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TOPICAL REVIEW

A Comprehensive Review on Power System Flexibility: Concept, Services, and Products

**MOHAMMAD BEHZAD HADI[1], MOEIN MOEINI-AGHTAIE[1], (Senior Member, IEEE),
MOHAMMAD KHOSHJAHAN[2], (Graduate Student Member, IEEE),
AND PAYMAN DEHGHANIAN[3], (Senior Member, IEEE)**
[1]Department of Energy Engineering, Sharif University of Technology, Tehran 11365-11155, Iran
[2]Department of Electrical and Computer Engineering, Texas A&M University, College Station, TX 77843, USA
[3]Department of Electrical and Computer Engineering, George Washington University, Washington, DC 20052, USA

Corresponding author: Moein Moeini-Aghtaie (moeini@sharif.edu)

ABSTRACT Massive proliferation of Variable Energy Resources (VERs) in modern power systems has posed a variety of challenges to the reliable operation of the power grid and has, at times, jeopardized the system flexibility. Flexibility is the system's ability to respond to and cope with the imbalances between supply and demand while managing the uncertainty and variability of VERs and maintaining the power system's security and reliability within the acceptable margins. Leveraging the system's available resources and capabilities, the system operators must take strategic actions to mitigate the impacts of VERs on the grid flexibility at a reasonable cost. The concept of flexibility is somewhat novel, which calls for profound studies and analyses to address different aspects of flexibility, but not limited to definition and characterization of standard metrics and indices to measure the power grid flexibility, flexibility-centred operation and planning models for the power grid, etc. This paper provides a comprehensive review of the state-of-the-art research on power system flexibility, including existing definitions and quantification measures, flexible resources, and flexibility products and services in electricity markets.

INDEX TERMS Electricity markets, flexibility, reliability, uncertainty, variability, variable energy resources (VERs).

I. INTRODUCTION

Contemporary power systems are generally made up as a combination of fossil-based generating units with renewable energy resources to balance varying demand at different timescales. However, large-scale integration of VERs, particularly solar and wind, has exposed the power system to an immense variability and uncertainty in the power generation portfolio which has consequently jeopardized the grid security [1]. The VER generation concerns the power grid in different operational horizons, e.g., the movement of a cloud above a Photovoltaic (PV) power plant in seconds or erraticism of wind power output in months [2]. System-wide impacts of VERs are featured with a wide spatiotemporal heterogeneity, e.g., temporary variabilities challenge the system capability in terms of frequency control services; however, generation variabilities in intra-hours involve the ability of supply to follow demand and operational reserves' capacity appropriation. The deeper the penetration of VERs in a power system, the more drastic change in the shape of the net-load (load minus VER). High penetration of the VERs makes it extra arduous to maintain an equilibrium between supply and demand since larger VER deployment comes with greater rate of variability and superior forecast errors on the generation outputs. These challenges have led to an introduction of the term "flexibility" in power systems with the goal to maintain economic and secure operation while coping with increasing levels of fluctuations imposed by extensive integration of non-dispatchable renewables [3]. It is inferred that the provision of flexibility depends on the net-load characteristics. Foremost features of the net-load which influence the system flexibility are net-load variation rate,

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daily breadth of the highest and lowest net-load values and the uncertainty of the net-load forecast errors [4]. Disregarding the aforementioned factors in the prognostication of the net-load, the system may encounter flexibility shortages. Power systems with flexibility shortages will have to exercise the VER curtailment during periods with downward ramp capacity requirement and load curtailments during periods with upward ramp capacity shortage [5], [6]. In [7], Lannoye *et al.* conferred the role of flexibility in power systems. In [8], a review on power system flexibility is conducted, but the research lacks the applications of the flexibility services in the energy markets. With the main focus on flexibility applications, authors in [9] epitomize flexibility products used in the electricity markets, while other flexibility aspects e.g., metrics and definitions, were neglected. Akrami *et al.* in [10] overviewed the concept of flexibility in many aspects that can be enhanced with new quantification metrics of flexibility and some notable services in the generation sector. Besides, their review suggests categorization of flexibility resources into two general groups, which might seem questionable due to the integrated and interdependent operation of the electric grid with heating sector. In [11], Emmanuel *et al.* discussed the application of flexibility in power systems, while it can be further extended to grid infrastructure and energy storage solutions.

