tertiary control, and emergency control loops. The ΔP_m, ACE, ΔP_{tie}, and ΔP_d are the mechanical power, area control error, tie-line flow power, and load disturbance, respectively. The ΔP_P, ΔP_S, ΔP_T and ΔP_E represent the produced control signals of the four frequency control systems. In Fig. 2, β, α, K_P, and K_S are control area bias index, generators participation coefficient in the LFC system, droop characteristic, and secondary controller, respectively.

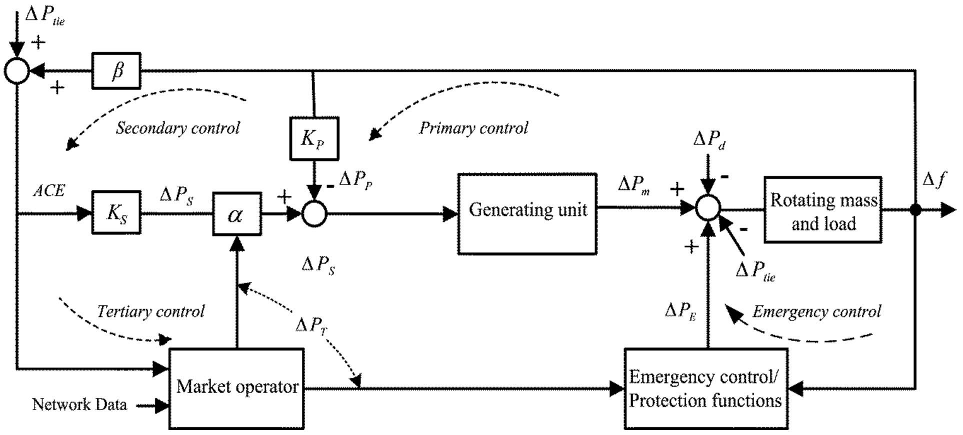

Fig. 2. Frequency response model with conventional frequency control.

The system (market) operator provides an overall management system to control the area frequency and to balance the system generation and consumption securely and economically. Therefore, the system operator is responsible to determine the generators participation factors, appropriate economic dispatching scheme, and set-point of main generating units. This operator may also apply special protection plans and emergency control actions in in case of contingencies [1]. In order to secure the power grid reliability and reducing the wear and tears of bulk generating units with an economic operation, some control performance standards (CPSs) have been introduced by numerous technical and reliability committees [16, 17, 33, 34, 42, 43]. These CPSs define some criterion and limiting terms for control area frequency and ACE changes.

4. Non-conventional frequency control

High penetration level of RESs in power grids, due to their high uncertainty, intermittency and non-synchronous grid connection, introduces some technical problems and challenges. This type of sources increases the necessity of more flexibility in operation and regulation power requirements. Furthermore, replacement of SGs by power electronic based DGs/RESs reduces system inertia. In power grids with significant integration of RESs, system operators are in face of serious frequency and tie-line power control issues. This condition is more critical in the islanded power grids that use few number of synchronous generating units with small amount of kinetic energy, because they do not have interconnections to provide inertia support.

Unpredictability of load is also an important challenge in a modern power grid frequency control. Loads are becoming more and more erratic especially in the distribution grids with new electric transportation systems. These grids, without LFC and a global frequency control system, can only rely on appropreate control of power converters setpoints for desirable shaping of output active and reactive power [129].

To have a secure and reliable power grid with high penetration of RESs and MGs, it is vital to use the significant potential of RESs and MGs in providing regulation power and frequency control supports. Recent works show the high ability of these fundamental blocks of future smart grids to contribute in the power system frequency control. In practice, several utilities have already revised their grid codes for this purpose, and some recent research activities have been also conducted to the synthesis more effective frequency controllers for control support of RESs, ESSs and MGs [12].

The capability of contribution to regulation power reserve is now needed by the grid code of some utilities. Furthermore, if due to congestion management, sufficient inertia, and reserve provision, some RESs/MGs are disconnected; their energy can be used to produce upward energy reserves. The allocation of regulation reserve by the RESs in future smart communities will be different from the same method for the SGs, since their outputs experience high intermittency [56].

