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Flexibility to support the future power systems

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SUMMARY

Power system flexibility relates to the ability of the power system to manage changes.
Solutions providing advances in flexibility are of utmost importance for the future power system. Development and deployment of innovative technologies, communication and monitoring possibilities, as well as increased interaction and information exchange, are enablers to provide holistic flexibility solutions. Furthermore, development of new methods for market design and analysis, as well as methods and procedures related to system planning and operation, will be required to utilise available flexibility to provide most value to society.
However, flexibility is not a unified term and is lacking a commonly accepted definition.
The flexibility term is used as an umbrella covering various needs and aspects in the power system. This situation makes it highly complex to discuss flexibility in the power system and craves for differentiation to enhance clarity. In this report, the solution has been to differentiate the flexibility term on needs, and to categorise flexibility needs in four categories: *Flexibility for Power, Flexibility for Energy, Flexibility for Transfer Capacity,* and *Flexibility for Voltage*.
Here, flexibility needs are considered from over-all system perspectives (stability, frequency and energy supply) and from more local perspectives (transfer capacities, voltage and power quality). With flexibility support considered for both operation and planning of the power system, it is required in a timescale from fractions of a second (e.g. stability and frequency support) to minutes and hours (e.g. thermal loadings and generation dispatch) to months and years (e.g. planning for seasonal adequacy and planning of new investments).
The categorisation presented in this report supports an increased understanding of the flexibility needs, to be able to identify and select the most suitable flexibility solutions.

KEYWORDS

Flexibility; Power system operation and planning; Power; Energy; Voltage; Transfer capacity

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1. INTRODUCTION – AN EVOLVING POWER SYSTEM

The evolution of the power system has significant impact on the operation and planning of the future power system. Five major global trends influencing the power system evolution [1]:

- **Decarbonisation** - Decreasing the carbon footprint from electric power production.
- **Decentralisation** - A transition from few and large, centralized, power plants to many smaller, decentralised, power production units.
- **Integration** – Increasingly integrated electricity markets, greater interconnection of previously independent grids and more integrated energy systems including sector coupling.
- **Digitalisation** – Extensive implementation of and dependency on information and communication technologies and solutions.
- **Inclusion** - Increasing demand for sustainable, affordable and accessible energy for all including increased electrification of e.g. industrial processes and transport.

These trends bring challenges in planning and operating the power system in a secure and reliable manner, such as:

- **Identification of true operational state** - As the utilization of the power system is increasing it becomes even more important to quantify uncertainties in measurements and modelling to better understand reserves to critical limits.
- **Changes in dynamic response** - As a result of power electronic (PE) interfaced devices taking over roles of rotating machines, the dynamic behaviour of the power system changes resulting in that commonly accepted rules and principles may no longer be valid.
- **New utilization patterns** - More dispersed generation units, new types of demand, more and larger interconnections, results in utilisation of the power system in new and previously unforeseen ways.

The flexibility of the power system is seen as a key to cope with some of the challenges of future power system. Solutions providing advances in flexibility are of utmost importance for the future power system, making this an increasingly important topic to consider for operation and planning and for policy makers [2]. An example of this is illustrated in the ENTSO-E R&I roadmap 2017-2026, [3], having flexibility as one of five dedicated research area clusters. Flexibility has been in focus for several years, with a large number of initiatives ongoing in various fields. The large number of recent publications on the subject further highlights its importance, as illustrated by the in-depth review presented in [4] and [5]. The increased need of flexibility relates largely to the significant increase of variable renewable resources as described in [6]. The Nordic TSOs have identified the need for flexibility as one of the main challenges in the near future [7]. Improved TSO-DSO coordination to utilise flexibility resources are discussed in [8]. ENTSO-E is further highlighting the importance of utilising flexibility from distributed resources, described as Distributed Flexibility Resources (DFR), in [9]. Strategies to utilise flexibility, available from power electronic interfaced generation and load, to enhance the stability and security of the power system is identified as a primary focus area for research and development [10]. An overview of flexibility for system support is presented in [11], and flexibility for forecast balancing presented in [12] and [13].

Development and deployment of innovative technologies, communication and monitoring possibilities, as well as increased interaction and information exchange, are enablers to provide local, regional and system wide flexibility solutions. In order to utilise the available flexibility to provide most value to society, there is a necessity for development of new market solutions and utility practices as well as enhancement of existing market rules, short-term and long-term markets [1].