In this paper, our goal is to present a clear-cut definition of flexibility capturing the latest updates on this concept. Besides, this research attempts to divvy the available metrics of flexibility which are essentially transacted in power system services and its related markets. Furthermore, with respect to the new rules and recent structural changes in some of the notable energy markets (in which the flexibility products are generally transacted), some flexibility services need to be reconsidered which will be extensively discussed in this paper. This paper also suggests the flexibility metrics within the system and in multiple interdependent sectors. While the modern energy systems widely consist of electrical and thermal sectors, this research also reviews the concept of thermal flexibility for further flexibility applications.

An exhaustive definition of flexibility is presented in Section II, and Section III discusses the potentials of flexibility. Section IV discusses the cost of flexibility options, and Section V is devoted to flexibility metrics and Section VI targets the power system services in which flexibility is provided or traded. Section VII is focused on flexibility timescales and the final section concludes the paper.

II. DEFINITIONS OF FLEXIBILITY

With the increasing integration of VERs in energy systems, the concept of flexibility has been receiving more attention in recent years. Experts in this area have tried to provide all-inclusive definitions on this concept. Based on [12], flexibility defines a power system's aptitude to manage the variability and uncertainty in both demand and supply, while preserving an acceptable reliability echelon at an equitable cost over various time scales. Another explanation in [13] declares that flexibility should acclimatize to numerous conceivable situations at a defined marginal price. Declaring additional explanation on this concept, flexibility stands for a proficiency that consistently and lucratively handles the net-load forecast errors through different timescales [14]. Although these studies have provided respectable definitions on the concept of flexibility, the key role of the definition is missing in the literature. The authors in [15] proposed that the time prospects in which flexibility is provisioned needs to be defined properly, and the flexibility needs to be discussed in these time scales. So that, the time scales need to be known to realize the suitable perception of flexibility. On this basis, Milligan *et al.* [16] portrays time scales for flexibility to be seconds (inertia response as a barrier in opposition to system frequency disproportions [17]) to multiple years (system planning prospect). It is noticeable that as the research in [15] is not devising an improved definition on the concept of flexibility in comparison with researches in [12], [13], and [14], the definitions of flexibility needed to be emerged with the precise definition of time scales.

Another definition in [18] describes *deliverable energy flexibility* equal to the total flexibility which is obtainable to propose to daily energy markets while disregarding endangering the technical constraints in the distribution system. The definition disparities can be observed in and attributed to the differences in the operation of energy systems facilities. Hence, the potential in providing flexibility should be discovered in each sector. Besides the existing concept of flexibility introduced and discussed earlier in the literature, another form of flexibility can be investigated within the heating sector of the energy systems, namely *thermal flexibility*. Thermal flexibility is mainly obtained from flexible heat generators, interconnections, and the combination of heat generators and thermal storage units [19], [20]. Accordingly, flexibility may be described as a system's ability to remain functionable amid rapid fluctuations and manage all system components so as not to surpass their operational constraints, while employing all of its infrastructure's potential in all time perspectives, such as from seconds to multiple years, without accruing additional costs to the system's owner(s).

III. MAIN POTENTIAL IN PROVIDING FLEXIBILITY IN POWER SYSTEMS

Traditionally, power systems are considered flexible if the operators implement Ancillary Services (AS) to handle sudden contingencies, such as unexpected generator or transmission line failures, and real-time supply-demand inequities due to erroneous projection of the demand. As a requirement, power system operators consider some amount of reserved capacity to afford regulation AS. This capacity is managed by Distribution System Operators (DSOs) and Transmission System Operators (TSOs); besides, this capacity is employed to recover the power system in case of imbalances via Frequency Containment Reserves (FCRs) and to reinstate the frequency back to its nominal rate [21]. In modern energy systems with massive integration of VERs, however, power systems are considered flexible if they:

- meet the peak net-loads cost-effectively and in a timely manner.
- avoid load and supply curtailments.
- sustain the supply-demand balance at different timescales.
- certify the accessibility of adequate ramp up/down capacities.
- ensure accessibility of enough fast-ramp and fast-start units.
- properly incorporate demand response programs while operating genuinely in an Active Distribution Network (ADN) with participation from smart loads [22].
- grants an acceptable level of AS at different time scales [23].
- operate under an elegant market, in which the flexibility is not compromised by market ineptitudes.
- have a well-planned transmission network to ensure the flexibility is not only available but also deliverable [24].

