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Review

Solar and Wind Energy Integrated System Frequency Control: A Critical Review on Recent Developments

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Abstract: A paradigm shift in power systems is observed due to the massive integration of renewable energy sources (RESs) as distributed generators. Mainly, solar photovoltaic (PV) panels and wind generators are extensively integrated with the modern power system to facilitate green efforts in the electrical energy sector. However, integrating these RESs destabilizes the frequency of the modern power system. Hitherto, the frequency control has not drawn sufficient attention due to the reduced inertia and complex control of power electronic converters associated with renewable energy conversion systems. Thus, this article provides a critical summary on the frequency control of solar PV and wind-integrated systems. The frequency control issues with advanced techniques, including inertia emulation, de-loading, and grid-forming, are summarized. Moreover, several cutting-edge devices in frequency control are outlined. The advantages and disadvantages of different approaches to control the frequency of high-level RESs integrated systems are well documented. The possible improvements of existing approaches are outlined. The key research areas are identified, and future research directions are mentioned so that cutting-edge technologies can be adopted, making the review article unique compared to the existing reviews. The article could be an excellent foundation and guidance for industry personnel, researchers, and academicians.

Keywords: renewable energy resources; frequency control; energy storage; supercapacitor; battery; inertia emulation; converter

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1. Introduction

Renewable energy sources (RESs) as distributed generators (DGs) are considered sustainable solutions to the scarcity of fossil fuels. Since the use of RESs has grown, the world's power networks have seen substantial changes in recent years. Because of the global environmental concerns with the conventional fossil fuel-based generations, RESs have played an increasingly essential role in the generation of power and meeting consumer load demands during the last several decades [1]. The use of several DGs such as solar panels, wind turbine generators (WTGs), diesel engine generators (DEGs), and energy storage systems (ESSs) such as battery energy storage systems (BESSs) and flywheel energy storage systems (FESSs) has provided significant benefits; however, this trend creates new challenges such as frequency control mechanism complexity, system susceptibility to faults, and voltage instability [2]. When referring to government-funded and large-scale corporate renewable energy projects with a capacity of 100 kW or higher [3,4], it is referred to as 'large-scale renewable energy.' The large-scale integration of RESs replaces the conventional synchronous generator in the power network [5,6].

The electric power system is mainly stabilized with the dynamic action of conventional synchronous generators. The generators are grid-connected, and their stored kinetic energy is immediately extracted in the event of a power outage [7]. For example, a sudden increase in load demand or a loss of a large grid-connected generating unit will slow down the grid's equipment and, as a result, reduce grid frequency. The frequency stability, a critical component of a power system's ability to operate reliably and safely, is important in the modern power system to maintain synchronism by balancing generation and demand [8]. However, integration of low-inertia wind and inertia-free PV systems significantly reduces the overall inertia of a power system since the addition of these sources replaces the conventional synchronous generators [9]. The low inertia is caused by a power electronic converter that decouples the power system from the wind generator. The frequency stability of the power system cannot be adequately maintained by low inertia wind generators. Because of the high penetration of PV and wind, overall inertia is reduced, and the rate of change of frequency (RoCoF) is increased, which could lead to frequent load-shedding controller activation [10]. The frequency stability is further degraded due to the reduction of the reserve power of the system because of high penetration of solar PV and wind [11].

It is anticipated that the electricity networks will see further transformation based on RES, distributed generation, and power electronic-based generators and loads [12]. In Europe, for example, 323 and 192 GW of wind and PV are expected to be deployed in 2030, covering up to 30% and 18% of demand, respectively [13,14]. If there is an imbalance, the system frequency may deviate indefinitely. When traditional generation (based on synchronous generators) is phased out on a large scale to accommodate more RESs, the systems' performance and stability may be degraded significantly. Excessive frequency fluctuation can cause cascading outages or even widespread power outages [15]. The advent of auxiliary control and storage control, which simulate the behavior of real synchronous generators without the use of prime movers or rotating mass, is one simple way to overcome these stability difficulties. In conclusion, different techniques with cutting-edge technologies must be introduced in order to facilitate the high-level integration of RESs.

Several strategies, such as droop and de-loading, load frequency control (LFC), energy storage assisted technique, and inertia emulation, are used to reduce the frequency oscillation [16–18]. The proportional-integral-derivative (PID) regulator is utilized in [19] as an auxiliary LFC approach to control the frequency of the Egyptian grid. However, the LFC method ignores tie-line power flow, which requires more research, and uses a simplified version of the Egyptian grid. In order to control system frequency, conventional PI and PID controllers are typically used [20]. These controllers' parameters are either fine-tuned empirically or using Ziegler-Nichols methods. However, the performance of PI/PID controllers may not be sufficient when tuned using the traditional approaches. For a low-inertia microgrid, the frequency controller is designed with a virtual inertia support system [21]. In [22], frequency control for RESs based system is developed with deep deterministic policy gradient (DDPG) based method. The given two-area system is trained using multiple deep reinforcement learning agents to reduce frequency fluctuation and tie-line power oscillation. Some other control approaches such as model predictive control [23,24], fuzzy-logic control [25], non-linear control [26], optimal control [27], soft computing based control [28] are also implemented to control the frequency of the solar and wind system.

Although existing control techniques are improved and new control techniques are proposed in frequency stabilization of RESs integrated system, integration of several auxiliary devices, including batteries, supercapacitor, superconducting magnetic energy storage (SMES), and flywheel energy storage, is imperative to achieve better frequency stability. In [29], frequency stabilization of AC microgrids with several clusters is presented with the supercapacitor. A small-signal model is developed, and a fractional order controller is employed to supply/absorb power during transient conditions. The frequency control of grid-connected and islanded systems has been proposed with SMES in some technical literature [30,31]. In [32], the battery is introduced to control the frequency of the Australian power system considering high-level renewable energy integration. Energy storage devices are also hybridized such as battery-flywheel [33], supercapacitor-battery [34–36], and SMES-battery [37–39] in frequency control of the low-inertia system.

In summary, frequency stability improvement of electric networks is of high importance while considering high-level renewable energy integration. Numerous control techniques and devices have been proposed with cutting-edge technologies. However, to understand the developments until now and to project future developments, it is important to summarize related works which are missing in the existing literature. Thus, the article comprehensively reviews the frequency stabilization techniques of high-level RESs integrated systems. In-depth and critical reviews are provided to guide the researchers and academicians in the area. The remainder of this review is structured as follows. The solar PV and wind systems descriptions are provided in Section 2, along with the frequency control. The wind and solar system's frequency control aspects with the auxiliary devices are described in Section 3. In Section 4, several auxiliary devices and their control strategies are summarized for frequency regulation of RESs' integrated system. Several challenges and current/future research opportunities are summarized in Section 5. Finally, Section 6 provides the conclusion of this review.

2. General Description of Solar PV, Wind System, and Frequency Control

Contrary to fossil fuel-based conventional synchronous machine-based power generating systems, which massively pollute the atmosphere, wind farms and solar energy provide clean energy. The highest level investment on RESs development is imperative to fight the climate change. However, the structure of the conventional grid system changes and control becomes complex due to the integration of RESs.

2.1. Solar PV and Wind Integrated System

Solar PV and wind systems, which include PV modules, wind generators, turbines, converters, filters, and control mechanisms, all work together to produce the system's output, which is influenced by sunlight variation, partial shedding, and wind speed [40,41]. Figure 1 depicts the general block diagram of grid-connected solar PV and wind systems consisting of PV modules, wind farms, thermal units, control and monitoring centers, auxiliary devices, loads, and protection systems. Series-parallel combination of solar cells is adopted to form a solar array which is further configured to form modules. The grid connecting PV inverter can not regulate harmonic and reactive currents. Utilization of a PV system as an active filter to correct for reactive and harmonic currents while also supplying power to the grid is described in [42]. Improvement in PV system inverter control has been made to provide auxiliary services including reactive power compensation and harmonic reduction, as presented in [43].

Wind energy generation and supply to the utility grid involves different techniques. The widely used energy conversion techniques include a wound rotor induction generator (WRIG), a squirrel cage induction generator (SCIG), a permanent magnet synchronous generator (PMSG), and a doubly fed induction generator (DFIG). Some wind generators facilitate connections of the wind turbine to the utility grid through a dedicated transformer, while others are connected through power electronic converters. Every single generator, regardless of how it is connected to a power grid, has an impact on the overall power quality [44,45]. In general, wind generators have inertia as compared to the inertia-less solar PV system. However, in most cases, the inertia of wind generators is decoupled from the utility grid since the power electronic converters are connected between them [46]. The load frequency controller (LFC) is employed with the conventional synchronous generator to support grid frequency. However, in case of excessive renewable energy integration, auxiliary devices, such as the battery, supercapacitor, and superconducting magnetic energy storage devices, are employed to support grid frequency [47–49]. The monitoring and control center measures several necessary system parameters and generates control signals for the protection devices and controllers. Recently, many techniques with auxiliary devices and without auxiliary devices have been developed to facilitate solar PV and wind system integration into the utility grid, which is critically reviewed in this article.

