1.1 Electricity Balancing Markets - Challenges in Regional Integration and Integration of Flexibility from RES, DSM and Storage

1.1.1 Introduction

Decarbonizing the electricity sector requires accommodating intermittent and highly variable generation from renewable energy sources (RES). This introduces challenges such as frequency regulation difficulties, system stability issues, and unpredictable power flows and voltages within transmission and distribution networks, all of which can compromise supply quality and security. To address these challenges, the system must become more flexible. Traditionally, this flexibility has been provided by conventional generation methods, primarily gas and hydro power plants. However, the growing demand for flexibility and the goal of phasing out emission-intensive power plants highlight the need to source flexibility from other areas, including RES generation, demand-side management (DSM), and storage (STO) units at both transmission and distribution levels [1], [2].

Advancements in electricity generation technologies, STO, and DSM, combined with improved data collection and advanced control systems, enhance the utilization of flexibility assets. Studies [3], [4] indicate that the full potential of STO systems can be realized by participating in multiple markets and providing various services. Similarly, RES generation can generate additional revenue by offering ancillary services [5], [6]. As fossil fuel-based generation is phased out, the market price for electricity, traditionally influenced by conventional generation, is expected to be lower, more volatile, and less predictable. Conversely, the cost of balancing and other ancillary services is anticipated to rise. Consequently, these services may become a primary revenue source for generation in the future. Additionally, the demand side, STO and RES generation can also benefit from extra revenue by offering diverse services across different markets including network support services [7].

1.1.2 Basic concept of electricity balancing

In an electrical power system, it is crucial to maintain a balance between electricity production and consumption at all times. This is because a method for efficiently and economically storing large quantities of electricity has yet to be developed. Failing to maintain this balance can have detrimental effects on the system's operation. For example, if at any given moment the active power demand exceeds the active power supply, there will be an imbalance in active power within the system. However, due to the law of energy conservation, part of the energy demand from consumers will be met by the stored kinetic energy in the rotating parts of electrical machines (generators and motors) connected to the system. This results in a reduction in the rotational speed of synchronous generators within the system and system frequency. Conversely, if there is an excess of generated power, the rotational speed of the generators will increase, leading to a rise in frequency. This

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demonstrates that any imbalance in active power in the system will lead to frequency deviations from its nominal value [8].

Even the smallest frequency deviations from the nominal value can adversely affect various elements within a power system. This includes consumers with electrical machines directly linked to the frequency of their power supply, as well as the production units themselves. Electrical motors and generators in the system have built-in protection that disconnects them in case of significant frequency deviations. Disconnecting generators and/or consumers due to frequency deviations can lead to further imbalances in power, causing even greater frequency changes and potentially resulting in the collapse of the power system and loss of supply in parts or the entire system. This underscores the need to maintain frequency within specified limits as defined by power quality standards and regulations governing interconnected and isolated power systems.

To illustrate the basic principle of frequency regulation, we will start with a simple system consisting of a single synchronous generator connected to consumers, as shown in Figure 1. The principle of frequency regulation in this case involves measuring the rotational speed of the synchronous generator and comparing it to the nominal speed at which the generator produces the nominal frequency of the output voltage. If the rotational speed is higher than the nominal speed, the generator needs to reduce its power output to decrease the frequency. Conversely, if the generator's speed is lower than the nominal speed, the generator’s power output must be increased. The adjustment of the generator's active power output is usually achieved by regulating the flow of the working fluid in the turbine that drives the generator. From the above, it can be concluded that frequency regulation in a system is closely linked to the regulation of active power [8].

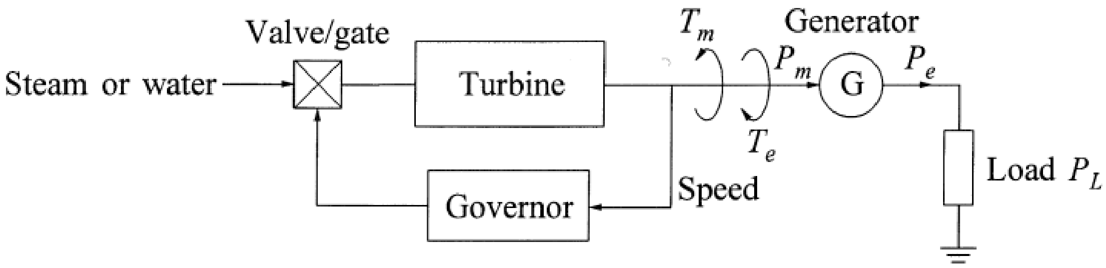

Figure 1. Basic principle of frequency regulation [8]