Main resources for supplying flexibility in energy systems can be categorized into:

- Supply Side
- Energy Storage Systems (ESSs)
- Demand Side
- Grid Facilities
- Market Products.

A. SUPPLY-SIDE

Supply side concerns the presentation of facilities enclosing the generation sector in power systems. Gas turbines are counted as the most flexible generators, while large steam turbines, e.g., nuclear power plant turbines, are likely to provide flexibility [25]. Besides, Combined Heat and Power (CHP) units are potential resources to couple the electrical and thermal assets in energy systems with the aim to provide levels of electrical and thermal flexibility [26].

As the VERs' probabilistic nature has increased the demand for flexibility services a flexible generation maintenance schedule system in supply-side also must be put in place [27]. It is also noticeable that the implementation of proper tools in modeling and scheduling of the supply-side infrastructures can lead to a flexible system [28]. For instance, the accuracy of the maintenance scheduling of supply-side utilities will increase with proper modeling and forecasting of the production of renewable energy resources by using deep learning approaches [29].

B. ENERGY STORAGE SYSTEMS

ESSs can adapt to the real-time variability of renewable energy resources and demand while reducing day-ahead operation costs, leading to greater flexibility, resilience, scalability, and privacy, among other benefits [30]. Moreover, generators' ramping up and ramping down will append an additional cost to the system, which could be avoided by strategic utilization of ESS [31]. When concerned with VER generation, the ESSs may be employed to assist higher VER penetration by extenuating their impacts on the grid operation [32]. VERs penetration effects are characterized in different time horizons ranging from seconds to years.

At the time scales of seconds, the ESS can provide inertia in case of sudden power fluctuations [33], thereby relaxing the role of generators in terms of system frequency response services [34]. Inertia, in a comprehensive sense, denotes the kinetic energy stored in the rotating mass of the synchronous generators to compensate the frequency deviation from its nominal value when huge disturbances occur [35], [36]. Higher penetration rate of wind energy in power systems causes a significant diminution in the average power inertia as wind turbines are not able to respond to the frequency fluctuations [37], [38].

At the intra-minute prospect, ESSs are mainly utilized to provide operational reserves, e.g., pumped-storage hydropower, Compressed Air Energy Storage (CAES), Battery Energy Storage Systems (BESSs), and thermal storages deliver flexibility over extended periods. Thermal ESSs e.g., hot water storages and most recently Concentrating Solar Power Storage (CSPS) systems, play a key role in providing thermal and electrical flexibility when power and thermal systems are coupled [39], [40], [41].

At the minutes to hours timescale, BESSs can hypothetically provide numerous services, i.e., the ones pumped-storage hydropower offers [42], for instance, providing multiple AS simultaneously [43], offering the mobility by utilizing batteries in Electric Vehicles (EVs), empowering the penetration of renewables in microgrids, among others. However, at high VER levels, sole dependency upon ESS to eliminate load/supply curtailments might become economically and practically futile [44]. Significance of the ESSs in Italian Ancillary Services Market (ASM)'s Balancing Market (BM) is a real-world example of their role in endowing flexibility when balancing services are deployed [45].

C. DEMAND SIDE

Demand response (DR) program or demand-side flexibility is used along with ESSs to mitigate the concerns VER may impose to the power grid. DR programs enable shifting of the demand pattern to cope with the mismatch between demand and supply [46]. DR is a promising approach enabling electricity customers to adjust their energy consumption subjected to financial incentives or long-term agreements [47]. In modern energy systems, these customers can be new energy system structures, namely energy hubs which can run a price-based demand response model based on energy market elasticity [48]. DR usage can be spread over providing AS, e.g., regulation services. A major challenge in DR is the coordination of the loads in distribution grids with different voltage levels. In particular, the coordination of various-size loads may hurdles achieving the expected frequency response rates of the system and reaching reserve capacity reduction goals [49], [50]. Aggregators contract with energy customers to inclining their flexible consumption or production; aggregators then amalgamate energy consumers' flexibility and renovate it for market services, e.g., for Balance Responsible Parties (BRP) [51]. Aggregators also integrate VER technologies, which afford energy system operators a profitable structure, relaxing the need for additional capacities. Besides, they exploit the demand-side flexibility by contracting with the demand sites [52], [53].