2. CATEGORISATION OF FLEXIBILITY NEEDS IN THE POWER SYSTEM

There is no common definition of flexibility, several suggested definitions are available in e.g.: [2], [6], [11], [14], [15], [16], [17], [18], [19], [20], [21]. These suggested definitions are extremely broad; thus flexibility can relate to many different aspects, which makes it highly complex to talk about flexibility in general terms. One solution is therefore to differentiate flexibility needs and create sub-categories each of which can be defined in a comprehensive and functional manner.

In this report, flexibility solutions and needs are considered in a holistic manner, both from the over-all system perspectives as well as from the more local perspectives:

- Flexibility needs from an over-all system perspective are related to maintaining a stable frequency and a secure energy supply.
- Flexibility needs from a more local perspective are related to maintaining bus voltages and securing transfer capacities.

This means that flexibility needs and resources may be found in the whole power system.

Solutions to provide flexibility in this sense are not limited to modification in supply and demand. On the contrary, many different types of solutions may provide value to increase the flexibility of the power system where solutions to influence rules and regulations in operation and planning of the power system may provide significant value to increase the flexibility. Similarly, needs for flexibility are not only limited to the balance of supply and demand. Flexibility needs are also relevant for maintaining voltages and securing transfer capacities.

In this report, flexibility solutions and needs are considered relevant for both operation and planning of the power system.

It is important to understand the flexibility needs to be able to identify and select the most suitable flexibility solutions and the resources which can provide the flexibility. The most suitable flexibility solution is dependent on the need, situational restrictions and regulations, and on available power system equipment. Selection processes may include both technical and commercial aspects, considering: type of loads as well as available generation units, storage solutions, DC connections to other systems, etc. Depending on the need, possible flexibility resources are found in the whole power system. Similarly, flexibility support is required in a timescale from fractions of a second (e.g. stability and frequency support) to minutes and hours (e.g. thermal loadings and generation dispatch) to months and years (e.g. planning for seasonal adequacy and of new investments). Detailed insights in timescales and resources are presented in [2] and [6].

In this report, categorisation of flexibility needs are presented in four categories: *Flexibility for Power*, *Flexibility for Energy*, *Flexibility for Transfer Capacity*, and *Flexibility for Voltage*. Each of the flexibility categories are described below.

2.1 Flexibility for Power

A functioning power system is required to maintain the equilibrium between power supply and power demand at all times. For the short term, this corresponds to maintaining the system frequency within pre-defined limits in order to prevent frequency instability (in an AC system). Conventional means of maintaining the frequency relate to the control of active power of generation units within the synchronous area. This is defined as the units balancing capability (upward or downward, depending on the requirement of increasing or decreasing the power generation). The balancing capabilities within a system are defined by the flexibility of the generation units. Control of flow on DC connections to neighbouring systems may also be considered to provide a part of this balancing capability. Furthermore, demand has also been

part of the balancing capability through bi-lateral agreements with dedicated load centres to decrease their demand if required.
Increasing the amount of intermittent weather dependent power generation, meaning also a decrease in available plannable generation, increases the uncertainties and variability of the power supply. To be able to maintain a secure future power supply, there is an increased need for flexibility solutions to provide balancing capability:

- For the remaining plannable generation units, this may result in requirements of increased flexibility of e.g. thermal power plants to widen their operating ranges (minimum load levels and ramping rates) and shorten their start-up time.
- For the intermittent power generation units, flexibility requirements may result in a requirement to provide upward and downward balancing capability implying curtailment of renewable energy.
- To utilise a large number of small production units and loads, aggregated control of supply and demand may be used to provide flexibility solutions.
- Furthermore, solutions may involve the utilisation of short-term storage units and interaction between multi-energy carrier systems.
- Evaluating possibilities of increasing limits within which the system is operated, e.g.: minimum/maximum frequency deviation; speed of frequency changes (rate-of-change-of-frequency); amount of time outside acceptable limits, may also prove to be suitable solutions for flexibility. Such changes may also cause altered requirements of the units and systems within the power system.

The flexibility need categorised as *flexibility for power* is required to support the system within fractions of a second up to an hour.