T_m - Mechanical torque of the turbine

T_e - Electrical torque of the generator

P_m - Input mechanical power

P_e - Output electrical power

P_L - Consumer power (load)

1.1.3 Frequency regulation in interconnected power systems

In complex interconnected power systems with multiple generating units that span across a continent, a different approach for frequency regulation is used, still it is based on the principle

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explained in the previous section. This approach is implemented in three control processes briefly explained below.

Primary control, also known as Frequency Containment, is achieved through automatic adjustments made by individual generators. When there is a frequency deviation (either an increase or decrease), the generators with primary control capability automatically adjust their output power to counteract the change. The purpose is to provide immediate response to frequency deviations. The response time is within seconds.

Secondary control, or Frequency Restoration, involves automatic or manual adjustments made by a central control system. It operates through a system of Automatic Generation Control (AGC) that adjusts the output of multiple generators to bring the system frequency back to its set point and restore the original power reserves. Its purpose is to restore frequency to its nominal value and correct any imbalance that primary control could not fully address. The response time is in minutes, as it requires coordination among various generators and control centers.

Tertiary control (replacement process) involves scheduling and dispatching additional generation or reserve resources to optimize the system's operation. It can include adjusting generation schedules, starting up or shutting down plants, and optimizing the economic operation of the power system. It is used to prepare the system for anticipated changes in demand and generation over longer periods.

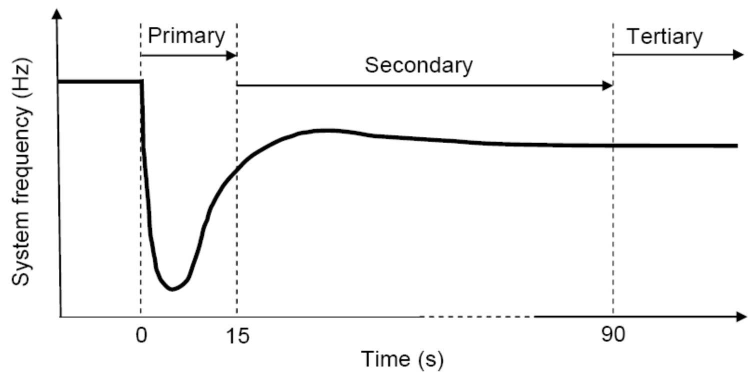

Figure 2. Impact of primary, secondary and tertiary regulation on system frequency

In these processes, both generation and consumption within the system must be adjustable at the appropriate speed to maintain power balance. This means that some generation capacity needs to be available for increasing or decreasing output, and demand can also contribute to balancing by varying its consumption. These functions are referred to as Frequency Support Services (FSS) and include balancing reserve capacity (frequency regulation reserves) and balancing energy [9], [10].

1.1.4 Electricity balancing markets and its regional integration

In a liberalized electricity market, each market participant makes offers and requests for buying and selling specific quantities of electricity for a given time period. Trading can begin well before the delivery time, can be conducted on the day-ahead market, and changes to the energy quantity and price that a participant offers or requests (position) can be made through trading on the day-ahead market up to one hour before the delivery time. However, despite efforts to adhere to market positions, deviations between the quantities of energy that sellers produce, and buyers consume often occur. This leads to power imbalances, where the production of electricity at a given time differs from consumption, causing the system frequency to deviate from its nominal value. Therefore, all participants in the electricity market incur penalties if they deviate from their positions, meaning if they produce or consume more or less electricity than they had announced. Despite this, real-time deviations in production or consumption from their defined positions occur due to various reasons, resulting in imbalances between the produced and consumed power. The most common causes for imbalances according to EU System Operation Guidelines (SOGL) [9] network code are shown on Figure 3.

