Utilization of Flexibility Mechanisms in Regional Outage Planning of Transmission Systems

Suvi Peltoketo
Fingrid Oyj.
Helsinki, Finland
suvi.peltoketo@fingrid.fi

Antti Kuusela
Fingrid Oyj.
Helsinki, Finland
antti.kuusela@fingrid.fi

Antti-Juhani Nikkilä
Fingrid Oyj.
Helsinki, Finland
antti-juhani.nikkila@fingrid.fi

Tuomo Mäkihannu
Fingrid Oyj.
Helsinki, Finland
tuomo.makihannu@fingrid.fi

Tuomas Rauhala
Faculty of Information Technology and Communication Sciences
Tampere University
Tampere, Finland
tuomas.rauhala@tuni.fi

***Abstract*—Energy transition challenges the methods used in the operational planning of transmission systems and increases the need for more extensive and coordinated use of flexibility mechanisms. This paper presents how different types of flexibility mechanisms can be utilized in the outage planning of transmission systems to mitigate the impacts of N−1 contingency condition during a planned outage and to reduce the need for preventive curtailment. The flexibility mechanisms presented in this paper focus on solving regional and local grid congestions caused by thermal overloading of grid components after a contingency. The analyzed flexibility mechanisms can be divided into two categories: technical and market-based flexibility mechanisms. Factors affecting the feasibility of the analyzed flexibility mechanisms are identified in this paper. The paper discusses how different types of flexibility mechanisms can be combined to solve regional grid congestions considering the short- and long-term thermal ratings of grid components as an enabler of market-based flexibility.**

Keywords—outage planning, flexibility mechanisms, congestion management, market-based flexibility

I. Introduction

Energy transition is changing power systems globally. The amount of renewable, decentralized, and variable production is rapidly increasing and the amount of conventional, centralized, fossil-fuel based generation is decreasing. Simultaneously, the electrification of different processes, e.g. transportation, heating and cooling, large industrial processes, changes the way electricity is consumed. Due to the major transformations, uncertainty and variability increases in the power system making predictability more complex than it was in the past. The major changes lead to an increasing need for flexibility in power systems to maintain balance between production and consumption, to manage grid congestions and maintain system security. Flexibility in power systems is a comprehensively studied topic in the literature [1–4].

Energy transition also challenges the processes and methods currently used in grid planning, operational planning and in real-time operation. Flexibility in grid planning is a widely discussed topic in the literature and it is studied e.g. in [5–7]. This paper focuses on operational planning, specifically on outage planning of transmission systems. Operational planning has been discussed in several scientific papers in the past from the viewpoint of optimal scheduling of planned outages [8–10], but it is a less discussed topic from a point of view of utilization of flexibility mechanisms to mitigate the need for curtailment as a preventive method. As the operation of a power system becomes more unpredictable due to a high penetration of weather-dependent production (wind, solar), scheduling of a planned outage well in advance, from months to a year ahead, to a suitable secure period may become extremely difficult.

Uncertainty and variability in the power system create a need for more extensive use of flexibility mechanisms in outage planning and a need for improved processes to select the most suitable flexibility mechanisms in advance. This paper presents an approach to assess the feasibility of different flexibility mechanisms of outage planning and provides examples of how to combine those to facilitate their efficient use. The paper discusses how different types of flexibility mechanisms could be used simultaneously to mitigate the impacts of N−1 contingency conditions during planned outages and to ensure system security. According to the N−1 criterion [11], the power system withstands normal individual faults and the disconnection of a faulty component. The paper is focused on the flexibility needs caused by regional congestions due to the thermal overloading of network components in N−1 condition during a planned outage. Factors affecting the decision-making of operational planners in the selection process of suitable flexibility mechanisms are also identified.

This paper is organized as follows: Section II introduces the legislative background in the context of European Union and defines flexibility mechanisms in outage planning. Section III categorizes the flexibility mechanisms and Section IV presents factors affecting decision-making and feasibility of flexibility mechanisms. Section V discusses how technical and market-based flexibility mechanisms could be combined. Section VI discusses key findings and future aspects, and Section VII summarizes conclusions.