D. GRID FACILITIES

The intermittency and variability of VERs are often regarded as a fundamental inhibitive, preventing their high penetration and integration to the power grid. The aforementioned concerns lead to a VER penetration cap called "economic carrying capacity of the energy grid", the violation of which may jeopardize the grid performance [54]. Grid facilities' flexibility refers to the existence of facilities that can facilitate power transfer and increase VER penetration into the grid while maintaining acceptable operational conditions, e.g., frequency profile, along with maximum benefit to the network [55]. A substantial case of this provision is managing power flows through high-voltage, direct current (HVDC) by virtue of its flexible regulatory capabilities and HVAC transmission switching in a hybrid HVAC/HVDC transmission grid [56]. Also, Evangelopoulos *et al.* [57] introduce a thorough framework to procure and carefully manage flexibility services from distributed energy resources in distribution network to work effectively along with the grid facilities.

E. MARKET PRODUCTS

As stated earlier, Demand Side Response (DSR) permits energy clients to increase, decrease, or alter their energy consumption in real-time via smart metering. DSR also facilitates preserving a safe, maintainable, and inexpensive energy supply through demand peak shaving while the system is facing power production shortages which leads to a copious and inexpensive power tide. A vast demand site, minor enterprise, or an aggregator is donor of this product [58]. The flexibility measure typically involved with this product is response time. A market product particularly designed to address real-time flexibility challenges is Flexible Ramping Product (FRP). As depicted in Figure 1, the FRP ensures ramping availability to encounter divined net-load from its prediction uncertainty.

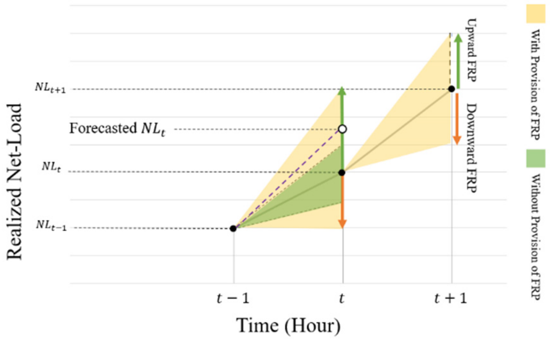

FIGURE 1. Role of FRP provision in power systems.

The FRP delivers potential ramp, concerning uncertainty as a result of net-load errors. The FRP is always recognized with Flexible Ramp Up (FRU) and Flexible Ramp Down (FRD) which attempt to address the upward and downward ramp capacity requirements of the system. The FRP lowers the operational cost of the system by preventing potential real-time energy price spikes and load curtailments. The FRP providers e.g., California Independent System Operator (CAISO), are compensated for providing flexibility in the form of FRP in both planning and operation processes based on their energy opportunity costs. This product is procured to cover forecasted net-load errors and associated uncertainty up to a certain confidence level [59], [60]. Capacity market as the other market product offers resource convenience in serving as power supply, in grid contingencies. This guarantees permanency of grid's reliability with the provision of sufficient resources to satisfy imminent energy needs. Midcontinent Independent System Operator (MISO) is an example for dealing with such market service, in which providers enjoin the market by increasing power production and reducing the power consumption. Contributors include new generators, retrofitted and enriched generators, DR aggregators, and Regional Transmission Enhancement Planners (RTEP) [61]. Generally, market products are derived from some policies that are potential solutions to enhance the power grid flexibility e.g., using the available resources, specifically, ramp capacity of dispatchable power plants, rapid response ESSs, spinning reserves, DR, power facility reinforcement, and launching new flexibility products in the electricity market in order to holistically provide certain levels of flexibility [62], [63], [64].

IV. COST OF FLEXIBILITY OPTIONS

As stated earlier, the flexibility options are established to maintain a cost-effective system. The provision of the flexibility in different power system sectors is recently been more imperative while nations are moving toward reducing emissions and Net Zero Energy (NZE) programs [65]. In this manner, higher proportions of VER are anticipated to raise the value of options to increase the flexibility of the energy systems, while reflecting economic advantages of energy system flexibility alternatives is essential [66]. A comparative analysis by the scholars in [67] show that demand response application (demand side), retrofitting the thermal units (supply-side), ESSs, and establishment of new grid facilities and interconnections are economically and technically sorted from top to bottom, respectively. Relative studies by [68], [69] show that as climate goals are modest, demand side flexibility options provision has a significant influence on system costs, but sector coupling with the district heat sector and investment in grid facilities have a growing impact among other flexibility options, when climate targets are more ambitious. As a result, the sector coupling needs accurately assessing the storage requirements, which leads to more flexibility from ESSs with more system cost charge [70]. It can be concluded that depending on the climate goals, scarcity of financial resources, and availability of energy resources, the flexibility options can be used by the governments.