4.1 DGs/RES frequency control

Planning the required power reserve, concerning the fast growth of intermittent renewable generation and its effects on power grid control and performance is a significant issue in modern power grids operation and control. The contribution of renewable power plants (such as solar/wind farms) in the ancillary/regulation services to provide the regulation power reserve can be considered as a proper solution. Currently, the design of RESs with comparable and even in some cases better performance functionalities than conventional SGs is possible [12]. For example, solar and wind farms can response to a received dispatching function from the market operator for seconds, while it may take minutes for a conventional generating unit whose have a slower output power ramp rate. Therefore, like conventional generators, these variable generation resources can be equipped to provide regulation tasks in electric power grids.

The inverter-based RESs can receive the frequency and power set-points and other required operation/control references from the corresponding electric utility or system operator to produce the required frequency regulation support. These references are distributed between the RESs to determine the amount of contribution for each participant power source in the grid frequency regulation. The required amount of RESs regulation power is mainly determined by considering the amount of reserve from those SGs that can be relocated.

Figure 3 depicts a block diagram to realize possible frequency control loops in variable speed wind energy conversion control system. It shows that WT can provide secondary frequency control loop in addition to the primary (droop) and inertial frequency regulation loops. In this control framework, the v, P_i, ω_T, ΔP_{ic}, ΔP_{pc} and ΔP_{sc} are used to represent the wind speed parameter, total accessible power, WT blade speed variable, inertial control action and secondary control action signals, respectively. The system operator as an overall supervisor may activate the secondary frequency loop. The parameter α that can vary between 0 and 1 shows the amount of frequency regulation power for the grid control support.

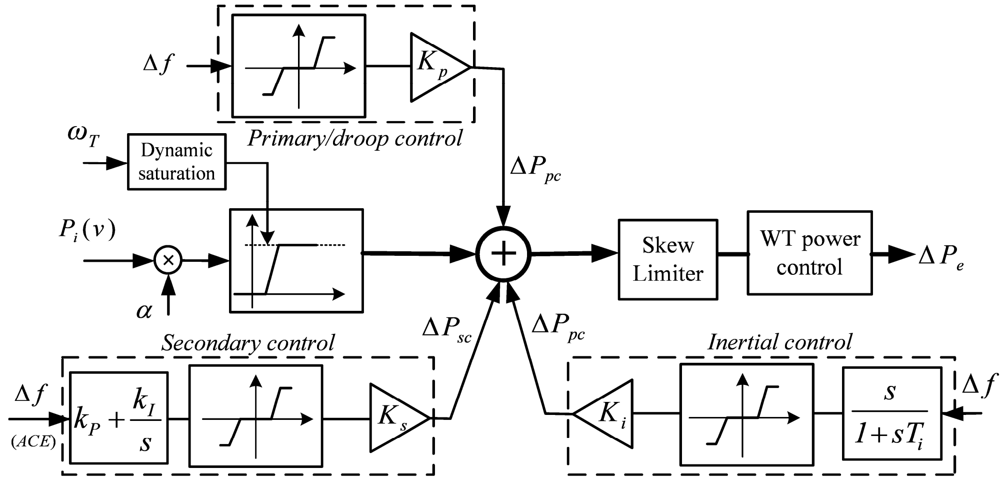

Fig. 3. Various frequency regulation supports provided by wind turbines.

Depending to the received feedbacks from the grid frequency deviation and/or area control signal, the WT decelerates the rotor speed, and thus extracts the stored kinetic energy in the rotating blades. This process leads to produce the required regulating power for the grid frequency regulation support. The control mechanisms showed in Fig. 3, including the role of each controller gain, skew limiter, and dead bands are extensively discussed in [12].

4.2 MG frequency control

MGs comprise dispersed energy resources, storage devices and controllable load blocks in order to provide enough control capabilities to the remote grid operation. The grid-connected operation mode is an important MG operating mode, because the MG not only must supply the load loads, but also may need to transfer its surplus generated power as an ancillary service for frequency control support to the main grid. Therefore, since both MG and connected grid must be simultaneously considered, this operation mode is more complex than the islanded operation mode. In order to manage the DGs in both mentioned operating modes, a microgrid central control (MGCC) is necessary.

The MGCC among the existing hierarchical control structure in a MG has an important role in the frequency control support of upstream grid. MG services can be further extended if ESSs are integrated in the MG. In such a case, functionalities like the extension of the operational reserve capability, overall frequency regulation, peak shaving, backup of intentional electrical islands, and optimized management of daily renewable energy cycles, might be implemented by the global control as well [12]. An example to show the capability of the MGs to provide required regulation power and to participate in the frequency regulation of the main grid is given in [12] (see Fig. 4).