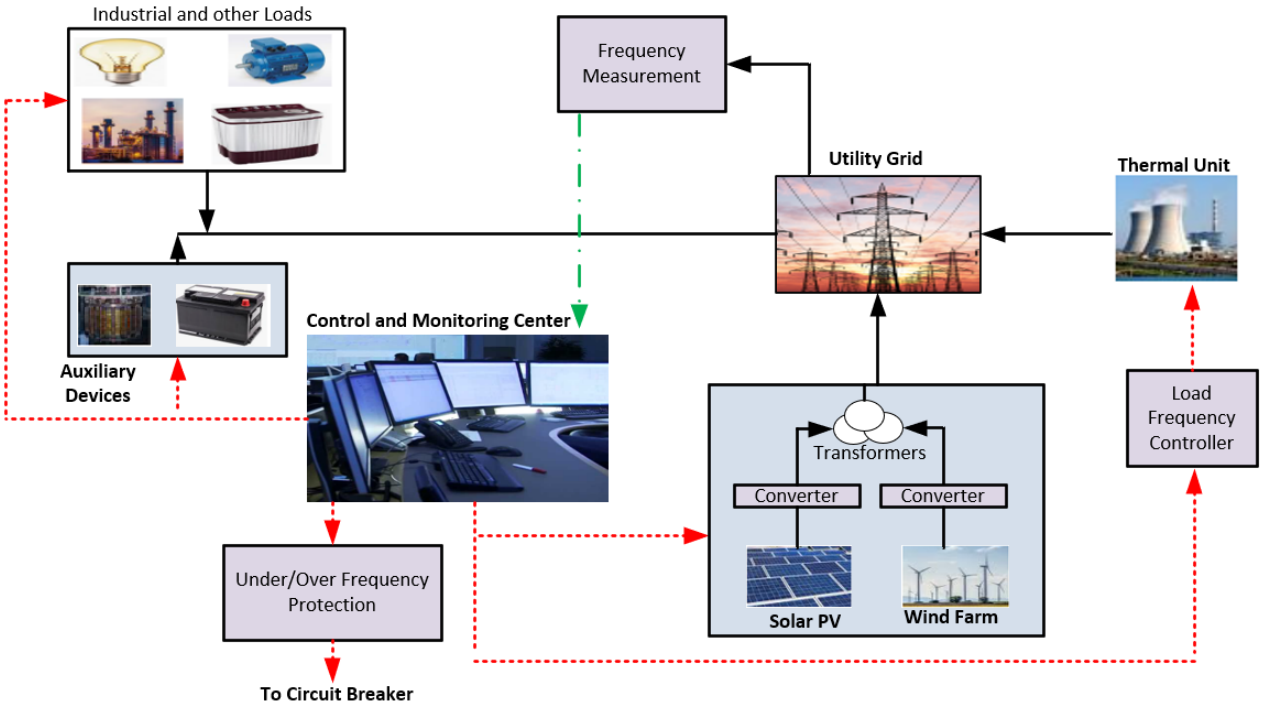

Figure 1. Power system and control block diagram with RESs and ESSs.

2.2. Frequency Control Issues

An essential factor that determines the robustness of an electrical grid is the rate of change of frequency (RoCoF), which is given by the following equation [50].

$$RoCoF = \frac{\Delta P}{\sum s} \frac{f}{2H} \tag{1}$$

where, ΔP is the load and generation power mismatch, $\sum s$ apparent power summation, f is the nominal frequency of the system, and H is the system inertia. The mathematical formulation clearly depicts that the system frequency is inversely proportional to the inertia.

Since the conventional synchronous generators are replaced with RESs, such as solar PV and wind, the total inertia of the system is reduced. Although inertia exists in variable-speed wind turbines, it is effectively separated from the system and cannot help with enhancing frequency response because the wind turbines are connected to the network via power electronic converters. Furthermore, solar PV plants cannot provide any inertia to the power grid, and the frequency response is further degraded. Therefore, replacing the conventional synchronous generator with RESs at a high level decreases the system's overall inertia and raises RoCoF, which, despite minor load-generation discrepancies, triggers the load-shedding controller [9,51].

Different control actions are implemented in a power system throughout multiple time frames in order to maintain the power generation and load balance. As shown in Figure 2, the inertia system works within 0–10 s, whereas the governor response, which usually occurs between 10 and 30 s after a frequency event, is the main control action with the goal of frequency deviation minimization. The inertia system can be further classified as hidden inertia, synthetic inertia, and emulated inertia. The primary frequency response involves frequency responsive reserves and contingency reserve [52]. The automatic generation control (AGC) is the secondary control operation that returns the system frequency to its nominal value within minutes (usually 10 to 30 min). The AGC control system is generally classified as turbine-governor control and load frequency control. The tertiary control, also known as reserve control, starts working after 30 min of the occurrence of a disturbance in the system. The initial response of the system, which is the most important for system stabilization, is mainly derived from the available total inertia of the system. Thus, if the inertia is reduced by replacing the synchronous generator with RESs, the system becomes more prone to contingencies.

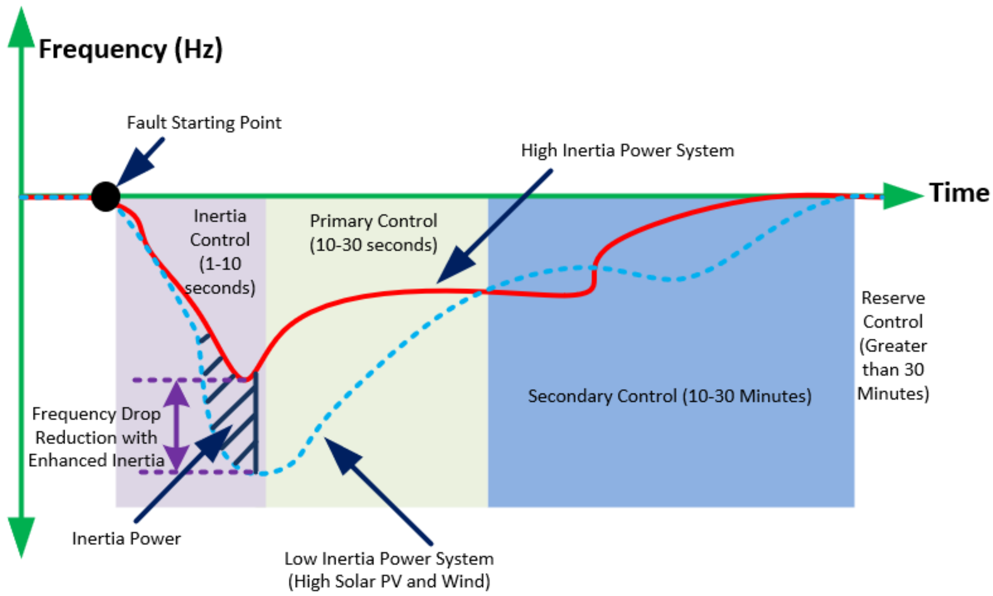

Figure 2. Post fault frequency response stages in power system.

3. Frequency Control with Auxiliary Devices

3.1. Wind System Frequency Control

The frequency of the high-level renewable energy integrated wind systems is mainly controlled with and without auxiliary devices. This section provides a detailed overview of the frequency control with different auxiliary devices, including superconducting magnetic energy storage (SMES), unified power flow controller (UPFC), battery, supercapacitor, flywheel energy storage, and so on.

3.1.1. SMES Control System

The widespread integration of wind farms into the power grid is complicated by the necessity of maintaining a constant frequency. The wind turbine generator is linked to the grid by means of a power electronics converter system, allowing the generator to operate at different speeds depending on the wind velocity [53,54]. Here, the output from the variable-frequency generator is converted to DC and then reversed to match the frequency of the grid. However, the peak of the variable wind power is what defines the capacity of the converter system if energy storage technologies are not used. Thus, utilization of superconducting type energy storage is inevitable for the wind energy system. When a SMES is used as the energy storage unit, the resulting system is able to store energy efficiently, respond quickly, and control precisely for power compensation.

A SMES system has three major parts such as a superconducting coil, a thyristor-controlled bridge converter, and a *Wye–Delta* transformer as shown in Figure 3. The power conditioning system (PCS) incorporating a rectifier/inverter is utilized to regulate power transfer between AC system and superconducting coil. A 12-pulse converter is mainly introduced to reduce the voltage harmonics [55,56]. On the magnetic coil, the converter provides a negative or positive voltage. In order to control the discharge and charge states, all that is required is a change in the firing angle α, which governs the thyristor sequential firing [56,57]. If the value of α is less than 90, the converter is charging. If the value of α is more than 90, the converter is in discharging mode. As a result, the SMES can absorb or release power from/to the utility grid without any losses. The following equation describes the relationship between the DC voltage and the firing angle of the converter.

$$Ed = 2V_{d0}\cos\alpha - 2I_dR_c \tag{2}$$

where E_d represents inductor DC voltage, V_{d0} represents the highest bridge voltage, I_d represents the inductive coil current, and R_c represents the equivalent commutating resistance. The system frequency deviation Δf is used as an input signal to operate the SMES in order to produce the necessary power (ΔP_{SMES}). As a result, using Δf to the SMES control logic, the inductor voltage (Ed) is proportionally regulated. It is necessary to restore the inductor nominal current quickly after any disturbance [57,58], so that it can respond instantly to the next changes in the power demand.