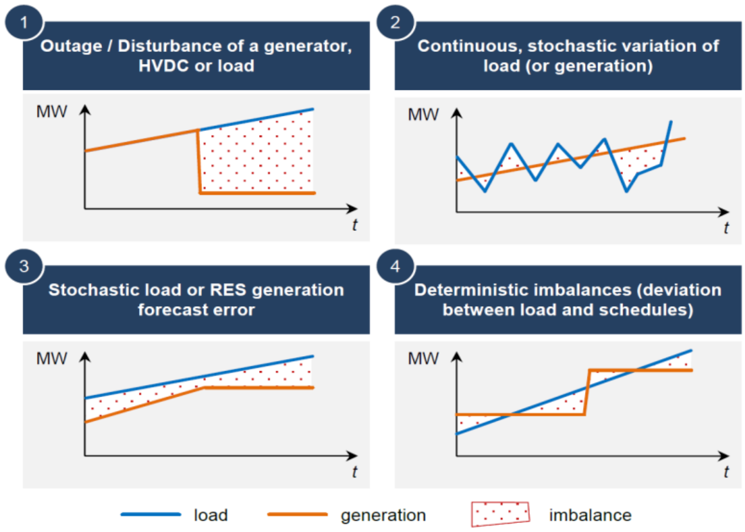

Figure 3. Common causes for imbalances in power systems according to SOGL [9]

The Transmission System Operators (TSOs) are tasked with frequency regulation and maintaining system security. In the interconnected power systems Load Frequency control (LFC) areas are defined, that in most cases correspond to the areas of each TSO or countries. The TSO is responsible for frequency regulation and balancing in its LFC area, however since the TSOs do not own generation or demand resources, balancing capacity and energy markets are established. The purpose of these markets is to select the most cost-effective FSS providers, thereby minimizing balancing costs. Traditionally, these markets are organized at the national level and are facing problems with liquidity and market power of incumbent generation companies.

The regional integration of balancing markets can enhance efficiency and lower the costs associated with frequency regulation. Research studies [2], [11] demonstrate that such integration in Europe, across general electricity markets and balancing capacity markets, leads to substantial cost savings. By integrating markets regionally, it becomes possible to select and utilize the most cost-effective FSS providers. This approach is a key priority in EU energy policy. SOGL [9] and the Electricity Balancing Guidelines (EBGL) [10] from the European Network of Transmission System Operators for

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Electricity (ENTSO-E) aim to harmonize frequency regulation processes at the continental level, standardize FSS products, and thus promote regional and pan-European market integration. The elements of standard FSS product are shown on Figure 4. According to the approach of primary secondary and tertiary control in ENTSO-E several standard products are defined. These products are: Frequency Containment Reserve (FCR), Frequency Restoration Reserve with Automatic and Manual mode of activation (aFRR and mFRR) and Replacement Reserves (RR), and also the balancing energy from each of these types of reserves.

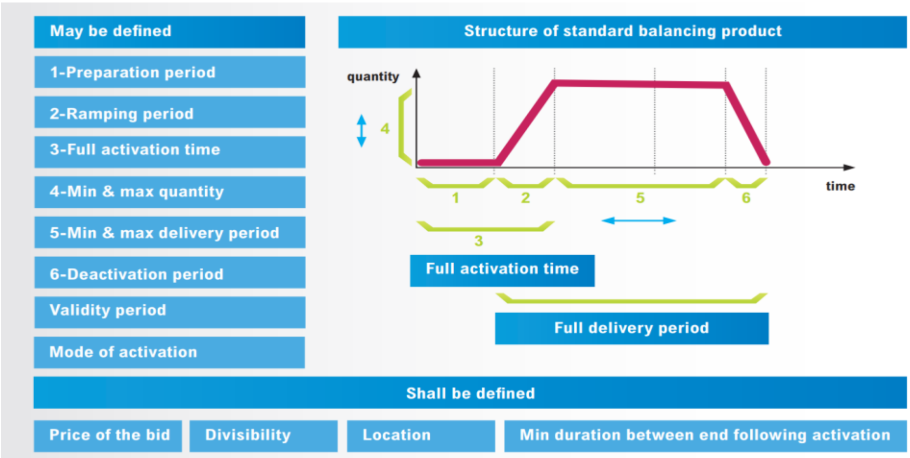

Figure 4. Definition of standard products (FSS) in balancing markets [10]

Another condition to enable creation of regional balancing markets is the establishment of the control processes for imbalance netting and cross-border exchange and sharing of reserves.