This MG is connected to the grid, via a transformer between the MG and HV buses and a high voltage (HV) power line. The changes in the connected loads to the HV bus can affect the exchanged power (P_{mg} ,Q_{mg}) between the MG and grid, as well as the main grid; and it may cause significant variations at the HV bus frequency and voltage.

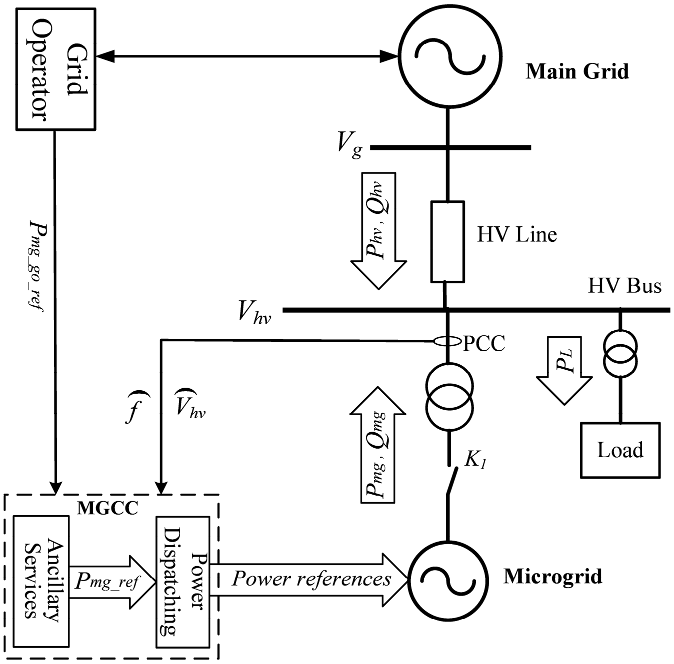

Fig. 4. Grid-connected microgrid system.

From the grid operator point of view, the connected MG is a potential regulation power reserve participator [133]. The MGCC must use an appropriate control scheme for providing enough regulation power in compliance with the main grid need ($P_{mg\_go\_ref}$). For this purpose, as shown in Fig. 4, the ancillary services coordinates the MG with the main grid to meet the grid requirement. The MGCC includes not only the frequency control support but it may cover voltage regulation support, interchange power control, protection, and additional measurement-based services.

4.3 Demand control

The demand side can be considered as an important potential frequency control contributor. This contribution may be realized by the frequency-based relays to connect or curtail some load blocks at the specified frequency thresholds. The frequency dependent loads such as induction motors can also have a significant role in the frequency regulation support. However, it is still difficult to consider the demand-side control support as a fixed participator in the overall frequency regulation requirement.

The DR is defined as the ability of the system operator to perform a flexible control of the grid loads and easily possibility of turning the existing load blocks off or on in response of coming up contingencies, economic/technical limitations, as well as regulation and protection requirements. This ability effectively supports the power system in all fields of voltage/frequency control, active/reactive control, reliability, security, and power quality.

In frequency control point of view, unlike UFLS, the DR is working in normal operation state and curtailing of system loads will be continuously done using sophisticated methods with a higher resolution load blocks. The DR can reduce the generation participation rate in the grid frequency regulation, and thus it helps to reduce the amount of required generation, power reserve, as well as operation cost and CO2 emission [106].

4.4 Virtual inertia control

High integration of DGs/RESs reduces the overall inertia of a power grid. A low inertia can negatively affect the grid frequency dynamic performance and stability. A solution to this issue is to fortify the system with virtual inertia. A virtual inertia can be produced using an ESS with a power electronics converter under an appropriate control scheme to emulate the required inertia. Reinterpretation of the figure in frequency domain is represented in Fig. 5. More details on internal virtual control are given in [12, 86, 90]. Virtual inertia loops include the transfer functions of the phase-locked loop, $K_f(s)$ applied in VSC control methodologies and inertia constant. It is noteworthy that the $K_f(s)$ uses the state of charge (SOC) of the ESS and frequency deviation as input feedback signals and provides the dynamic of virtual inertia control loop. While, the power system in Fig. 5 refers to M in the block diagram, $K_f(s)$ visualizes the virtual inertia control mechanism. Some relevant research on the virtual inertia are given in [90-92].