II. Flexibility mechanisms in outage planning

A. Background

Emission reduction targets and legislation are guiding the evolution towards low-carbon energy systems. In Europe, Clean Energy Package (CEP) [12], EU directive 2019/944 [13] and regulation 2019/943 [14] facilitate the development of market-based, flexible, sustainable, and low-carbon power system. According to the Commission regulation (EU) 2017/1485 [11], system operators shall apply the principles of proportionality and non-discrimination and ensure transparency. To ensure network security and stability,

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 957739.

transmission system operators (TSO) shall make use of market-based mechanisms as far as possible [11]. The paper discusses how technical and market-based flexibility solutions could be used efficiently and how the technical flexibility capabilities of grid components could be utilized as an enabler of market-based flexibility mechanisms.

B. Definition of outage planning

Planned outages are needed regularly to facilitate maintenance and construction of transmission system components. Outage planning refers to preparatory phases (scheduling, planning, preparation of remedial actions) needed before real-time operation, and it aims to ensure that correct decisions are taken in advance. As presented by [10], there are generally four categories of outages: 1) maintenance-related planned outages, 2) project-related planned outages to connect new transmission assets to the existing system, 3) outages related to safety (grid component is taken out-of-service due to personnel working in proximity), and 4) forced outages (forced / unplanned outages caused by a fault in a power system component). The duration of a planned outage may vary highly, from a few hours to days, weeks and months depending on the type of outage. The outages of categories 1 to 3 can be scheduled in advance and forced / unplanned outages may occur during planned outages. The impact of a contingency during a planned outage to the power system needs to be understood and analyzed in advance. Being prepared during a planned outage is crucial for system security since a contingency may result e.g. in the violation of thermal ratings of grid components or cause stability issues.

C. Definition of flexibility mechanisms

IEA [4] defines power system flexibility as "the ability of a power system to reliably and cost-effectively manage the variability and uncertainty of demand and supply across all relevant timescales, from ensuring instantaneous stability of the power system to supporting long-term security of supply". The need for flexibility in a power system may arise for different reasons, e.g. due to balancing, congestion management, adequacy, or security of supply. In this paper, grid congestions and related flexibility needs caused by the thermal overloading of grid components in N−1 contingency condition during a planned outage are focused. In the context of the paper, flexibility mechanisms refer to measures taken by a TSO prior to a planned outage to be prepared for a contingency condition during a planned outage.

III. Categorization of Flexibility Mechanisms

A. Introduction

Planned outages are scheduled by a TSO in advance. TSOs utilize scheduling of planned outages to find a period that has minimum impact on local and regional system security and on the connecting parties. Scheduling may remove or significantly decrease the need for flexibility mechanisms in N−1 condition during a planned outage. Planned outages are scheduled in cooperation with connecting parties to minimize the impacts on both, the connecting parties and system security, when it is technically possible. As an example, some planned outages of transmission grid components can be scheduled according to the yearly maintenance breaks of large-scale centralized production units and the need for flexibility mechanisms may be avoided.

However, if there is a planned outage in a region with a high share of weather-dependent, variable production (wind, solar), scheduling of a planned outage in advance to a period where no overloading of grid components occurs in N−1 condition during a planned outage may be extremely challenging and flexibility mechanisms may need to be utilized to maintain system security. In the case of variable production, scheduling may still be a possibility if the duration of a planned outage is very short (from hours to couple days), its timing is flexible, and the power flows in the specific region can be forecasted accurately enough in short-term (from hours to couple days before).

B. Technical flexibility mechanisms

1) Investment: Grid investments may be used to remove the need for flexibility especially if the need is expected to be recurrent, high and very likely in the future. Grid investments need to be planned and scheduled several years ahead based on the best estimates for the future scenarios making it a long-term solution and not a suitable mechanism for short- (days to weeks) or mid-term (months to two years) operational planning. Investments (e.g. a new high voltage line, a power transformer, a compensation device) may ease the planning of outages in the region when implementation is finalized.

2) Special protection scheme: Special protection scheme is used to protect individual power system components from damage by activating a predefined scheme of actions automatically after triggering conditions are met. As an example, in a case of N−1 condition during a planned outage, special protection scheme can be used to quickly disconnect a power generation unit from the transmission network to avoid overloading and damage to grid components.

3) Temporary switching arrangements: Busbars and switchgears at high voltage substations can be utilized in different switching configurations depending on the operating situation. Depending on the type of busbar, there may be an opportunity to temporarily organize transmission lines and power transformers to different groups and buses as a measure to prepare for N−1 condition during a planned outage. Temporary switching arrangements can be also implemented via special protection schemes.