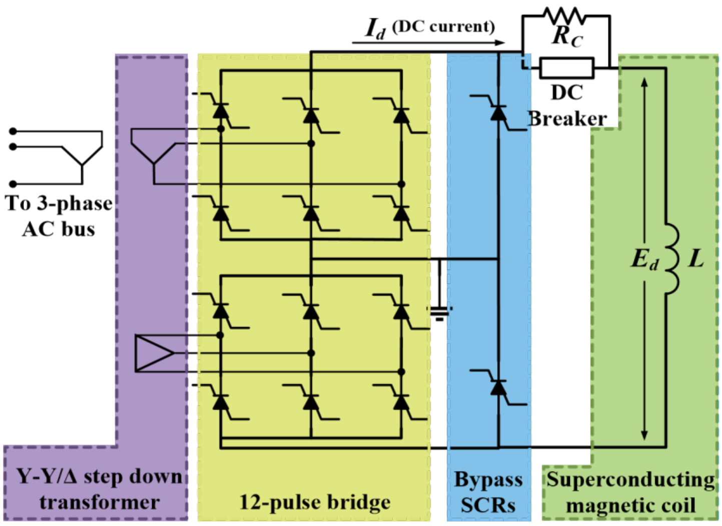

Figure 3. Configuration of SMES technology.

The dynamic equations for inductor voltage and current deviation (ΔE_d and ΔI_d) are as follows:

$$\frac{T_{SMES}}{sT_{direct}} \cdot \Delta f - K_{id} \cdot \Delta I_d \tag{3}$$

$$\Delta I_d = \frac{1}{sL} \cdot \Delta E_d \tag{4}$$

where T_{SMES} is the SMES loop control gain, K_{id} is the feedback gain, T_{direct} is the SMES converter time constant, and L is the induction coil. As a result, the SMES system's active power deviation can be calculated as:

$$\Delta P_{SMES} = \Delta E \cdot (I_{d0} + \Delta I_d) \tag{5}$$

The SMES has several distinctive characteristics, including large quantity active power delivery within a short period, high efficiency, and a long lifetime. Thus, it is regarded as a very promising device for improving power system dynamic stability [59]. Based on the dynamic model equations, fractional order controller (FOC) is recently applied to improve the frequency stability wind integrated multi-area power system [60]. The approach is based on using a hybrid fractional order controller for the LFC side and a fractional order proportional integral derivative (FOPID) controller for the SMES side.

Combining the FOC and tilt integral derivative (TID) controllers led to the development of the hybrid controller. The FOC-integrated SMES model is depicted in Figure 4. Nowadays, the power system is becoming more complex due to the incorporation of several distributed controllers, hybrid AC/DC transmission systems, and auxiliary devices. Thus, in order to avoid the complexity in control, in [61], a modified tilt FOC cooperative controller is designed to support the frequency of a high-level wind integrated complex power system. However, most of the methods only consider short-time power support by the SMES to minimize frequency deviations without considering the impacts of faults. Therefore, the authors in [30] propose a new hybrid approach with both superconducting fault current limiter (SFCL) and SMES, which can simultaneously reduce fault current and improve the frequency stability DFIG integrated system. An objective function incorporating point of common coupling (PCC) power deviation, equipment ratings, and maximum fault current is developed to determine optimal locations of SMES and SFCL. The fault current limiting and energy storage functionalities are combined in a compact device named SMES-FCL in [62] to support grid integration of the DFIG system. It is worth mentioning that the superconducting current limiters are a costly solution for the power system. Thus, future research can be conducted with some non-superconducting current limiters [63,64] and their coordinating controllers with SMES. The reduction of the fault current will decrease the chance of tripping the generators, and the frequency stability will be improved. The overall summary of SMES application in the frequency stability improvement of the wind energy system is depicted in Table 1.

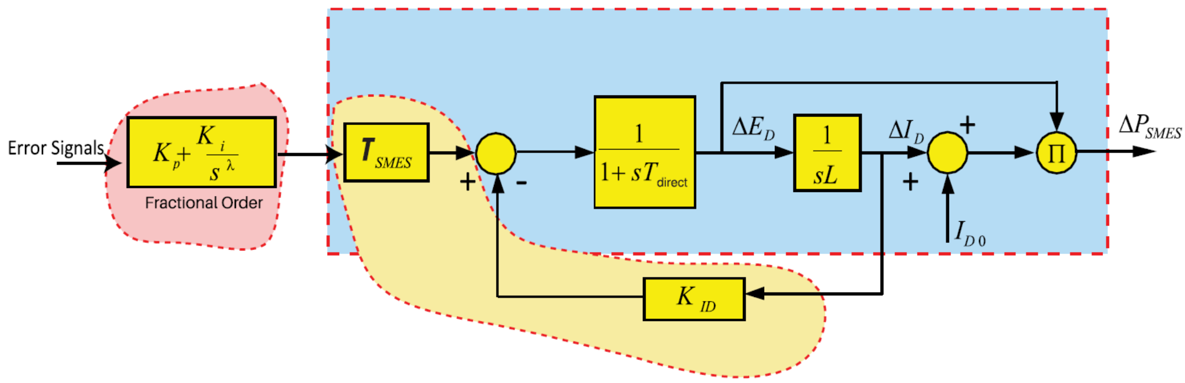

Figure 4. Dynamic model of SMES along with FOC.

Table 1. Summary of SMES technologies for wind system frequency control.

Reference	Wind Generators				Systems			Analytical Platform			SMES Hybridization
	DFIG	PMSG	SCIG	Multiple	Microgrid	Multi-Area	Utility Grid	MATLAB	Digsilent Power Factory	PSCAD	
[62]	✓						✓	✓			✓
[65]					✓			✓			
[66]		✓			✓			✓			
[67]			✓				✓				
[68,69]	✓	✓		✓			✓	✓		✓	
[70]									✓		
[70]				✓					✓		
[71,72]	✓					✓		✓			

3.1.2. FACTS Devices

Many flexible AC transmission systems (FACTS) devices have been developed [73] to solve frequency oscillation problems. One of the FACTS devices proposed to enhance frequency stability during grid faults is the unified power flow controller (UPFC), which has the ability to provide decoupled active and reactive power correction. Using a unified power flow controller, it is possible to manage the impedance, phase angle, and reactive power of a line [74], which can have a positive impact on frequency control. The UPFC is made up of two voltage-sourced converters that make use of gate turn-off thyristors (GTO). These converters obtain their power from a common DC circuit that is made up of a DC storage capacitor [75,76]. This capacitor can be charged to absorb the fault energy, which generally augments frequency stability. The UPFC facilitates current flow in both directions. Thus, during grid faults and wind generator faults, it can control frequency as it allows active power flow in either direction. A parallel-connected transformer connects the converter to the ac terminal. Additionally, it is capable of generating or absorbing reactive power, which can be used to supply the line with separate parallel reactive compensation.

The major function of the UPFC is provided by the second series-connected converter, which injects an AC voltage whose amplitude and phase angle can be controlled. An active and reactive power exchange occurs between the AC system and the transmission line current through this voltage source. Active power exchange is given via the parallel branch, whereas reactive power exchange is generated by the converter internally. With the implementation of UPFC, it is possible to perform loop-flow control, load sharing along parallel corridors, enhancement of transient stability, a decrease in system oscillations, and voltage regulation [73,74]. For the purposes of performance analysis and control design, the steady-state model of UPFC as well as the dynamic model are required. Reference [77] presents a model for a UPFC that operates in a steady state and is based on a perfect single voltage source connected in series. One of the ideal voltage sources is connected in series, while the other is connected in parallel in the steady-state UPFC model described in reference [77]. The steady-state UPFC model that was proposed in [78] is built on the foundations of an ideal series voltage source as well as an ideal shunt current source. Several simplified models of UPFC have been developed to properly investigate the frequency control aspects of wind generation systems. For a multi-area wind integrated power system, a modified integral derivative controller with UPFC and Redox Flow batteries is proposed in [79]. Power swing and frequency oscillation damping of multi-area power systems is studied [80] with FACTS device considering governor deadband (GDB) and generation rate constraint (GRC). To enhance the frequency control of multi-area networks, a decentralized control based on static var compensator (SVC) devices is proposed in [81]. The design of a nonlinear adaptive SVC controller is based on a sufficient condition of rigorous Lyapunov energy function for a realistic structure-preserving power system with voltage-dependent loads. Utilizing a PID controller and a static synchronous series compensator (SSSC), the authors in [82] proposed improving load frequency control. To identify the optimal parameters, particle swarm optimization (PSO) is employed as an optimization technique. The interline power flow controller (IPFC) is another FACTS device that is implemented in [83] with a derivative filter for LFC. A thorough comparison of static synchronous compensator (STATCOM) versus SVC-based fuzzy controllers is presented in [84] regarding the improvement instability of wind farms connected to a multi-machine interconnected power system. Another FACTS member, thyristor controller series capacitor (TCSC), is widely applied for power frequency control [85]. A combined approach of AGC and TCSC is presented in [86].

A comparison of several methods for frequency control with auxiliary devices is summarized in Table 2.

Table 2. Comparison of frequency control methods with auxiliary devices.