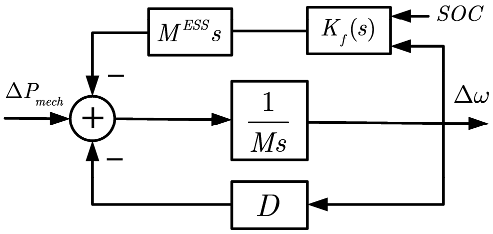

Fig. 5. A simplified virtual inertia based frequency response model.

4.5 Updated frequency response model

An updated frequency response model that includes all mentioned frequency control loops and new control possibilities for a typical control area (i) in a multiarea power grid is presented in Fig. 6. In this figure, M_i, D_i, β_i, and Δf_i are the area's constant inertia, damping coefficient, bias factor, and frequency deviation, respectively. $\Delta P_{tie\text{-}i}$ represents the area tie-line power flow, and T_{ij} is the tie-line coefficient between two areas. Here, the R_{ki}, α_{ki} and $M_{ki}(s)$ are droop characteristic, participation factor, and generator model, respectively.

As shown in Fig. 6, the generating units employ primary and secondary controllers. The secondary control system (LFC) senses the combination of area frequency deviation and tie-line power change, then feeds the result as the ACE signal to a proportional-integral (PI) controller and finally supplements the primary control system. The secondary control output (ΔP_C) is added to the primary controller output signal to restore the grid frequency and scheduled tie-line power. In practice, this controller usually contains a PI (as shown in Fig. 6) or a simple integral (I) term. After a serious imbalance in the grid load-generation, each participant generator unit according to the specified participation factor by market operator produce an appropriate regulating power (ΔP_m) for tracking the load and compensating the grid frequency and tie-line power flow.

In a real-world power system, to clean the feedback signals (frequency deviation and ACE) from the additional noises and undesirable rapid perturbations, suitable washout and low-pass filter (LPF) must be used at the start point of secondary frequency control loop. The important physical constraints such as communication time delay, governor dead band and GRC that are different in each control loop and generator are required to be taken account in a complete frequency response model. However, in this model, only a linearized low-order model is sufficient to present the frequency response dynamics of the generating units. In Fig. 6, T_W shows the rolling window time interval for passing the ACE data to the LFC system.