4) Dynamic rating of grid components: Dynamic rating refers to a method of evaluating thermal loadability of power transmission lines, underground cables or power transformers in real-time based on the current conditions at the component (e.g. ambient temperature, conducting component temperature, wind speed and direction, electrical current or ground clearance of transmission line). The method is used to adjust the loading limits of these grid components. Dynamic rating can be utilized in outage planning to reduce congestions and the need for flexibility by dynamically adjusting the thermal ratings of grid components instead of using fixed values. Benefits of dynamic rating in the context of renewable energy integration, especially integration of wind power, to improve the utilization of grid components has been studied e.g. in [15].

C. Market-based flexibility mechanisms

1) mFRR special regulation: Manual Frequency Restoration Reserve (mFRR) is a balancing energy market used in Europe and defined by the Commission regulation (EU) 2017/2195 [16]. mFRR special regulation refers to regulation ordered by a TSO for other purposes than balance management [17], e.g. ordered due to regional or local congestion management. In mFRR special regulation, the mFRR energy bids suitable for the transmission situation are selected and thus bids are not necessarily used in the price order [17]. mFRR regulation should be fully activated in 15 minutes [17], and after the European mFRR (MARI, Manually Activated Reserves Initiative) platform is implemented, it is fully activated in 12.5 minutes [18]. If N−1 condition during a planned outage occurs, mFRR special down-regulation can be ordered by a TSO to solve grid congestions if suitable bids are available. Another option could be to activate mFRR down-regulation in advance as a preparation for N−1 condition during a planned outage. To maintain the balance in the control area, a corresponding amount of up-regulation is ordered by the TSO outside the congested grid area.

2) Tender process of bilateral contracts: Bilateral contracts between a connecting party and a TSO can be used to solve e.g. grid congestions or voltage issues to prepare for N−1 conditions during planned outages. Bilateral contracts can be used in a market-based way by organizing a public tender process. As an example, a bilateral contract can be activated (customer reduces / increases production / consumption as agreed in the contract) if N−1 condition during a planned outage occurs or a customer can provide e.g. voltage support as a preparatory measure for N−1 condition during a planned outage.

3) Regional flexibility auction: Regional flexibility auction can be organized as a preparation for N−1 condition during a planned outage. Auction could be considered as an option e.g. in a case where it is foreseen by the TSO that there will not be suitable market-based resources available in mFRR for activation in a case of a fault during a planned outage. The TSO could procure resources in advance by organizing a regional or local flexibility auction. The flexibility service providers should be selected based on the pricing of the bid and on the location of the flexible resource in the grid, i.e. on the effectiveness of activation of the resource to the grid congestions.

There are at least two possible options to activate flexibility procured via regional flexibility auction for congestion management: 1) obligation to offer mFRR regulation during an agreed time period is set in the contract between the TSO and the connecting party and, in a case that congestion during the planned outage occurs, the flexibility is ordered by the TSO as mFRR special regulation or 2) the activation of flexibility is done by other manner agreed in the contract between the TSO and the connecting party (full activation within 15 minutes). The connecting parties selected in the auction process are financially remunerated for the provision of flexibility as defined in the rules of the auction, e.g., a capacity fee may be paid for availability and an energy fee for the activation of flexibility.

Local flexibility auctions have been used by distribution system operators e.g. in the UK [19], and new flexibility market models including auction mechanisms have been studied e.g in [20].

4) Flexible connections: Flexible connections refer to non-firm connections between a system operator and a connecting party. The availability of resources of the connecting party to provide flexibility is secured with a flexible connection arrangement [21]. The concept of market-based flexible connection in a transmission system has been presented in [21] utilizing the short-term rating of system components and the active power control capability of flexible resources. The resources under flexible connection agreements are activated on-demand through a balancing market (mFRR) [21]. As an example, in the context of planned outages, resources subject to the flexible connection agreements could be activated as mFRR special down-regulation in a case of local or regional congestions.