In interconnected power systems, the imbalance netting process is used to manage and correct discrepancies between the actual and forecasted power generation and consumption across different LFC areas. Imbalance netting is a method for balancing the power system by offsetting over- or under-production in one area with the opposite in another, reducing the overall imbalance. The principle is shown on Figure 5.

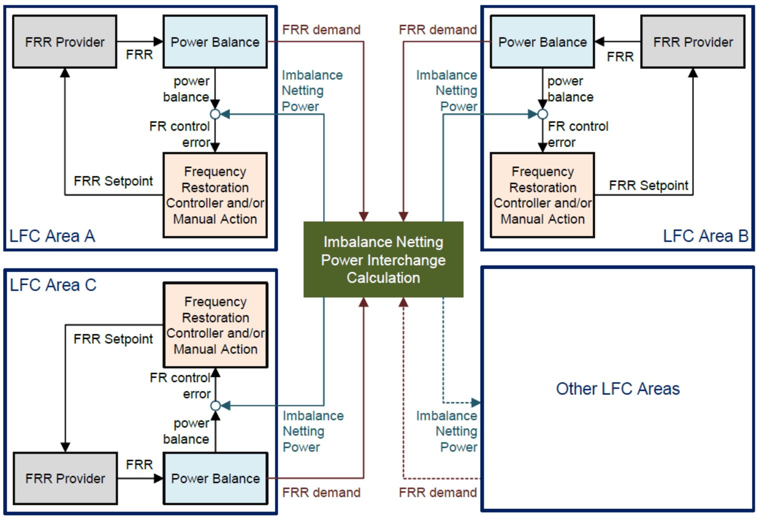

Figure 5. Principle of imbalance netting between different LFC areas [9]

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The principle of exchange of reserves means that reserves used to balance one LFC area can be located in a different LFC area, whether within the same or a different synchronously interconnected system. Through reserve sharing, multiple LFC areas can utilize the same reserve, which is unlikely to require activation simultaneously, thus reducing the total amount of reserve that needs to be maintained. This approach (shown on Figure 6) enables establishing competition between providers of FSS on a level of multiple LFC areas which in most cases is internationally, and additionally reduces the amount of reserve that have to be kept to ensure secure operation of the power system.

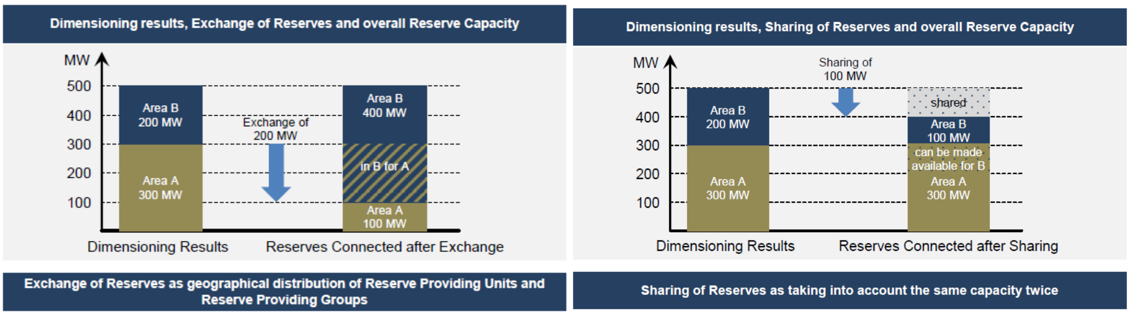

Figure 6. Principle of exchange and sharing of reserves

In addition to harmonizing procedures and products, regional integration must account for the limited capacity of transmission networks. Typically, this integration involves creating a Common Merit Order List (CMOL) by combining bids from FSS providers across multiple LFC Areas, which often align with national borders (Figure 7). Network constraints are managed by restricting power exchanges between LFC Areas to the Cross Zonal Capacity (CZC) limits. Numerous studies highlight the importance of considering the limited CZC when reserving and activating balancing capacity which is done by the so-called Activation Optimization Function that aims to activate the cheapest bids in the region to balance all LFC areas, also by taking into account the limited CZC.