2.2 Flexibility for Energy

For the medium to long term, the equilibrium requirement between supply and demand implies the requirement to secure the supply of energy for future scenarios.
Managing and maintaining a secure energy supply in the long-term perspective is complex and involves seasonal optimisation of the value of stored energy including forecasted outage periods for power plant maintenance, future load scenarios, etc. Conventional solutions include stockpiling of fuels for thermal plants and the use of hydro reservoirs to level out seasonal variations in precipitation and load. Seasonal variations in load are also considered when scheduling appropriate timing for the maintenance of the traditional base-load thermal units (such as nuclear and coal), in such way long-term flexibility is provided maximising the availability for high demand seasons. Pumped hydro is a flexibility solution for daily demand variations, to utilize available generation capabilities during hours with low demand in order to increase the amount of supply available for hours with high demand. Photovoltaic (PV) solar energy production has a strong seasonal variation in countries far from the equator and has a negative correlation with weather dependent loads in colder climate.
Decreasing the amount of fuel storage-based energy supply (such as nuclear and coal), and increasing the amount of non-fuel storage based energy supply (such as solar and wind), increases the uncertainty of the future energy supply. To be able to maintain a secure future energy supply, in a medium- and long-term perspective, there is an increased need for flexibility solutions to provide possibilities of storing energy from situations of high supply to situations with low supply. Altering demand behaviour, to follow variations in supply, may provide part of such flexibility on the daily perspective but likely not significantly on the seasonal level.
The flexibility need categorised as *flexibility for energy* is required to support the system in the multi-hour, daily, seasonal and annual perspective.

2.3 Flexibility for Transfer Capacity

Dealing with power system security, the topology and capacity of the power grid plays a most important role. As grids are typically dimensioned and planned in a socio-economic way, with available grid capacity placing restrictions on operation and operation planning. Thus, flexibility does not only relate to the ability to balance supply and demand, but also to the location of reserves to be activated given a certain disturbance or unbalance and the grid capacity between the demand and supply.

Flexibility is to a certain extent a built-in functionality in the power grid itself. In an AC system, the use in operation of real-time or anticipated changes in grid topology (so called "remedial actions") is a well-known and cost-free flexibility resource. Besides, other measures which provide increased transfer capacities or flexibility in the control of the power transfer system are available in operation like increasing nominal voltage levels, or the use of phase-shifting transformers. At the grid expansion planning stage, series-compensation, or, power electronics based Flexible AC Transmission Systems (FACTS) devices can be installed. They can be used to control voltage, re-direct power flows or to improve stability properties.

New installation to strengthen the power transfer may be not possible or justifiable from different perspectives. Such limitations may occur locally and regionally, influencing the power system on a national and international level. In such cases, other solutions to increase the flexibility for transfer capacity may be needed to cope with increasing peak transfer situations.

System integrity protection schemes (SIPS or SPS) may be used to increase transfer capacities. Such protections may be designed to act as a response to an event, in order to prevent or limit the extent of a disturbance.

Dynamic line rating (DLR) for overhead lines increases the flexibility in utilization of assets, where the use of measurement system solutions provide ambient dependant utilization levels of lines instead of predetermined fixed ratings. Utilizing dynamic rating for other assets, such as cables, may be future solutions for increasing flexibility to cope with peak transfer situations.

Time variable transfer tariffs are possibilities to influence the behaviour of demand and supply, in order to prevent congestion during peak transfer situations.

Power systems are usually operated and planned in accordance with the *n-1* reliability criterion, implying that no single contingency should result in a large disturbance. The *n-1* criterion imposes restrictions on power transfer, where e.g. thermal or stability limits of lines places constraints on transfer on parallel connected lines in a power transfer corridor. Such limitations may lead to bottlenecks in the system and result in regional price difference for customers or limitations on generation. The *n-1* criterion is quite simple to implement but does not consider the relative probability or the consequence of a specific outage. Furthermore, power systems may be subject to multiple or "cascading power transmission outages". Such outages may propagate nonlocally; after a fault occurs on one component, the next fault may be very distant, both topologically and geographically. In the end, such propagation may get out of control and lead to system wide blackout. In order to avoid such events, additional restrictions may be imposed on power transfers in which case limitations are due to security concerns rather than thermal ratings. The use of probabilistic reliability criteria instead of, or as complements to, deterministic criteria such as the *n-1* could provide additional flexibility for transfer capacity and further increase the available grid capacity.

The flexibility need categorised as *flexibility for transfer capacity* is required to support the local and regional grid, which means that the location of resources to provide flexibility is highly important. The time frame relevant for *flexibility for transfer capacity* is in the ranges of minutes to several hours.

2.4 Flexibility for Voltage

Maintaining the bus voltages within predefined levels throughout the power system is important both from a stability perspective as well as for power quality.
Voltage stability is largely related to the location and reactive power capabilities of generation units and other reactive power compensation units. The behaviour of demand, as well as the operation of distributed generation units, has a strong influence on the voltage.
FACTS devices, such as static var compensators (SVC) or static synchronous compensators (STATCOM), are increasingly important as means for TSOs or DSOs to control voltage and at the same time being flexible and independent of services from generators.
The increased amount of distributed generation creates completely new power flows in the system, altering voltage profiles in the distribution system and may lead to decreased power quality. To be able to maintain the bus voltages within predefined levels, there is an increased need for flexibility solutions to provide voltage support.
Ancillary services from distributed generation and storage may become useful solutions for distributed voltage support. Demand side response solutions may be used in a similar way.
Broadening of acceptable ranges for power quality may also prove to be suitable solutions for flexibility. Such changes could lead to increasing requirements on components and systems within the power system.
The flexibility need categorised as *flexibility for voltage* is required to support the power system on a local and regional level, which means that the location of resources to provide flexibility is highly important. The time frame relevant for *flexibility for voltage* is from seconds to tens of minutes.