Methods	Advantages	Disadvantages	References
SMES	Increasing frequency stability by lowering frequency oscillation and transient excursion as well as boosting inertia emulation capabilities	To keep the coil at low temperatures, a lot of power is needed.	[87]
FACTS Devices	These devices are suitable for low frequency oscillation damping	Steady-state frequency cannot be well controlled	[73,74,88,89]
Flywheel	Very fast response and high flexibility	It has mechanical stress and fatigue limits	[90]
EDFC with Storage System	i. Control is accomplished out using a precalculated or projected operating point when a disruption arises ii. EDFC does not contravene the grid-code criteria while in operation	Proper information is required to demonstrate the expected performance for a specific event	[91,92]
Storage Devices with RDFC	It can modify its output as per measured frequency; RDFC exploits the local measured frequency, which has the major benefit of eliminating the need for communication.	Due to the nonlinearity of the system frequency characteristics, it is hard to procure reliable information	[91,93]
BSS	i. Battery storage is utilized to provide inertia and primary frequency regulation ii. A battery storage system can be used to control the grid frequency when wind power plants are widely deployed iii. During the microgrid's primary frequency control level, the battery is utilized to regulate active power transfer	Batteries' lifespan will be diminished if significant power peaks are handled. When a power imbalance occurs suddenly and repeatedly, the battery will experience continual charging and discharging activities. It puts more stress on the battery and shortens its life.	[94,95]
Supercapacitor	For high-frequency power variations, a a supercapacitor can be implemented easily ii. By absorbing power in frequency deviations, a supercapacitor can react faster to offset the frequency deviation than other auxiliary devices	i. Even though using SC, another storage system is required to restore the frequency to its nominal value ii. High power density SC is required for improved performance which raising the cost level	[95]

3.1.3. Supercapacitor

A supercapacitor is an electrochemical device made up of two porous electrodes, a potassium hydroxide electrolyte, and an ion-exchange membrane separating the two electrodes. A conventional capacitor and a supercapacitor are both subject to the same laws of physics in many respects [96]. In contrast to a conventional structure, a supercapacitor has a huge surface area due to its liquid electrolyte structure and porous electrodes. The capacitive energy storage devices have been applied to load frequency regulation in many studies [29,97,98]. These ubiquitous capacitive energy storage technologies have a high power density to support active power promptly in case of any imbalance. The authors in [29] developed a small-signal model of supercapacitor along with the microgrid clusters to analyze the frequency stability. The analysis showed that the fractional order supercapacitor significantly improves the frequency of microgrid clusters under renewable energy uncertainties. The block diagram of supercapacitor control-based microgrid clusters is visualized in Figure 5.

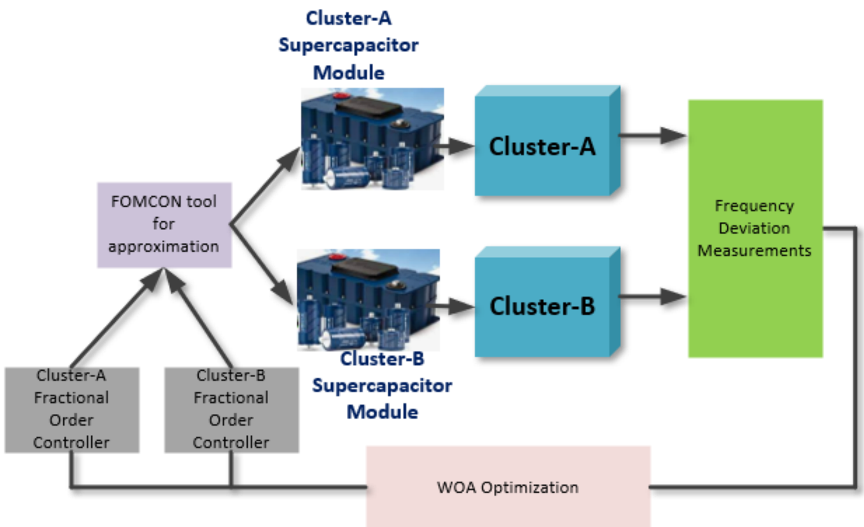

Figure 5. Supercapacitor for frequency control.

In [99], a supercapacitor approach is presented to minimize the impacts of uncertainties in frequency control. To improve RoCoF, a fuzzy logic control-based supercapacitor is proposed in [100]. Based on the frequency deviation and RoCoF, the proposed fuzzy logic controller calculates the necessary inertial power. To change the load angle for the power electronic inverter of the supercapacitor, the output of the fuzzy controller is combined with the traditional emulated inertia control technique. A new cooperative supercapacitor control is presented in [101] for frequency stability improvement. This approach improves the frequency stability of autonomous microgrids with minimal cost. In [102], a novel passive fractional-order sliding-mode control technique is developed for the supercapacitor to support the frequency of a microgrid incorporating highly intermittent wind generation system. A hybrid seeker optimization and fuzzy logic based control technique is presented [103] to improve the frequency control and energy management efficiency of a microgrid system.

3.1.4. Electric Vehicle, Batteries, and other Devices

Recent years have observed an increase in the number of electric vehicles (EVs), which can be attributed to the quick technological breakthroughs that have occurred within the industry [104]. The EVs are solely powered by electricity and are propelled by one or more electric motors that are rechargeable battery packs. Electric vehicles have the capability to quickly manage active power through electronic power converters, which enables them to provide a wide variety of services. One example of these services is frequency control, which regulates the frequency of the main supply system by providing vehicle-to-grid service [105,106]. From the electrical system point of view, having the capability to regulate voltage and primary frequency is of the utmost importance. Three different techniques of control have been identified for frequency stabilization with electric vehicles: primary control, secondary control, and tertiary control [107,108]. When the electric vehicle's battery is being charged, it is possible to achieve down-regulation, and when the battery is being discharged, it is possible to achieve up-regulation [109] for frequency control. In [110,111], a vehicle-to-grid (V2G) frequency regulation service is provided by the battery of the EV for a microgrid system consisting of wind generators. In most cases, the EV battery cannot alone participate the frequency regulation. Thus, clusters of EVs are considered in [112] with the hierarchical distribution frequency control method considering demand charge load optimization. The reference [113] proposed the adaptive and model predictive approaches for a combined energy storage system (ESS) and EVs in regulating frequency.

Battery energy storage systems (BESS) are excellent wind system frequency control options because of their speedy and adaptable response times. A comprehensive, data-driven methodology to choose the best size, controller, and investment for a battery storage system that provides frequency control was provided in the reference [114]. In order to supply frequency control services that complied with regulatory criteria, the authors optimized the controller to ensure that it would degrade as little as possible over its lifetime and consume as little electricity as possible. Taking into account the dynamics and degradation when exposed to real frequency data, a thorough battery model was developed. A first-order transfer function can be used to illustrate the dynamics of the power that is transferred between a BESS and the grid in the frequency domain. In [115], a robust controller is presented for the clusters of BESS to support wind integrated low inertia system's frequency. Figure 6 depicts the block diagram for the control area i of a power system with BESS [115]. An equivalent steam generator with a speed governor, a turbine, and a secondary controller represents thermal power plant control dynamics. The governor and turbine are related to the time constants T_{gi} and T_{ti}, respectively, whereas the governor speed drop is represented by R_i. The generalized LFC model of the i-th area of the system is augmented with the robust controller.

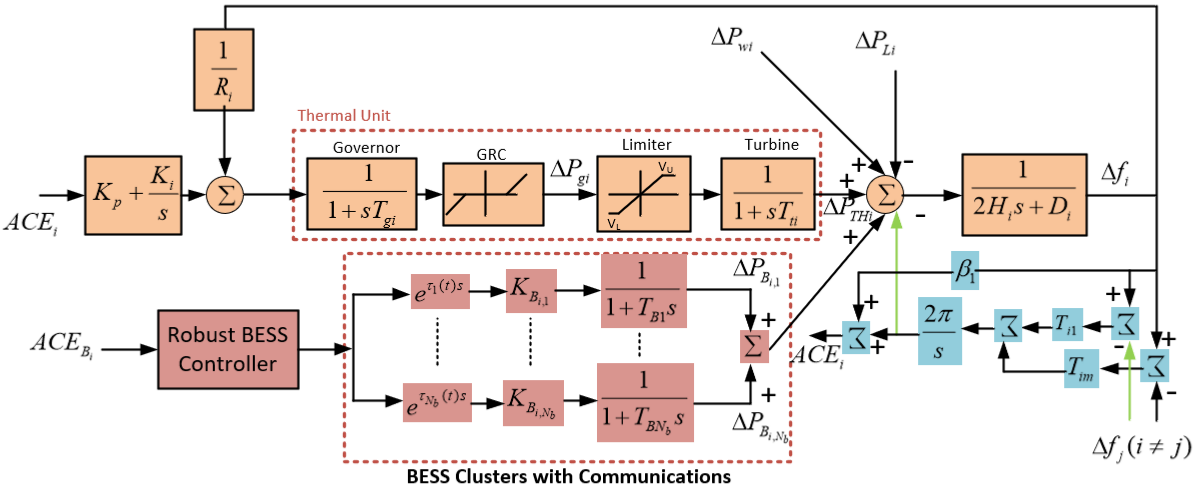

Figure 6. Dynamic control model of distributed BESS.

Some other auxiliary devices are also utilized for wind-integrated system frequency control in addition to the battery, supercapacitor, UPFC, and SMES. For example, in order to control the frequency of a wind system, the reference [116] proposed a method that combines an integral controller with a redox flow energy storage system (RFESS) and a static synchronous series compensator (SSSC). A novel control of PV systems with FACTS devices called a PV-static synchronous compensator (PV-STATCOM) to reduce power oscillation in a connected power system is presented in [117]. In [118], the thyristor-controlled phase shifter (TCPS) optimized by craziness-based particle swarm optimization is utilized for frequency control in wind systems. In some literature, [119–121], flywheel energy storage devices are proposed for the primary control frequency of wind energy systems. In [122], six different flywheel energy storage system governor control schemes are developed to augment the frequency stability of the microgrid. Using different tuning criteria, the governors' parameters are selected in the proposed technique. The design and experimental testing of an energy management algorithm based on feedback control methods for a flywheel energy storage device are presented in [123,124]. The flywheel's function is to even out the net power that wind turbines or wind power plants inject into the grid. The goal is to balance out the power disturbances caused by the wind turbines' cyclic torque disturbances as a result of the airflow deviation via its tower section [125]. In [126], a supervisory control unit (SCU) in conjunction with short-term ahead wind speed prediction is used to manage the energy stored in a small capacity flywheel energy storage system, which is utilized to reduce the output power variations of an aggregated wind farm. The proper energy management of grid-connected microgrids can decrease the frequency oscillation as reported in [127,128]. A new optimal energy storage system control technique is introduced in [129] to improve the frequency stability of highly renewable energy integrated system with minimal impact of phase-locked-loop (PLL) dynamics.