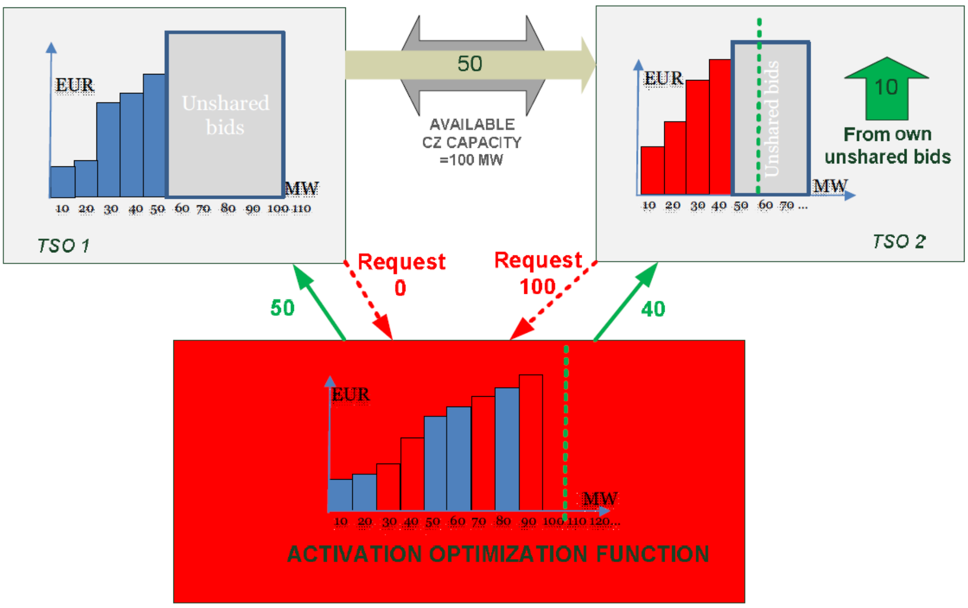

Figure 7. Creation of CMOL for regional balancing market of two LFC areas

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On European level there are multiple projects and initiatives for establishing platforms for exchange of balancing services. These projects aim to create markets on continental (pan-European) level for specific products. For example, PICASSO project [15] aims to create platform for trading with capacity and energy from aFRR, MARI project [16] is associated with mFRR product, etc.

1.1.5 Simulation of the electricity balancing markets

In this material a procedure for simulation of the operation of electricity balancing markets is shown. This procedure can be used to assess the benefits of regional integration of balancing markets explained in the previous chapter. The procedure involves simulating the Day-ahead Market (DAM) and using the results to calculate the generation units' schedule at hourly intervals for a single day. The next step involves simulating power imbalances and calculating the required balancing energy needs from aFRR. Finally, a method from [11] is applied to determine the optimal activation of reserves on a regional level. The simulation procedure is shown in Figure 8.

The simulation requires input data for the generator units, including the coefficients of a quadratic cost curve, minimum and maximum power, network topology data, parameters for DC load flow calculations, and hourly load data, such as the forecasted load for each node on an hourly basis.