V. FLEXIBILITY METRICS

State-of-the-art research and existing literature mainly assess power system flexibility in terms of ramping capability, and power and energy capacity [71]. However, these terms do not capture the effects of delay in DR action and system contingency response, while the Response Time (RT) do. In [72], [73], [74], [75], [76], [77], [78], and [79], several flexibility indices are acknowledged. Authors introduced the RT as a new metric to quantify system flexibility [72]. Likewise, the authors in [73] proposed a new flexibility index, named Insufficient Ramping Resource Expectation (IRRE), that evaluates power grid's failure to overcome the variability in demand and supply. A conceptual metric presented in [74] based on system's general operational norms, namely, power limit, ramp rate, start-up time and dispatchability. Another quantifiable flexibility measure which is introduced in [75] is defined as Lack of Ramp Probability (LORP) wherein no inter-zonal transmission constraint is considered. This operational index is used to quantify inter-temporal ramping flexibility at the real-time dispatch time scale. Another index defined in [76], based on the System Capability Ramp (SCR), quantifies accessibility of the flexibility by representing the possibility of a ramping capability shortage due to major system uncertainties e.g., Failure of Power Plants (FoPP) and VERs forecast error in a certain period. Another metric mentioned in [77] is Ramping Capability Shortage Expectation (RCSE) that embodies the possibility of ramp shortages once facing uncertainties at particular time intervals. The authors in [78] introduced a new flexibility metric called Flexibility Area Index (FIA) which is defined as the combination of power system units' flexibility, and reflects the whole systems' ability to manage the VERs curtailment by FRU and FRD components. In the case of thermal flexibility, a new index, namely Building Energy Flexibility Index (BEFI), can be used to represent the quantity of available thermal flexibility from thermal storages, inside the buildings [79]. A fleeting delineation of the technical basis of the above flexibility metrics and indices is annexed in Table 1.

TABLE 1. Flexibility indices.

Name	Basis on Time	Basis on Ramp	Basis on Power
Minimum Power Limit			✓
ramp rate		✓	
start-up time	✓		
RT	✓		
IRRE		✓	✓
LORP		✓	
SCR		✓	
RCSE		✓	
FAI	✓	✓	✓
BEFI		✓	✓

VI. FLEXIBILITY SERVICES

Flexibility services can be categorized into voltage and frequency response, reserves, reactive power services and system security [9], [80]. These services guarantee that the availability and delivery of the flexibility is consistent in all time prospects. Some studies suggest revisions in these services to facilitate and widen the standard's implementation e.g., reevaluating the permitted trip clearing time setting ranges in IEEE standards [81]. These changes benefit the system in providing more flexibility through the power system.

A. FREQUENCY RESPONSE SERVICES

Frequency response services uphold the system constancy and counteract frequency changes through active power generation or demand adjustment. These services are mainly categorized as dynamic and static products. The dynamic frequency response focuses on the response ability in the intra minutes (or even in seconds); however, static frequency response focuses on degradations lower than a particular frequency limit [82]. Dynamic Frequency Response (DFR) is further classified as Rapid Frequency Response (RFR), Primary Frequency Response (PFR), Secondary Frequency Response (SFR), High Frequency Response (HFR) and Rapid High Frequency Response (RHFR) for which the accessibility times are in 5, 10, 30, 5 and 10 seconds, respectively. These operational timescales are illustrated in Figure 2.

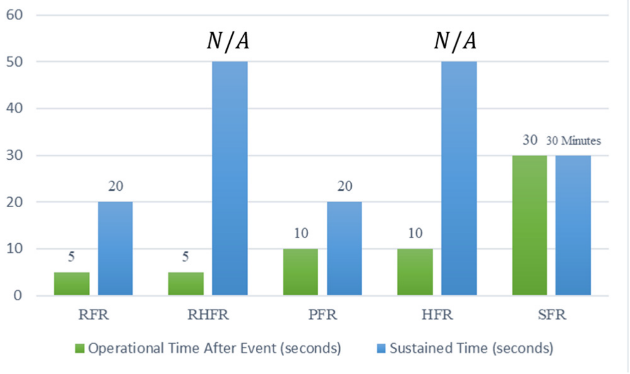

FIGURE 2. Dynamic frequency response services time action.