3.2. Solar Based System

Due to the intermittent nature of solar PV production and the unanticipated variation in load, hybrid solar systems are expected to experience severe frequency variations. To ensure smooth operations of solar power systems, it is required to stabilize frequency with advanced control techniques and auxiliary devices. Several auxiliary devices including battery, flywheel, SMES, and FACTS devices are used to control the frequency of the solar-based system.

3.2.1. Battery Storage System

Battery energy storage systems (BESSs) have been studied and explored for frequency regulation in the reference [130] for the solar-based system. A new control strategy to coordinate large batteries for improving their cooperation in frequency stability supports is proposed in [131]. Several important frequency control aspects of this study include: (1) Showing how the combined wind-battery frequency response positively interacts with the steady operation of nearby large-scale PV farms, (2) Outlining a complete dynamic model, which includes its de-loading strategy, converter control loops, and reference generation strategy, and (3) additional frequency supports from wind-battery units by improving the fuzzy logic control performance with optimized internal parameters. However, this study considers conventional PI controllers in which the parameters are tuned with the PSO-fuzzy system. This work could be extended by utilizing fractional order PI controllers, which, in general, provide a higher degree of freedom [132,133]. An adaptive frequency control method for multi-area microgrids is introduced in [134] by utilizing the clusters of electric vehicle batteries. In [135], a coordination mechanism for battery charging was provided by adjusting the frequency and voltage of surrounding batteries. According to [136], BESSs should be used for direct load control (DLC) to regulate the system frequency. Electrical load, building load level, and regulated devices were used to test the DLC application. Managing a large number of small BESSs was also discussed in regulating the system frequency.

3.2.2. Flywheel Energy Storage

Flywheels offer a higher power density and a significantly longer lifespan than batteries. The flywheel acts as an energy buffer, absorbing and releasing kinetic energy to support inertia by controlling its speed in relation to the grid frequency. The flywheel is able to either absorb or deliver the exact quantity of electrical power that is required on demand [137,138]. The flywheel energy storage systems (FESSs) to supply virtual inertia and frequency support is proposed in [139]. The FESS modeling, control, and location are presented in [140] for Chile to control the system frequency considering solar PV integration. The frequency regulation of the weak grid consisting of large-scale renewable energy is presented in [141,142] with flywheel energy storage devices. A frequency regulation service is a prime example of a highly cyclic application because it requires thousands of charge-discharge cycles on an annual basis. Because this application requires charging and discharging the storage device at a wide range of rates, from extremely slow to rapid and deep cycling, none of the conventional storage devices, including battery and supercapacitor, can support operation in this scenario. Thus, grid operators are increasingly relying on flywheels as fast-acting regulators in order to address the problem of frequency regulation. In this particular application, it is anticipated that flywheels will perform better than batteries due to the rapid response and frequent charge-discharge capabilities of the flywheels [143].

3.2.3. Superconducting and other Storage Devices

Among the several superconducting storage devices, the SMES is considered a promising solution for solar PV system frequency control. A genetic algorithm designed SMES is utilized in [144] for solar PV system frequency regulation. The operation of dual and single magnet SMES for the frequency regulation of an islanded microgrid operation is examined in [145] considering high-level solar PV integration. A novel idea for increasing the efficiency of SMES and lengthening their discharge time is the multi-staging method. This method is evaluated in [146] for frequency stability improvement. In [147], the authors designed a fractional order PID-based SMES approach with an optimization approach to reduce low-frequency oscillation. In some applications, storage devices are represented as generalized ESS. The ESS frequency control methods are classified into two types: response-driven frequency control (RDFC) and event-driven frequency control (EDFC). The first approach involves modification of output based on frequency. RDFC approaches are widely utilized in ESSs, and other DG systems that employ frequency management [91]. The second method, also known as customized control, is mainly utilized when there is disturbance in the system. The RDFC and EDFC techniques are depicted in Figure 7A,B, respectively. F_{meas} is the measured frequency, while P denotes the ESS output. Each ESS in RDFC is governed by a distinct local frequency. The EDFC is driven by the information provided to the main control unit by the energy storage devices. This enables numerous ESSs to collaborate as a single giant ESS. This approach helps the frequency stabilization of high-level renewable energy integrated systems.

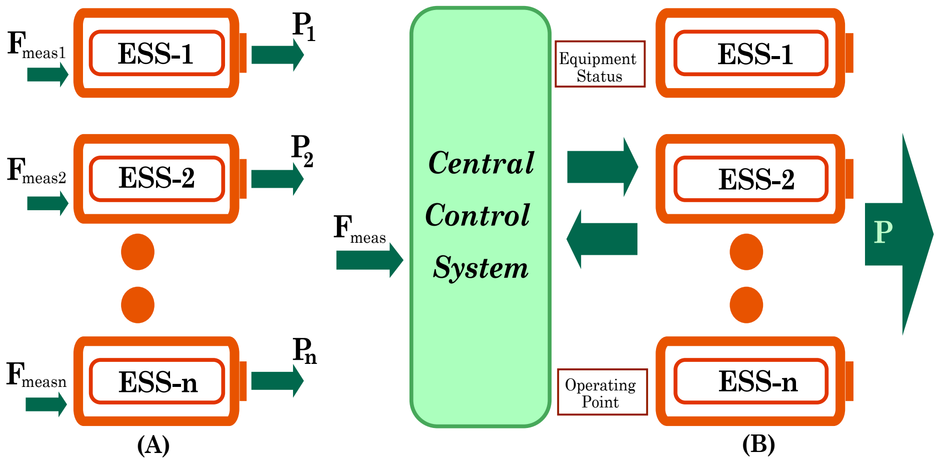

Figure 7. (**A**) RDFC and (**B**) EDFC.

4. Frequency Control without Auxiliary Devices

4.1. Wind-Based System

The inertia of the wind energy system is inversely proportional to the rate of change of frequency (RoCoF). Additional inertia is needed to meet stability standards as more energies are added to the system. Utilizing power electronic converters and control algorithms, virtual inertia technologies enable the release of wind turbines' stored kinetic energy to facilitate frequency management. Several methods have been developed, including de-loading, inertia emulation, droop, and fast power reserve techniques to support reduced RoCoF of wind systems, as shown in Figure 8.

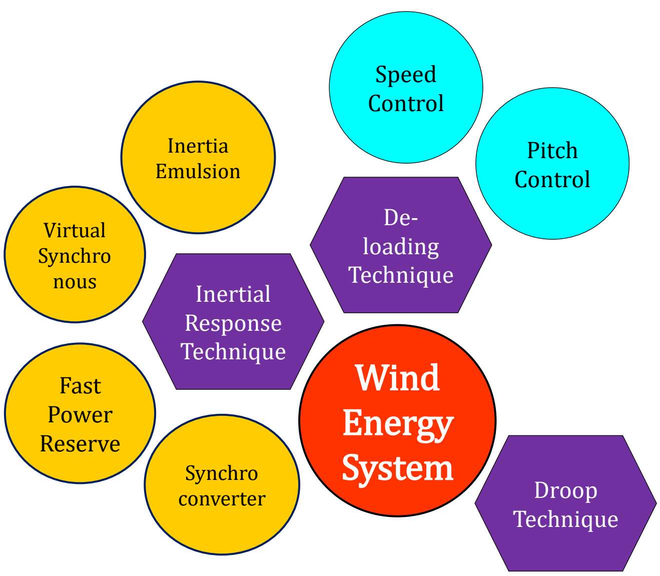

Figure 8. Several approaches of frequency control by wind systems.

4.1.1. De-Loading Technique

The de-loading is defined as a technique for wind energy generation system having the ability to offer reserve power in emergency case to reduce frequency oscillation [148,149]. The de-loading factor related to the control of the wind power generation system regulates the reserve power. The reference [150] determines the de-loading factor in order to activate the load scheduling and control algorithm. In the de-loading approach, an operating point is selected that is below to the optimal operating point; thus, the wind generator produces reserve power that can be used to assist with frequency management [151,152]. There are two types of de-loading techniques applied for wind systems: pitch-angle and speed controls [153]. In the pitch control method, a higher value of pitch angle is used instead of a lower value, whereas a constant wind speed is maintained. Speed control mode de-loading strategies include under and over-speed controls, both of which are capable to support wind system frequency control under a wide range of disturbances. A slightly higher value of rotor speed is maintained by the rotor speed controller system considering a constant pitch angle. Participation in frequency control means that rotor speed is reset at its highest point. In summary, the main objective of the de-loading technique is to shift the operating point to some value from the optimal operating point so that reserve power is obtained. It is worth mentioning that the de-loading techniques reduce the power delivery by the wind system in normal operating mode. Thus, the efficiency of the wind energy conversion system is decreased. The de-loading approach can be activated just for a set period of time by developing a new technique to sense the higher power requirement beforehand. More importantly, the amount of de-loaded power is yet to be calculated to maximize the inertia benefit and minimize the cost of de-loading.