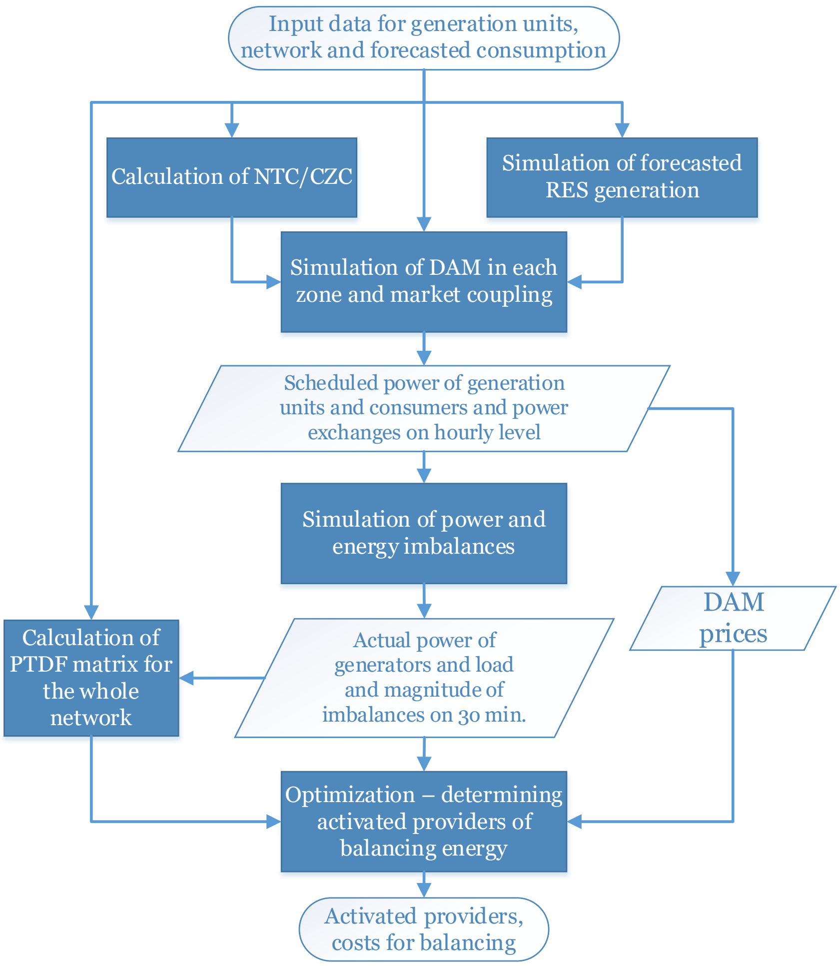

Figure 8. Simulation of regional balancing markets [11]

The calculation of cross-border transmission capacity, or net transfer capacity (NTC), which equals the cross-zonal capacity (CZC), is done initially based on network data. In parallel, the simulation on the forecasted values of renewable energy source (RES) generation, is done. Using this data, an electricity market simulation is conducted to determine hourly schedules for both generation and load, electricity prices, and the scheduled power exchange between zones. Next, a simulation of power imbalances is performed, resulting in the required quantities of balancing energy for each LFC area in 30-minute intervals, as well as actual load and generation values that deviate from the forecasts. This data, along with the Power Transfer Distribution Factors (PTDF) matrix of the network and DAM prices, is used to carry out the procedure for the optimal activation of reserves. The simulation ultimately determines the amount of balancing energy needed from each provider and the associated costs.

The presented simulation considers two scenarios. The first scenario assumes that each price zone or LFC area obtains the required balancing energy solely from providers within that area, without the existence of a regional balancing market. The second scenario involves a regional balancing market where imbalance netting occurs between LFC areas, and reserve activation provides balancing energy at a regional level, regardless of the location of the reserves.

In [11] the simulation procedure was applied to IEEE RTS 96 network with three areas. From the paper results the application of imbalance netting and regional balancing leads to decrease of about a quarter of the needed balancing energy, in addition the balancing costs are decreased by 40%. This reduction emphasizes the significance of the regional integration of balancing markets, especially in future when the share of balancing costs in total costs for electricity supply is expected to rise due to the increased RES penetration.

1.1.6 Integration of flexibility from DSM, STO and RES generation in balancing markets

The development of balancing markets and its regional integration is important also for attracting providers of balancing services (flexibility) from sources different than the conventional generation. This is critical in the process of energy transition since the increased share of RES generation leads to increased need for balancing capacity and energy and reduced amount of traditional generation as most common provider to these services. In such situation the demand, STO and RES generation entities connected mostly at distribution level shall be attracted to participate on the balancing markets and offer FSS. In this process the development of aggregators of resources that can optimize groups of different providers of flexibility and enable them to participate in different markets including balancing is crucial [7], [12], [13], [14].

This material presents business models for participation of flexibility from DSM, STO and RES generation in different markets that include a product that can act as coordinator/aggregator of different flexibility providers. The aggregator should coordinate, optimise and control a portfolio of multiple flexibility assets to provide bids for selling electricity to the DAM/IDM in periods of high electricity prices. In the periods of low electricity price, energy should be bought from the DAM/IDM

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to enable charging of STO units and because the decreased load would be shifted to periods with lower prices for DSM assets. This generates income for the product owner and is known as price arbitrage. In this case, the coordination /aggregation product acts as a Trader. Modification of injected power from flexibility assets can be done to provide frequency support/balancing services. When the product for coordination/aggregation of flexibility is used for balancing market participation, it acts as a Resource Aggregator of multiple flexibility assets. In this case, its role is to provide bids for balancing energy to the balancing market. In this case the product also has the role of a balancing service provider (BSP) [7]. More details about this business case are presented in the value network graph shown at Figure 9.