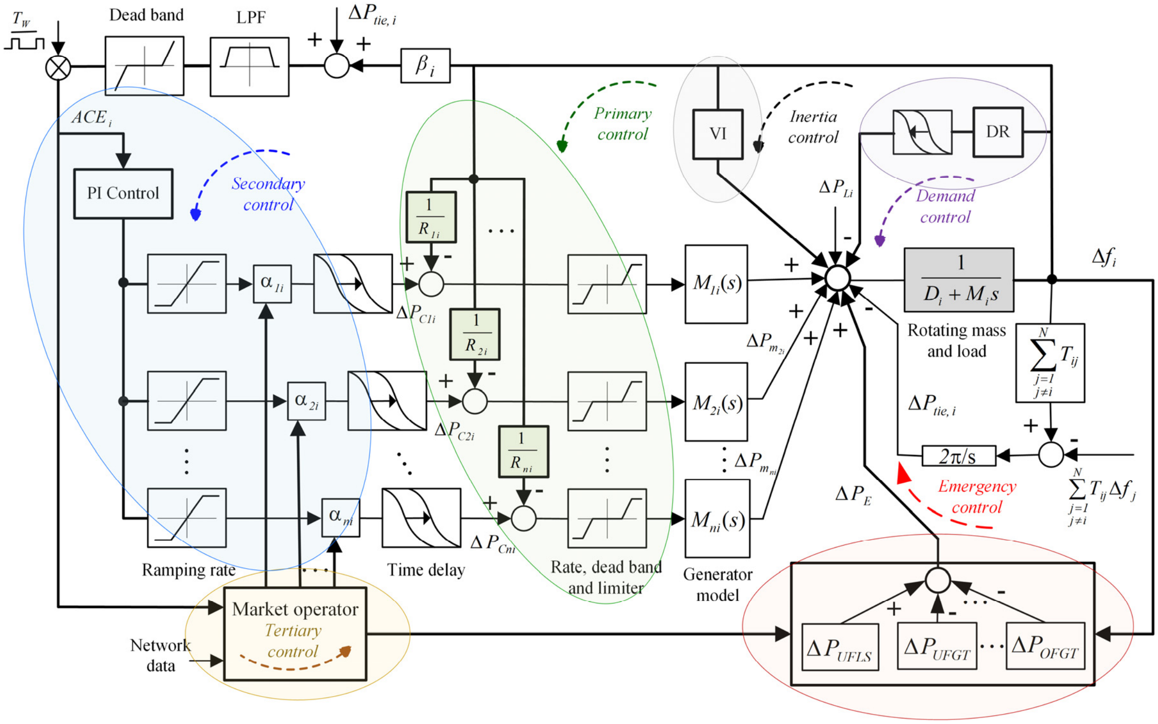

Fig. 6. An updated frequency response model.

As discussed above, following a large load-generation imbalance, the provided regulation power by the conventional triple frequency control loops in both power amount and response time points of view may not adequate to compensate the grid frequency and maintain the tie-line power at the scheduled values. In this situation, the system operator have to activate the available emergency control actions and special protection algorithms such as UFLS, power sources tripping/connecting, and frequency-sensitive protection relays/equipment.

The dynamic impacts of the emergency control and protection scheme must be also properly reflected in the frequency response model. One may simply translate these impacts according to their dynamic role in the grid frequency and active power response, and can be represented by adding a new (emergency) control loop to the updated overall frequency response model as shown in Fig. 6. In this control loop, the $P_{UFGT}(s)$, $\Delta P_{UFLS}(s)$ and $\Delta P_{OFGT}(s)$ illustrate the equivalent dynamics models of under frequency generation trip (UFGT), UFLS and over frequency generation trip (OFGT) as three important emergency action examples, respectively. The contribution of DR control system is also depicted in Fig. 6, where τ_i is the DR delay of area *i*.

Operation dynamic timescale of DGs/RESs and MGs that can provide regulation power during hundreds of milliseconds to a few seconds following received command from system operator, makes them effective and useful to support the power system frequency regulation in both primary and secondary frequency control layers. Resiliency and dynamics of future power grids (with inverter-based power generation systems), that mainly rely on variable generating units, also could be enhanced by means of ESSs and DGs. In this way, ESSs or wind farms accompanied with the associated power electronic interfaced control loops would be appropriately controlled to emulate virtual inertia. This in turn supports frequency dynamics in inertial response horizon, as shown in Fig. 6.

5. Conclusions and future work

This paper provides an updated review on most important frequency control achievements and challenges. The impacts of high penetration of renewable energy options, DGs and MGs on system frequency dynamic performance and stability are highlighted. New frequency control opportunities due to regulation supporting of RESs/MGs, virtual inertia and demand response are discussed.

Based on the current issues concerning frequency control and the impact of distributed energy sources and microgrids, relevant research priorities and future work are as follows:

i) Effective control solution for the power grids with high integration of RESs and microgrids, particularly in islanded grids due to their relatively low inertia, significant power fluctuation and various uncertainties. In this direction, providing an appropriate coordination between the generating units and energy storage systems is important. Effective coordination schemes must leverage the storage units to assist primary and secondary control.

ii) Measurement-based dynamics identification and system modeling for adaptive control and online parameters tuning. The increasing size and diversification of demand/power sources magnifies the importance of this issue in the modern power grids. Online computational aspects of frequency control is an important issue in a modern power grid. Online tuning of frequency control set-points considering the unpredictably load changes can be quite challenging in operation and control. This emphasizes the significant role of data-driven modeling and control techniques in future relevant studies.

iii) Flexible and fast data filtering and processing algorithms, considering huge amount of recorded data and growing advances in computer, communication, intelligent electronic tools, and control technologies. Artificial intelligence and machine learning can play a significant role in frequency regulation issues such as load forecasting and analyzing the frequency regulation markets of the future grids. This direction also requires highlighting the cyber security in the frequency control systems.

iv) New mechanisms for frequency control supports using flexible load blocks, storage system technologies, and distributed RESs/MGs. In this direction, new demand response and virtual inertia based frequency control approaches could be considered as more attractive solution methods.

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