4.1.2. Inertial Response Technique

In order to address the frequency control issue, inertial response technologies such as inertia emulation, virtual synchronous generators, quick power reserves, and synchroconverter have been developed. These techniques have the fundamental concept of imitating the behavior of conventional synchronous generators [154–156]. Typically, wind systems employ one-loop and two-loop control approaches to achieve inertia emulation. Torque reference (T_{refw}) in typical operating conditions can be determined via the MPPT controller loop as indicated in Figure 9 However, the inertia torque ($T_{inertia}$) loop is activated while a frequency deviation is observed in the system.

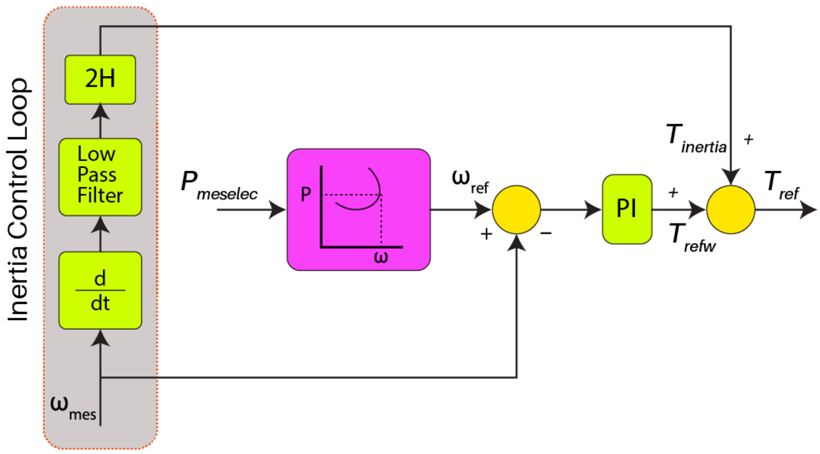

Figure 9. One-loop inertia control.

A technique for dynamically modifying the inertia constant during frequency response support is proposed by [157] with the goal of increasing the inertia constant as the system's frequency drops. Using a DFIG-based system, this strategy is used in [158] and compared for a variety of K_{in} and K_f values, as depicted in Figure 10. However, these strategies have been developed to alter the inertia amount by integer-order proportional-integral controller. There is room for improvement in the performance by means of a fractional order controller. Additionally, the coordination between the MPPT loop and the inertia loop has been overlooked. Some other strategies, for example, the one proposed in [16], allow wind turbines to simulate inertia by giving additional signals based on RoCoF and which is further extended in [159]. The PLL), which is the most common type of synchronization device, has been shown in the literature to have certain negative impacts on system stability. Therefore, another inertial response device known as the synchroconverter was developed in order to overcome the problem [160,161]. However, as reported in [51], the synchroconverter still requires PLL for initial synchronization. Thus, the improved synchroconverter should be developed, which is fully independent of PLL.

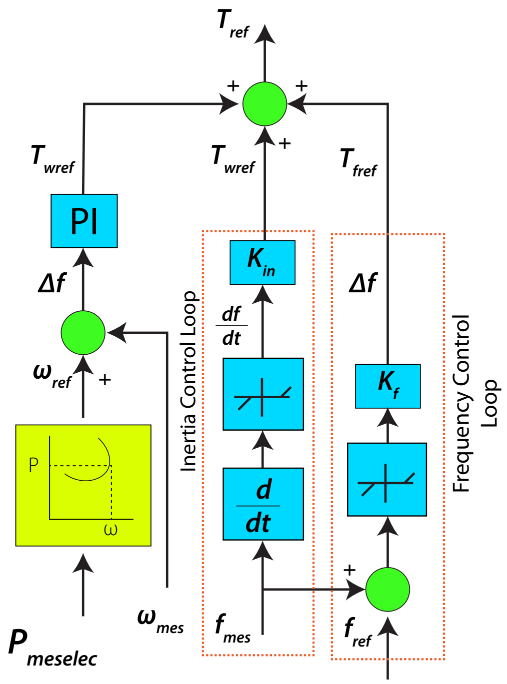

Figure 10. Two-loop inertia control.

4.1.3. Droop Control System

Using the droop setting, the droop controller has evolved to automatically adjust the output power when the system frequency changes, thereby providing primary frequency regulation [162,163]. Using the following equation, the droop gain and power relationship can be established.

$$\Delta P_{droop} = K_{droop} \Delta f \quad (6)$$

where, P_{droop} is the droop power, K_{droop} is the droop gain, and Δf is the system frequency deviation.

When the system frequency variation exceeds a specified threshold, the droop controller is enabled [164], as shown in Figure 11. The droop controller modifies the torque value in accordance with the system's frequency deviation to stabilize the system. To control wind farms for primary frequency response, synthetic inertia with a novel frequency-dependent multi-gain droop control approach is presented in [165]. In [166], experimental validation of droop control for wind systems is provided to support system frequency.

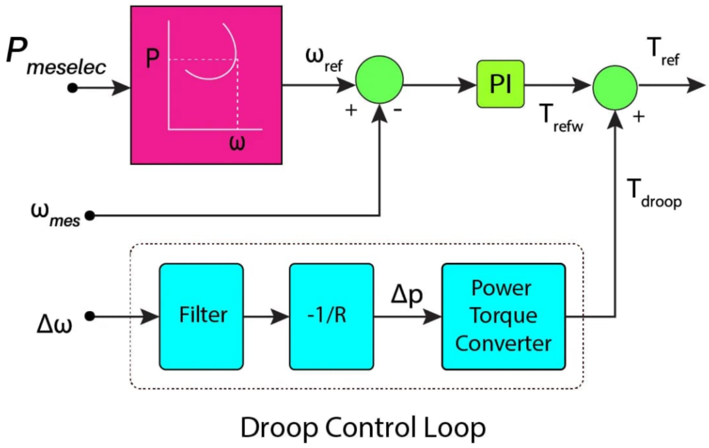

Figure 11. Droop control technique.

4.1.4. Other Techniques

The restoration of the nominal frequency by transmitting less data is offered through an area-based event-triggered (ET) sliding mode control system [167]. The primary characteristic of an area-based ET system is the independent transmission of each area's state information to the controller via a separate triggering mechanism. In some recent articles, an active disturbance rejection controller is presented for the frequency control of different wind generator systems [168–170]. The model predictive control approach for energy storage devices is also proposed for wind system frequency control [171,172]. A modified stacked denoising autoencoder-based stepwise inertial frequency modulation control for wind power is proposed in [173]. Heuristic dynamic programming is applied to adjust the virtual inertia parameters of doubly fed induction generators in order to improve the frequency response in the worst-case scenario [174]. A distributed inertia emulator is augmented with the conventional double control loops of the inverter in [175]. This approach avoids the use of PLL and the initial synchronization is achieved with accurate and fast frequency locked-loop (FLL). However, this inertia emulator is complex, and the cost of implementation is high. The distributed generation aggregators and microgrid operators in the electric market can adopt blockchain to facilitate energy trading among the microgrids [176,177]. Therefore, the energy imbalance is minimized and frequency stability is improved.

4.2. Solar-Based System

Although the solar PV system has no inertia to support the system frequency regulation, different control strategies can improve the frequency response. The control techniques for solar PV systems for frequency regulation are described below.

4.2.1. Inertial Response Technique

Reference [178] demonstrates that by using an inertia emulation method, a solar PV system may control the frequency. Using the inner and outer control loops of the PV system's DC/DC converter, as shown in Figure 12, the duty cycle for the PV system is generated [162]. The former regulates the PV array voltage to its reference value, whereas the latter regulates the PV power to its reference value, which can be performed either using MPPT or through the use of power controllers.

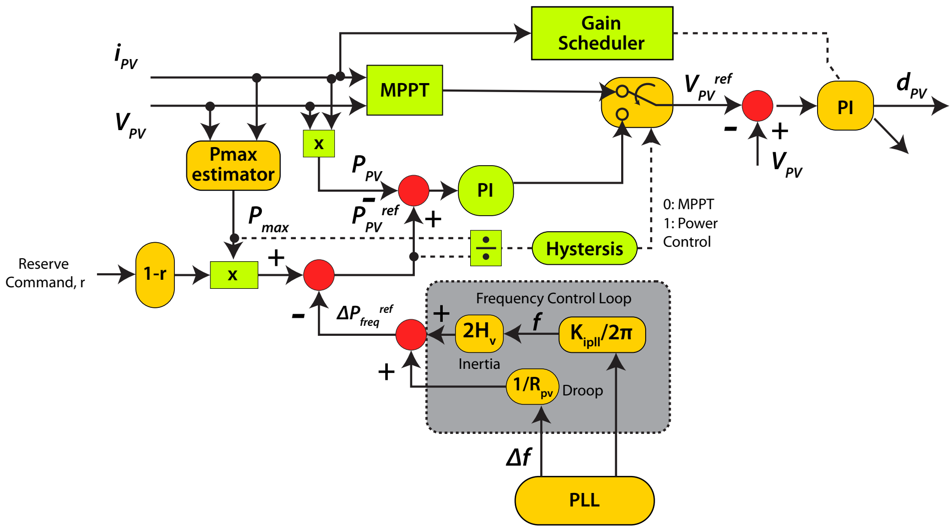

Figure 12. PV system inertia emulation and primary frequency regulation.