Mandatory Frequency Response (MFR) ensues through active power changes of generators, especially transmission-connected sizable generators. They should be capable of providing enduring power in response to a pre-set frequency deviation limit. UK national grid Energy System Operator (ESO) and Australian Energy Market Commission (AEMC) are some example MFR service providers. Providers join into the market on a monthly basis via online Frequency Response Price Submission (FRPS) [83].

Firm Frequency Response (FFR) is a service open to small generators (<1MW) and is accessible by Balancing

Mechanism Units (BMUs) and non-BMUs. It should be noted that, BMUs consist of generating units and utilization metering [84]. Providers report the transmission and distribution system's energy flows via a monthly-tendered procedure; PFR, SFR and HFR frequency services [85]. Generally, the term ''tender'' refers to platforms through which providers are requested to confirm that all the information and their technical requirements are accurate to the best of their knowledge before submission to be able to contract in the market. The providers can tender in an electronic platform e.g., Ariba platform by Systems, Applications, and Product corporation (SAP) in Short Term Operating Reserve (STOR) services [86].

High impact contingencies (e.g., loss of large generating units) instigate large frequency deviations. Consequently, these deviations affect service delivery to the consumers which needs to be tackled via Frequency Control by Demand Management (FCDM) [87]. FCDM providers are contracted to automatically respond under frequency deviation circumstances and assist in recovering the system frequency within the agreeable range, by momentarily end a portion of their working procedure to reduce demand on the network [88].

Enhanced Frequency Response (EFR) service offers a fast response in supporting the power grid during low system inertia times sustained for 15 minutes. The service enhances the transition back to the normal frequency after sudden fluctuations. EFR reduces the grid charges and is procured through economic offers [89]. A summary of frequency response services is presented in Table 2.

TABLE 2. Frequency response services.

Name	Operational Timeframe	Base service	Specification
DFR	5-30 sec	RFR-PFR-SFR-HFR-RFHR	Base of some frequency responses services
MFR	10-30 sec	PFR, SFR or HFR	Applied specific days of month
FFR	10-30 sec	PFR, SFR or HFR	Applied single or multiple months (Depending on the contract with ESO)
FCDM	Within 2 seconds of instruction	SFR	Delivering minimum 3 MW within 30 minutes
EFR	within 1 second of frequency deviation	DFR	Capability of delivering 1 MW up to 50 MW

B. RESERVE

Reserve service indicates supplementary resource requirement when the power grid encounters energy disproportions in a short period. Reserve services are categorized into two general classes, i.e., fast products and short-term products. Fast reserve product providers have to offer at least 50 MW of the power for up to 2 minutes [90]. An application of the reserve services can be further investigated in heating sector of the energy systems. In [91], a model for district heating systems is introduced to enhance the thermal flexibility of the CHP units through participation in reserve services. STOR is offered in case of generation surplus or shortage. STOR providers must be available all throughout market openings i.e., daily hours during which the supply margin is expected to be tighter and, upon request, they must be able to deliver full active power for up to 2 hours [92]. Other short-term operating reserves, different from STOR category, are highlighted in Figure 3, e.g., Enhanced Operation STOR [93], STOR runaway [94] and, Balancing Mechanism (BM) start-up [95]. Demand Side Balancing Reserve (DSBR) provides supplementary reserve in order to balance the unlikely situations in which there is insufficient capacity to meet the demand. DSBR concerns large energy users who could voluntarily reduce electricity consumption, solely in the winter period, with a payment in return [96]. Supplemental Balancing Reserve (SBR) provides generating capacity; however, DSBR provides an opportunity for major energy consumers and aggregators to get paid in return for their contributions to moderating the energy consumption during peak times [97]. SBR is utilized when all market-based actions exhausted, where generators are dispatched in economic order (i.e., utilization price and duration required).

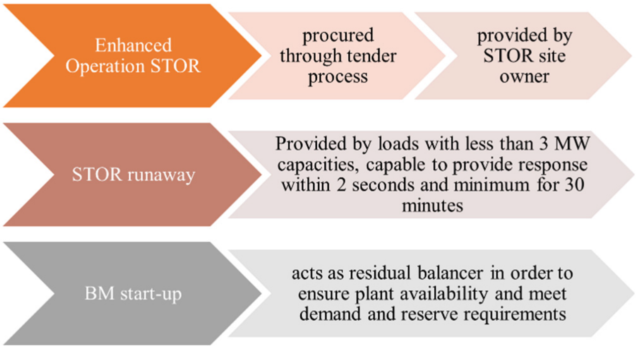

FIGURE 3. Different categories of short-term operating reserves.