3. DEVELOPMENTS OF SOLUTIONS FOR FLEXIBILITY

A large number of research development and demonstration initiatives are and have been addressing flexibility aspects in the recent years. In this section a few of these projects have been highlighted.
The EcoGrid EU project worked on the development and testing of a new market concept allowing to improve the balancing mechanisms by introducing a 5 minutes real-time price response to provide additional balancing power from smaller customers directly to the Transmission System Operators [22].
The concept developed by the Cell Project looked at dividing the power system into virtual fully autonomous grid areas in terms of control, so-called cells. The cell concept could be realized through the development and implementation of an advanced monitoring and control system capable of monitoring the state of the cell and – in extreme situations – taking control of its individual units such as circuit breakers, transformers, wind turbines and CHP plants [23].
Division of the grid into semi-autonomous units is studied by the Fractal Grid project [24] and the C/sells project [25]. The web-of-cells approach has also been utilised in the ELECTRA Integrated Research Programme on Smart Grids (ELECTRA IRP), which addresses the issue of deployment of RES connected to the network at all voltage levels as well as establishes and validates proofs of concepts that utilize flexibility from across traditional boundaries in a holistic manner [26].
The possibility to exchange and trade electricity at small scale within local communities is sometimes suggested as a possible route for integrating large amounts of distributed energy resources in a cost-effective way. The Fossil Free Energy District (FED) project is demonstrating one such local energy market [27].
Peer-to-peer electricity markets based on blockchain technology has received a considerable amount of interest in recent years, with the Brooklyn Microgrid in New York as an example [28]. The peer-to-peer blockchain structure enables decentralized transactions without the

involvement of a central intermediary. This may have benefits from an information security and resilience perspective.
Local electricity markets can also be oriented towards providing a platform where system operators, including DSOs, can procure balancing services from local distributed resources and demand response aggregators. One such example is the FLETCH concept [29], developed as part of the iPower platform in Denmark [30]. The concept is based on a flexibility clearinghouse that streamlines the business interactions between DSOs and aggregators in order to keep transaction costs as low as possible. With this market structure, DSOs submit requests for services that aggregators can bid for. By standardizing the flexibility services and bidding format, the clearinghouse concept aims at reducing transaction costs and thereby making market-based flexibility solutions a competitive alternative to more traditional grid infrastructure investments.
The project From micro to Mega-GRID (m2M-GRID) develop of solutions related to: enhancement of distribution grid planning; control functions for effective coordination with distribution grids; and a toolbox to exploit potential flexibility of micro-grids [31].
A new marketplace capable of exploiting decentralised flexibility is being developed by the Norwegian energy company Agder Energi and the Power Exchange Nord Pool through the recently established subsidiary NODES [32].
Flexibility for power, utilising wind farms aggregated kinetic energy, has been studied in [33] providing methods for quick responses in systems based on slower governors containing high levels of renewable generation.
The OSMOSE project (Optimal System-Mix Of flexibility Solutions for European electricity), [34], focuses on four topics: power transmission technologies; storage technologies; control tools for enhanced transmission grid flexibility; improved energy market efficiency, in a context of high shares of RES. The project aims to define conditions for an optimal mix of flexibility.
The MIGRATE project (Massive InteGRATion of power Electronic devices) is seeking to devise a grid-forming solution for 100% power-electronic grids (wind and solar), [35].
The SmartNet European research project [36], aims at comparing different TSO-DSO interaction schemes and different real-time market architectures with the goal of finding out which would deliver the best compromise between costs and benefits for the system.
The EU-SysFlex project (Pan-European system with an efficient coordinated use of flexibilities for the integration of a large share of RES), [37], works on identifying a mix of flexibility and system services to support the secure and resilient operation of the power system.