The outer controller's reference power is given by the following equation:

$$P_{pv}^{ref} = (1 - r) \cdot P_{max} - \Delta P_{ref}^{freq} \tag{7}$$

where r is the system operator's reserve power, P_{max} is the estimate of maximum available power, P_{ref}^{freq} is the output frequency controller. The frequency controller generates the frequency-dependent PV power reference illustrated below, which contains proportional and derivative terms.

$$P_{pv}^{ref} = \frac{\Delta f}{R_{pv}} + 2H_{pv}f \tag{8}$$

where R_{pv} represents constant and H_{pv} represents inertia gain.

4.2.2. De-Loading Technique

Using a de-loading strategy, it is possible to offer reserve and support system frequency by operating the PV system beyond the maximum power point. A de-loading technique presented in [178] is visualized in Figure 13, in which the proportional integral controller adjusts the voltage compensation term ($V_{dc\Delta f}$) based on the frequency deviation. The maximum power point voltage (V_{VMPP}), de-loaded voltage ($V_{deloaded}$), and frequency control loop voltage ($V_{dc\Delta f}$) are utilized in the outer loop to calculate the reference DC voltage (V_{dcref}), as below.

$$V_{dcref} = V_{VMPP} + V_{deloaded} - V_{dc\Delta f} \tag{9}$$

The approach presented in [178] has a non-uniform distribution of frequency regulation control signals. This is the most common situation in which PV units with varied reserve levels produce the same amount of power. Because of this, PV units with smaller reserves reach maximum power points faster than PV units with bigger reserves. As a result, they are unable to adjust their frequency even if they have unused reserve power. Therefore, the reference [179] suggests that the output power of each unit be dictated by the reserve, rather than each unit producing exactly the same amount of output power as the other units. The modified reference voltage calculated by the outer controller is given by the equation below.

$$V_{dcref} = V_{VMPP} + V_{deloaded} - V_{dc\Delta f} - (\Delta f \cdot \Delta V_{reserve} \cdot K_p) \tag{10}$$

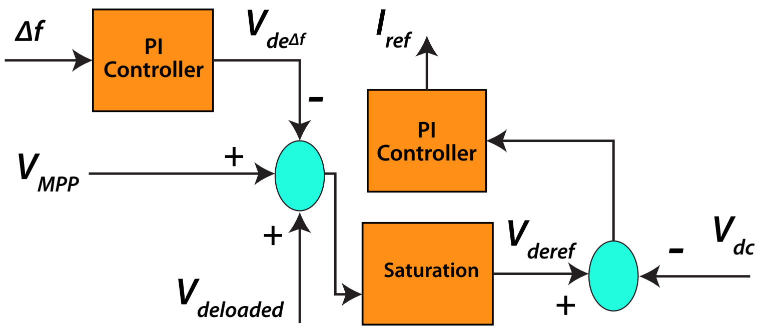

Figure 13. De-loading technique for PV system.

The use of a DC-link capacitor with the de-loading approach is offered in [180] to regulate frequency. A DC-link capacitor in an inverter is used to store energy when the frequency variation is detected, enabling the virtual inertia feature for the system frequency support. In order to support the system frequency based on reserved generation, a de-loading control method is also triggered at the same time.

4.2.3. Grid-Forming Control Techniques

Grid-forming control techniques can be used to reduce frequency variations when inverter-based PV and wind systems are connected to a weak grid infrastructure [181,182]. A generalized grid-forming control technique for weak grid frequency regulation is shown in Figure 14. The magnitude and angle of the voltage at the point of common coupling (PCC) are adjusted by grid-forming control. As a result, it is not strictly necessary to be familiar with the fundamental frequency phasor of the grid voltage at PCC. By utilizing additional outer loops, it is possible to modify the injected instantaneous active and reactive power in order to offer voltage and frequency support, depending on the characteristics of the network to which the converter is linked, whether it be an isolated system or a slack bus. A grid-forming unit might act as a slack bus in an islanded system. The grid-forming converter controls the active power by adjusting the angle when it is connected to other power sources through an inductive line.

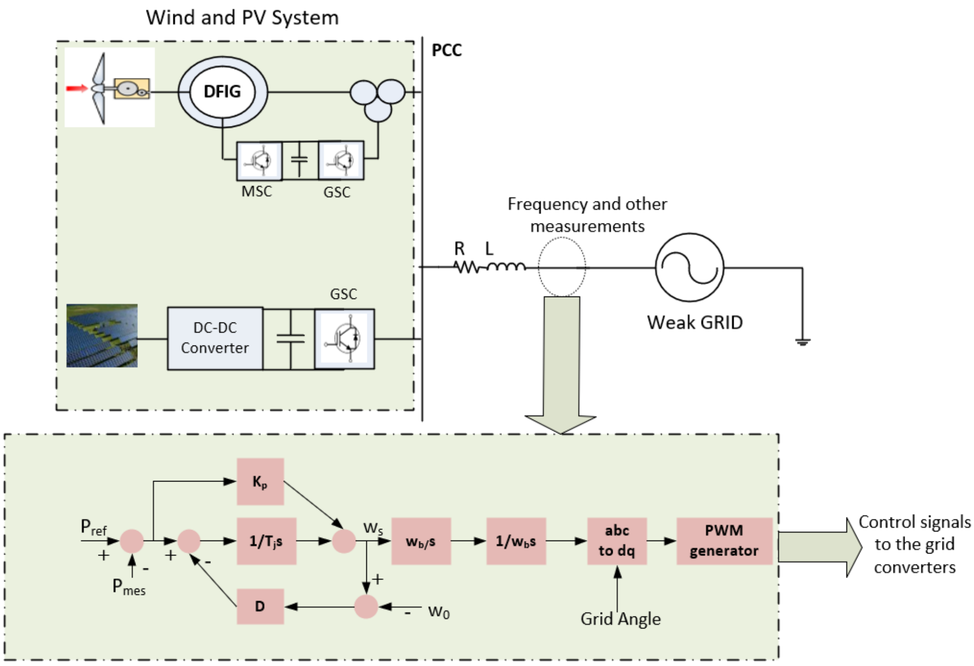

Figure 14. Grid-forming control technique for weak grid.

Inverters, as opposed to traditional synchronous generators, can react more quickly before load shedding is triggered if they are provided with a better controller. Voltage and frequency are controlled using the droop characteristics of the grid-forming inverter. In the case of a power outage, the grid-forming inverters instantly alter output power based on droop settings in order to restore system frequency and restore power balance. This type of control is particularly well suited for low-inertia PV and wind power systems. With the use of the grid-forming inverters control technology, which offers enough reserve margin [183], the dynamic frequency stability of PV-integrated systems can be improved. For two-stage solar PV systems, the reference [184] presented a grid-forming control technique that keeps the power reserve by operating below the maximum power point. In full or partial grid-forming mode, depending on the reserve availability, the PV plant acts as a voltage source to support the grid during disturbances. This approach is model-free and eliminates the usual real-time calculation of MPP power in the literature. The drop in the system frequency, sag in bus voltage, and current overshoots in a multi-sources microgrid are improved with grid-forming control technique [185]. A grid-forming hybrid angle control is missing in the existing literature for the large-signal stability analysis of the multi-converter system.

4.2.4. Artificial Neural Network

In contrast to other traditional modeling techniques, the artificial neural network (ANN) technique has a flexible mathematical framework that makes it capable of detecting intricate non-linear correlations between input and output data. The articles [186,187] looked into the use of layered neural networks in nonlinear power systems and the control intelligence in conjunction with a typical adaptive load frequency control scheme. In [188], a controller is developed with ANN technique for a two-area interconnected power system that took into account the governor deadband and reheat effects. In [189], the PID controller tuned by ANN is implemented in a multi-area system to improve the frequency response. The frequency support and output power fluctuation reduction with the ANN-based PV system are developed in [190], including battery storage. However, this study does not consider the SoC balancing of the batteries. A PID controller designed with ANN is presented in [191] to support the microgrid frequency incorporating solar PV.

4.2.5. Fuzzy Logic Technique

Instead of relying on mathematical models in traditional control, the fuzzy logic control makes use of the system's experience and expertise to solve problems. In [192], a fuzzy logic LFC was developed for solar PV systems. Using the fuzzy logic controller, the frequency regulation technique for distributed PV and electric vehicles is developed to minimize the impact of EV and PV on grid frequency deviation. Fuzzy gain scheduling of PI controllers is used to address the LFC problem in a four-area power system with deadband and governor rate constant (GRC) [193]. Using GA, Chia and Chun proposed a fuzzy gain scheduling approach for a two-area thermal power system that accounted for governor dead-band and GRC [194]. Fuzzy logic controller implementation with GA in a four-area power system with GRC and saturation as nonlinearities for AGC is presented in [195].

4.2.6. Particle Swarm Optimization and Genetic Algorithm

In [72], PSO optimized fractional order controller is presented to control the frequency of PV/wind integrated low inertia system. In [196], an adaptive weighted PSO-based multi-objective PID controller for LFC is described. Due to the fact that PSO is less susceptible to local optima than GA and SA, a heuristic evolutionary search technique based on hybrid PSO has been employed to discover optimal PID gains for LFC in deregulated four-area power systems [197]. The modified PSO and other algorithms are presented in [198] for the frequency control of a multi-area power system. A PSO-GA optimized robust LFC for a hybrid solar power system is presented in [199] to stabilize the system frequency. In [200], a cutting-edge multi-objective uniform-diversity GA is presented for the Pareto optimization of PI/PID controllers in the LFC of power systems.