DSBR and SBR, together, present Contingency Balancing Reserves (CBR) as a transitional product to regulate the grid frequency during contingencies. Industrial and commercial entities which can structure the rules of AS programs can serve as DSBR providers. Energy system operator in National-grid ESO is no longer procuring this service, as they transition to capacity markets.

C. VOLTAGE CONTROL AND REACTIVE POWER BALANCE SERVICES

The necessity of reactive power services arises from presence of the generators with quite high nominal rating, the connection of the DGs along with DGs configuration [98]. Hence, many services have been propelled. Obligatory Reactive Power Service (ORPS) maintain voltage fluctuations at a certain level and the providers of this service should supply their rated output power under certain operational circumstances. Enhanced Reactive Power Service (ERPS) is procured and applied where reactive power capability exceeds minimum prerequisite of MVAr lagging capabilities [99].

D. SECURITY PROVIDE SERVICES

Some flexibility services can help prevent consecutive tripping of the generating units, disruption of the generators, transmission congestion and power shortages, e.g., providing Black Start support by VER units, Inter-trip guarantees the generators' disconnection from the power grid, Constraint Management is procured for efficient and economic operation of the power transmission system [100], [101], [102].

VII. FLEXIBILITY TIMESCALES

According to [7], the operational flexibility acclaims the ability of a system's utilities to manage the net-load uncertainty and variability under deep VERs integration. Reference [12] intuits that more augmented operational flexibility leads to a more secure power system. Consequently, to enhance the operational flexibility, one first needs to define proper measures to evaluate the network's existing level of flexibility and the associated inefficiencies. According to [58], [103], [104], [105], [106], three general categories on the existing methods are introduced i.e., visualized methods, metrics and comprehensive models. Visualization methods, e.g., illustration of dynamic upward and downward ramping capability curve [107], [108], are easy to understand but need lots of information. Comprehensive methods [109], [110] are widely used when overall margins on accommodations of VERs' uncertainty and variability are desired. Finally, metrics e.g., operational flexibility, are another approach to evaluate the current level of flexibility and offer a better understanding on how to improve the flexibility of the system infrastructures [111], [112].

Operational flexibility can be defined in different time scales, including long term, long to medium term, medium to short term and short to very short term [113]. A brief schematic with analytical solutions and corresponding highlights is depicted in Figure 4. Experiments have shown that the planning timeframe is the most economically advantageous way to take flexibility into account [114]. Considering yearly horizon, system requirements of sufficient flexible resources are ensured to operate properly with high shares of VER generation. The output of VERs is inexorably stochastic, which causes reliability challenges in power system operations over years. In power grids with low levels of flexibility, during the periods with high VER generation spikes, large amounts of generation may be curtailed in order to maintain a balance between supply and demand [115].

To overcome this challenge, regulators might need to encourage investment in flexibility enhancement programs by providing certain tariffs/incentives, increase time and space granularity in market design, and re-designing capacity markets [116]. Energy system operator should balance the seasonal energy capriciousness on monthly basis operations, arising from uncertainties of hydro units scheduling [117]. With high penetration of VERs in power systems and their impacts on net-load uncertainty and variability in hours and intra-hours prospects, market operations should be analysed in real time. The necessity of day-ahead decisions comes from the fact that hourly scheduling protocols in real-time operation are insufficient to provide system operators with the required flexibility to manage their system effectively [118], [119]. Designing intra-day markets is crucial in terms of leveraging the full flexibility potential of the power grid. Besides, setting a shorter span between gate closure and actual market transactions can notably enhance the flexibility in this timescale. According to [6], it can be justified that this setting is preferred as the changes in VERs, especially in wind, could be extremely large in real-time, which is not reflected in the offline sight (day-ahead) of the system operation. This vision concerns the timescale of the system operation which directly alters the system flexibility. In minutes to seconds, utilization of AS is necessary for reliable and flexible grid operation, particularly compensating unexpected imbalances between demand and supply. Regulators must introduce new products and deploy operating reserves to incentivize flexibility providers to partake. Generally, an ingenious service launched into practice by several ISOs e.g., National Grid ESO, is the Fast Frequency Response (FFR) delivered by BESSs and VERs [120]. Flexibility is provisioned in PJM, CAISO and EPEX in day-ahead, intraday, and the intraday continuous market auctions [121].