4. CONCLUSIONS AND DISCUSSION

The broadness of the use of power system flexibility craves for differentiation to enhance clarity and to present comprehensive and functional definitions of the sub-categories of flexibility.
In this report, the following categorisation of flexibility is used to differentiate flexibility needs:

- **Flexibility for Power:**
  Need description: Short term equilibrium between power supply and power demand, a system wide requirement for maintaining the frequency stability.
  Main rationale: Increased weather dependent power supply in the generation mix.
  Activation timescale: Fractions of a second up to an hour.
- **Flexibility for Energy:**
  Need description: Medium to long term equilibrium between energy supply and energy demand, a system wide requirement for demand scenarios over time.
  Main rationale: Decreased fuel storage-based energy supply in the generation mix.
  Activation timescale: Hours to several years.

- **Flexibility for Transfer Capacity:**
  Need description: Short to medium term ability to transfer power between supply and demand, where local or regional bottlenecks resulting in congestion costs.
  Main rationale: Increased utilisation levels, peak demands and peak supply.
  Activation timescale: Minutes to several hours.
- **Flexibility for Voltage:**
  Need description: Short term ability to keep the bus voltages within predefined limits, a local and regional requirement.
  Main rationale: Increased distributed power generation in the distribution systems, resulting in bi-directional power flows and increased variance of operating scenarios.
  Activation timescale: Seconds to tens of minutes.

It is important to understand the flexibility needs, to be able to identify and select the most suitable flexibility solution. Given a functional flexibility market, flexibility solutions can compete against each other with their specific technical advantages and constraints.
Some examples of flexibility solutions are included in Figure 1, divided on flexibility category and ordered on power system implementation level from local to system wide.

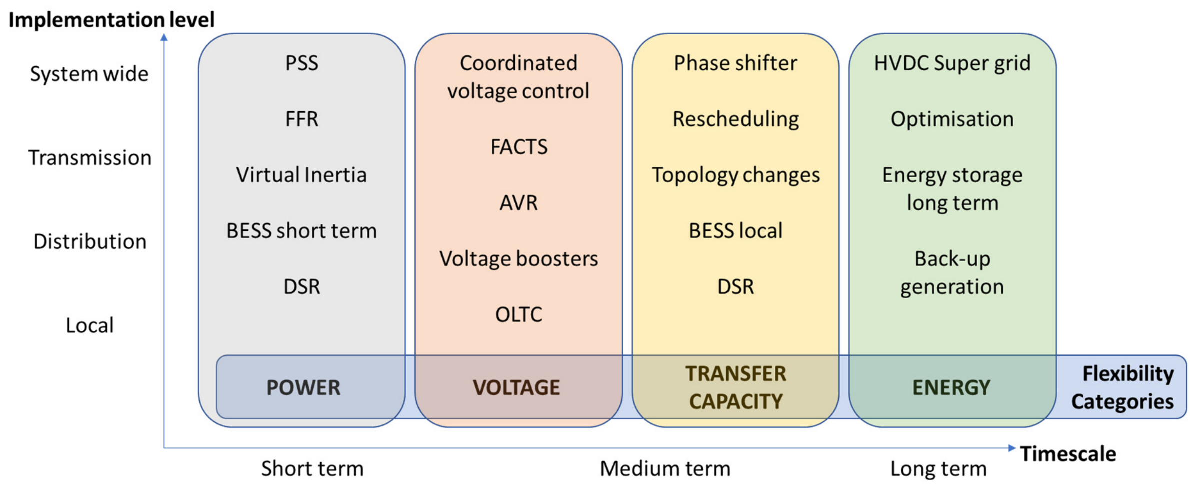

Figure 1: Examples of flexibility solutions. (PSS: Power System Stabiliser; FFR: Fast Frequency Response; BESS: Battery Energy Storage System; DSR: Demand Side Response; FACTS: Flexible AC Transmission System; AVR: Automatic Voltage Regulator; OLTC: On-Load Tap-Changer)

Providing long-term flexibility (e.g. seasonal storage) is in general much more expensive than short-term flexibility. However, flexibility to support short-term needs may be provided at almost zero costs from installations intended to provide long-term flexibility.
Furthermore, sector-coupling analysis examining the flexibility needs of the whole energy sector paves the way to a coordinated use of existing cross-sectoral flexibility solutions which reduce the over-all need for investments.
Coordination between TSOs and DSOs is essential to ensure that flexibility resources in distribution networks remain available for balancing purposes without inducing unmanageable local congestions, which could jeopardize the local grid.
Given a long term stable and enabling regulatory framework, with an innovative and transparent market environment: properly designed systems for measurement, information and communication, monitoring, control and protection, can provide key solutions for increasing the different categories of flexibility needed in the future power systems.

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The vision of ISGAN is to accelerate progress on key aspects of smart grid policy, technology, and related standards through voluntary participation by governments.

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