4.2.7. Other Soft Computing Approaches

In response to changes in weather conditions, season, and geographic location, the output power of the PV system varies, resulting in a high-level frequency deviation of the electrical power system. According to Laut [201], soft computing methods are used in solar power systems to reduce power fluctuations while simultaneously improving the frequency response. Most of the soft computing approaches are considered supplementary in frequency control, whereas inertia-supporting devices are the key technology. A fuzzy logic controller is utilized to produce an output power command for a photovoltaic system based on the frequency deviation and average isolation of the PV system, as demonstrated in [201]. In [202], another soft computing approach comprising fuzzy logic controllers and PSO is used to improve the frequency response to its maximum extent by the PV output adjustment. A hybrid fuzzy and neural network is presented in [203,204] to control the solar PV system frequency.

In [205], a modified version of the chaotic-based atom search optimization method is proposed to enhance the searchability by stepping up the exploration and exploitation phase for the LFC of renewable energy integrated systems. For the frequency regulation and power dispatch of smart generation control, a deep Stackelberg heuristic dynamic programming (DSHDP) is presented in [206]. First, the heuristic deep dynamic programming, whose networks are replaced by three deep neural networks, can be trained offline using historical data to fit the best performance index. Once the frequency of connected power systems has been stabilized, the generation command can then be optimized using an online update technique. Table 3 summarizes several methods for frequency control without auxiliary devices. The deloading and inertial response techniques are mainly applicable to the renewable energy system. However, the heuristic approaches can be implemented with primary and secondary frequency controllers. Most of the heuristic approaches are applied offline, which is not suitable for many cases. The deloading techniques, on the other hand, are implemented in real-time. The main techniques are discussed, and the research gaps are listed to utilize the cutting-edge technologies.

Table 3. Comparison of frequency control methods without auxiliary devices.

Methods	Advantages	Disadvantages	References
De-loading	i. This technique can be observed as a way to offer more active power in situations where it is needed. ii. It maintains the frequency by providing reserve power	The quantity of backup power varies sometimes. The majority of de-loading approaches entail operating a wind turbines in the de-loaded mode for an extended period of time, which results in financial losses.	[164]
Inertial Response	i. Through the use of RESs, the inertial response technique simulates the behavior of conventional synchronous generators. ii. It has more virtual inertia, which helps to slow the rate of change of frequency.	i. The fundamental disadvantage of this system is that the amount of torque delivered by the second control loop is fixed, resulting in quick rotor speed reduction and controller operation delay. ii. It has a negative impact on the system's stability.	[207]
Neural Network	i. By controlling the speed of the turbine blade with the help of pitch angle management, neural networks can regulate the power output and system frequency ii. When there is a major change in the system, a neural-based controller can quickly restore the frequency to its nominal value.	i. A substation is required in a neural system to maintain software and hardware control. ii. The planning and construction of a neural network is complex.	[208]
Particle Swarm	i. It has the ability in tuning the parameters of the controllers for intelligent frequency control in an AC microgrid. ii. It can also help AGC in multi-source nonlinear power systems with AC/DC connections.	i. It has some drawbacks in real-time economic dispatch applications and a limited mathematical foundation for analysis. ii. It can occasionally fall into a local optimum in a high-dimensional space	[209,210]
Genetic Algorithm	For interconnected power networks, it can be utilized as a load frequency controller and allows for multi-objective load frequency control	It cannot be used for online LFC parameters tuning	[211]
Tabu Search	PI parameters designed by Tabu Search for LFC provide stable operation over wide range of uncertainty	In LFC designing process, it may fall to local optimum	[212–214]

4.2.8. Industry Trends in Frequency Control

The frequency regulation in different countries in the utility grid-level is achieved with different techniques and devices. The secondary frequency regulation architecture of the China Southern Power Grid with a unified frequency control strategy in order to actively respond to the call for the reform of the national electric power system and promote the construction of a frequency regulation auxiliary service market in southern China is introduced in [215]. In [216], the frequency stability of the real power system for Sardinia, which is powered entirely by renewable energy, is evaluated. A free open-source environment uses an electro-mechanical model to describe the grid and the power-producing park. Due to the shutdowns of conventional power plants, the grid lacks synchronous generators, which places greater demands on the synchronization and inertial response capabilities of renewable power plants. The large-scale energy storage device integration with the utility grid is considered a potential solution to the frequency control issues in many countries. For instance, it is forecasted that between 2021 and 2023, roughly 10,000 MW of large-scale batteries will be linked to the grid in the United States [217]. In central European nations, the battery is already lucrative when the frequency containment reserve is remunerated. For instance, in 2021, the "Frequency Containment Reserve for Normal operation (FCR-N)" in the Danish market had an almost 100% potentially profitable usage rate [218]. Meanwhile, a great degree of flexibility shortage has been noted in the local markets of the British Isles and several other islanded regions. As a result, for flexible market operation and frequency control, the high-level integration of batteries will be encouraging. The EVs are also evaluated to control grid frequency in many countries, including the Europen Union, USA, UK, and China [219–221]. The FACTS devices' real-world installation, control, performance analysis, and utility experiences are documented in [222].

5. Challenges and Opportunities

Power systems' complexity has increased due to rising renewable energy penetration, smart grid implementation, and digital control of power systems employing insecure communication technologies. Frequency control is important to protect the power system from any major blackouts. The uncertainty of active power production grows as the number of renewable energy sources such as wind farms and solar plants increases. In addition to the stochastic nature of the electrical power demand, an increase in active power fluctuation causes a large increase in the power system's frequency, causing it to oscillate. To overcome these challenges, future power systems will need improved and appropriate frequency control approaches that are more resilient and efficient. Many control mechanisms in grid-connected PV systems have been developed. Modern control approaches, such as optimal control methods, sliding mode control schemes, and adaptive control systems, are augmented with traditional control approaches. Intelligent control schemes, such as fuzzy control systems, and soft computing-based approaches for controller parameterization are also developed. However, the improvement in control techniques is not sufficient to regulate the system frequency. Thus, many auxiliary devices including batteries, supercapacitors, FACTS, SMES, and flywheels are extensively applied in solar PV and wind-integrated systems. Several techniques for frequency control of solar PV and wind systems with and without auxiliary devices have been documented throughout this manuscript. The key research gaps, to the best of the authors' knowledge, are listed and discussed below.

- Hybridization, sizing, and locations of energy storage devices need further research to improve the frequency stability of renewable energy integrated systems.
- Frequency control in a microgrid is still a challenging task due to its small-scale nature. Such systems should consider both frequency protection and control issues together with auxiliary devices.
- Accurate system modeling is required for the successful implementation of advanced control systems. The stochastic behavior of renewable energy sources should be taken

into account in new and improved models to further improve frequency stability. Model complexity should be minimized as much as possible in order to make it easier to put these models into practice in the actual world.

- Advanced control approaches (such as adaptive, intelligent, resilient, optimum, and hierarchical control) can improve the integration of high-level RES while reducing frequency stability.
- The impacts of the lifetime of energy storage devices should be investigated in frequency control.
- Low inertia is a major challenge when integrating RES. Virtual inertia and droop controllers have helped to tackle this challenge, but the performance of such controllers can be improved with a better design approach. Advanced techniques can optimize virtual inertia for high RES systems, which can then be supported by enhanced virtual controllers.
- It is necessary to investigate further what kind of storage systems (either high power density or high energy density) should be employed in low-inertia grids in order to reap the most significant benefits.
- The de-loading techniques have been utilized for the solar PV and wind systems. However, the calculation of the de-loading margin is still an open question.
- The batteries of the EVs can support the frequency of the system. However, determining the optimal assistance from an EV's battery can be challenging due to a variety of factors, including car charging and discharging times, unforeseen vehicle arrival and departure from parking spaces, and others. More research efforts should be put in this direction, considering high-level EVs' penetration in the next few years.
- The renewable energy integration capacity and energy storage devices sizing should be optimized together for the best frequency response.
- The RESs integrated system frequency control is adversely affected by the application of various types of loads. However, the simulation of linear loads alone is routinely used to validate research findings. With non-linear loads, which are hardly ever used in the literature, such as dynamic loads, inductive motor loads, and constant power loads, there are possibilities to test the frequency response. Future studies should reassess the use of these types of loads with the experimental setup.

6. Conclusions

Renewable energy sources such as solar PV and wind are heavily integrated with modern power networks to support green efforts in the energy sector. However, replacing the conventional synchronous generators with less-inertia solar PV and wind systems exasperates the frequency control of power networks both in grid-connected and off-grid conditions. This article provides a comprehensive and in-depth review of the frequency control of the RESs' integrated system with the state-of-art literature. Several frequency control mechanisms, approaches, and devices are reviewed critically, considering both grid-connected and islanded modes of operations. Several methodologies with and without auxiliary devices are well documented. This review identifies many research gaps in the frequency control of solar PV and wind-integrated systems, which can be filled with advanced methodologies and new research. Specifically, the system frequency control methodologies need further improvement, including inertia emulators, synchronverter, and virtual synchronous generators, as most of the methods are complex and do not consider coordination between the MPPT loop and inertia loop. The researchers can find this article as an essential foundation for understanding the recent developments in the frequency control of solar PV and wind-integrated systems. Finally, future research directions are listed to guide the researchers and industry personnel.

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