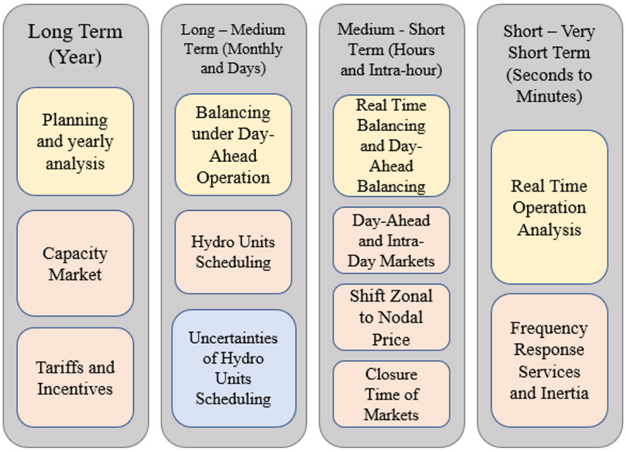

FIGURE 4. **Operational flexibility timescales.**

VIII. CONCLUSION

Most recently, the research community has recognized the need for flexibility in power systems while renewable energy sources are being aggressively integrated worldwide. Highlighting the latest updates on the concept of flexibility, this paper tried to epitomize the required information about the electrical and thermal flexibility and the services in which this concept is impudent. This research focused on unifying the available meanings and metrics of flexibility and introducing the markets wherein the flexibility is traded in the form of power system utilities options. It should be noted that a unified framework to evaluate power systems flexibility and demonstrate it with a global index is yet to be addressed. Although there are numerous studies conducted addressing different aspects of flexibility, there still exist large gaps in mathematical techniques to evaluate operational flexibility which need research attention. The effect of transactive energy markets on the operational flexibility of the system, thermodynamic conditions across a variety of energy storage technologies, effects of reactive power, and optimizing facilities in an intra-connection design of energy systems should be further examined. Financial policies by the system operators to incentivize the prosumers to participate in energy market transactions, and deployment of energy hubs are other suggestions for further research.

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MOHAMMAD BEHZAD HADI received the B.Sc. degree in electrical engineering from Shahed University, in 2018, and the M.Sc. degree from the Department of Energy Engineering, Sharif University of Technology, Iran, in 2021. His research interests include the electricity market, power system optimization, power system flexibility, and integration of renewable energy systems in power systems.

MOEIN MOEINI-AGHTAIE (Senior Member, IEEE) received the M.Sc. and Ph.D. degrees in electrical engineering from the Sharif University of Technology, Tehran, Iran, in 2010 and 2014, respectively. He is currently an Assistant Professor with the Department of Energy, Sharif Energy Research Institute, Sharif University of Technology. His current research interests include reliability and resilience studies of modern distribution systems, especially in the multicarrier energy environment, and charging management of plug-in hybrid electric vehicles.

MOHAMMAD KHOSHJAHAN (Graduate Student Member, IEEE) received the B.Sc. degree in electrical engineering from the Amir Kabir University of Technology, Tehran, Iran, in 2015, and the M.Sc. degree in electrical engineering from the Sharif University of Technology, Tehran, in 2017. He is currently pursuing the Ph.D. degree in electrical engineering with the Department of Electrical and Computer Engineering, Texas A&M University, College Station, TX, USA. His research interests include power system operation, electricity market, power system flexibility, energy storage, and smart electricity grid applications.

PAYMAN DEHGHANIAN (Senior Member, IEEE) received the B.Sc. degree in electrical engineering from the University of Tehran, Tehran, Iran, in 2009, the M.Sc. degree in electrical engineering from the Sharif University of Technology, Tehran, in 2011, and the Ph.D. degree in electrical engineering from Texas A&M University, TX, USA, in 2017. He is currently an Assistant Professor with the Department of Electrical and Computer Engineering, George Washington University, Washington, D.C., USA. His research interests include power system protection and control, power system reliability and resiliency, asset management, and smart electricity grid applications. He was a recipient of the 2014 and 2015 IEEE Region 5 Outstanding Professional Achievement Awards, the 2015 IEEE-HKN Outstanding Young Professional Award, and the 2021 Early Career Award from the Washington Academy of Sciences.

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