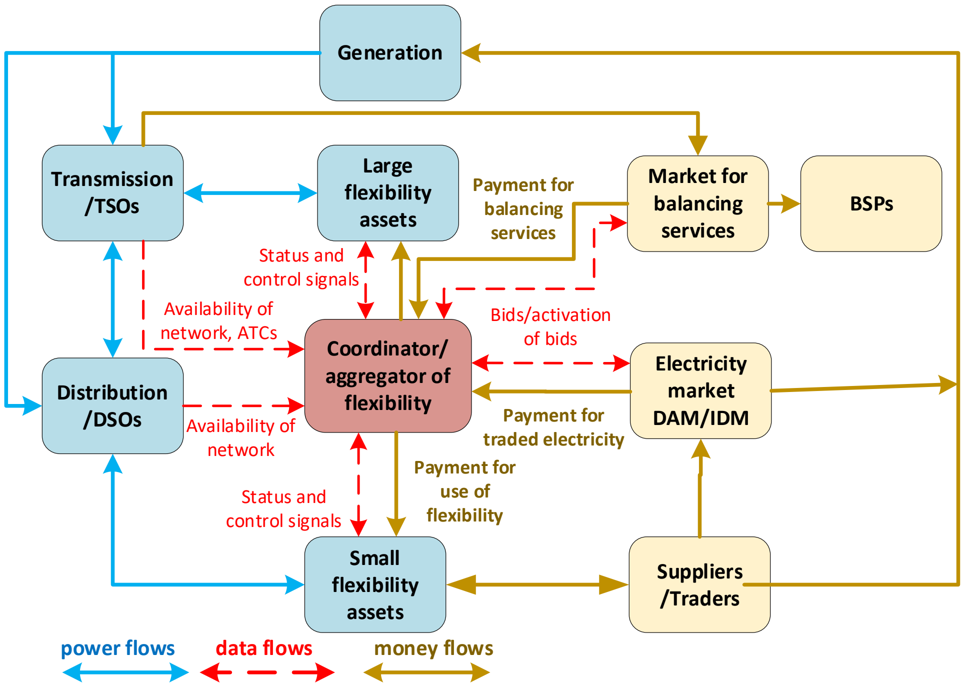

Figure 9. Value network graph for market participation of DSM, STO and RES generation [7]

Since the product for coordination/aggregation of flexibility provides price arbitrage and balancing services, its market participation will provide steady revenue stream. This revenue shall be distributed to the owners of flexibility assets as a payment for their services. For this purpose, clear rules for remuneration of the services provided by the owners of flexibility assets should be defined.

Established communication is a precondition to enable the product to control the flexibility assets.

1.1.7 Provision of network services from DSM, STO and RES generation

The provision of network services can help owners of RES generation, STO and consumers to achieve new revenue streams. The network services help grid operators (TSOs and DSOs) to optimize the grid operation under physical and market constraints and can take various forms such as congestion management, voltage control and contribution to system stability. Markets specially designed for these services are not established yet [7], [12].

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The optimal activation of flexibility assets for solving problems with congestion, voltage or stability depends on the exact location of the assets as well as the conditions in the network (generation, demand, voltages, power flows, etc.), while for the process of frequency regulation, only the LFC area (in most cases the country itself) where the asset is located is important. Therefore, these network services differ from the products traded to the wholesale and balancing markets, since they require exchange of larger amount of data related to the model and the operating state of the transmission networks, i.e. require close cooperation with system operators.

By using the product for coordination/aggregation of flexibility, the system can be operated more efficiently, which could enable operators to defer investments. The usage of flexibility assets for this purpose should be appropriately remunerated. It is not likely that the system operators can determine the financial value of the product and distribute it to the owners of the assets. Therefore, the owners of flexibility assets should declare the prices for its use, and the system operator will decide on their cost-effectiveness. More details about this business case are presented in the value network graph shown at Figure 10.

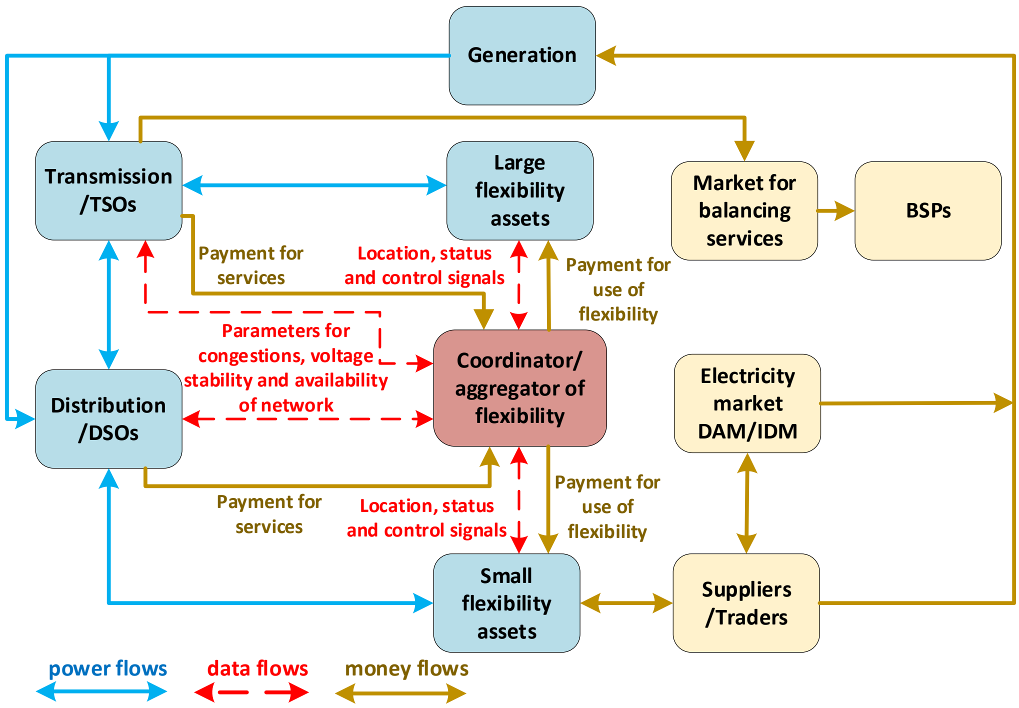

Figure 10. Value network graph for provision of network services from DSM, STO and RES generation [7]

1.1.8 Contribution to development of low carbon technologies, sustainability and circularity

The focus of this training course is on understanding the need for electricity balancing in power systems and the problems arising from the energy transition that includes increased need of balancing services and decreased number of providers of these services from conventional generation. The course presents the solution on these problems by engaging new providers of

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balancing services and flexibility in general from RES generation, DSM and STO. One of the preconditions to attract these providers to participate in the balancing market is to have well developed and competitive markets for FSS.

The course enables trainees to grasp the benefits of regional integration of balancing markets and the amount of savings that are achieved in this process, thus contributing to more efficient power system operation with increased share of RES generation and facilitating the process of energy transition.

1.1.9 Highlight on application in industry

The course also presents business models for participation in different markets for various providers of flexibility from RES generation, STO and DSM. The presented models offer additional revenue streams to owners of such assets and using the full value of the new technologies. This should increase the interest of industry to invest in RES generation, STO and DSM assets and control systems and participate not only in the wholesale electricity markets, but also to provide balancing and possibly in future network services.

1.1.10 Contribution to development of skills and competences

This training course is designed to develop essential skills and competences in the field of power electronics, renewable energy integration, and grid management. Participants will gain a deep understanding of the theoretical foundations and practical applications of GFL inverters, with a focus on control strategies, modeling techniques, and the latest technological advancements. The course's hands-on approach, including the development of inverter models in MATLAB/Simulink, ensures that participants not only learn the concepts but also acquire the ability to apply them in real-world scenarios.

By completing this course, participants will be equipped with a range of technical skills that are highly relevant to the renewable energy and power electronics industries. These skills include advanced modeling and simulation, control system design, and the ability to optimize inverter performance under various grid conditions. Moreover, the course enhances problem-solving abilities and critical thinking, as participants learn to address complex challenges such as grid stability, fault ride-through, and power quality improvement. The competences gained through this course will empower participants to contribute to the development and deployment of innovative solutions that support the transition to a sustainable energy future, making them valuable assets in their respective fields.

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