5) Redispatching and countertrading: Redispatching is defined in the EU regulation 2019/943 [14] as "a measure, including curtailment, that is activated by one or more TSOs or DSOs by altering generation, load pattern, or both, in order to change physical flows in the electricity system and relieve physical congestions or otherwise ensure system security". Redispatching rules and congestion management shall be transparent, objective and non-discriminatory to all market participants [14]. Market-based redispatching can be used in N−1 condition during planned outages if suitable market-based resources are available for activation to solve grid congestions, e.g. activated as mFRR special regulation, see Section 3.C.1). Countertrading is defined in the EU regulation 2019/943 [14] as "a cross-zonal exchange initiated by system operators between two biding zones to relieve physical congestion". This paper focuses on regional planned outages and congestions (inside the bidding zone) and cross-zonal countertrading is in practice potentially applicable only if the planned outage is in proximity of a cross-zonal exchange.

D. Curtailment

Curtailment refers to limiting the output of a generator or a load from what it could otherwise produce or consume. In the context of this paper, curtailment is done by connecting parties at the request of the TSO due to a planned outage to manage regional and local power flows in the system and to prepare for N−1 condition during a planned outage. Thus, curtailment is done as a preventive action in advance, i.e. the connecting parties are informed about the curtailment well in advance (several weeks or months prior to the planned outage), so that the restrictions do not cause imbalances for the connecting parties. The practices related to curtailment are typically dependent on the grid service terms and conditions, which usually address the need to restrict or interrupt the grid service due to maintenance, modification, or investment. Curtailment of generation and load should follow the principles of transparency and non-discrimination. The TSO could follow e.g. the pro rata principle if curtailment is used as a preventive action in outage planning to ensure system security. A process to inform dozens of connecting parties about curtailment in advance is needed.

IV. Factors Affecting the Feasibility of Flexibility Mechanisms

A. Identification of factors

The identification of high-level factors affecting the feasibility of flexibility mechanisms is done from the perspective of congestion management, which in this context, refers to the thermal overloading of grid components. Other technical aspects, e.g. grid stability or voltage violations due to a planned outage or N−1 condition during a planned outage are not focused on this paper. However, these technical perspectives need to be considered in the overall outage planning process as those may impact the amount of flexibility need as well as the technical suitability of flexibility mechanisms to solve grid congestions.

1) Number of connecting parties (CP): The number of parties connected to congested transmission line or substation may impact the suitability of a flexibility mechanism, e.g. a high amount of connecting parties with active power control capabilities increases competition if market-based flexibility is procured.

2) Amount of flexibility need: The amount of flexibility need due to overloading of grid components is estimated by a TSO for a planned outage condition and for the most difficult N−1 conditions during a planned outage identified by operational planners. The planned outage itself may not create overloading of grid components but N−1 condition during a planned outage may do. The amount of flexibility need can be estimated e.g. by comparing the historical or simulated time series data of the power flows of transmission lines and power transformers with the thermal ratings of these grid components. Both, the short- and long-term ratings of the components, could be considered in the calculation as those impact the amount of flexibility need and the requirements of activation time.

If the short-term ratings of grid components are exceeded, there is a need for immediate actions (in less than seconds) or a need to implement preventive actions in advance (e.g. curtailment) to prepare for N−1 condition during a planned outage and to guarantee system security. If only the long-term ratings of grid components are exceeded and not the short-term, flexibility (down-regulation) should be activated considering the capability to tolerate such loading levels, e.g. within 15 minutes. In addition, the impact of dynamic rating of grid components should be considered in the amount of flexibility need if it is available. Moreover, the rating of current transformers should be checked as it may also become a restrictive component.

3) Required activation time: In this paper, activation time refers to the time that is needed to fully activate the flexibility and to secure the N−1 compliance during a planned outage. Generally, the activation of flexibility can be done immediately (in less than seconds), within 15 minutes or in advance as a preventive action to mitigate the impacts of N−1 condition. The activation time requirement is dependent on the thermal ratings of grid components and the amount of flexibility need as explained in section IV.A.2).

4) Factors specific for the mechanism: Flexibility mechanisms may have other factors that are specific to a certain mechanism and these factors may become crucial in the decision-making. The factors specific for each of the analyzed flexibility mechanisms are presented in the Table I and Table II.

B. Analysis of identified factors per flexibility mechanism

Table I and Table II present a high-level analysis of factors affecting the feasibility of each technical and market-based flexibility mechanism studied in this paper. Tables I and II illustrate which types of flexibility needs each mechanism is in principle suitable to solve. Tables I and II can be used as a tool that assists to identify suitable mechanisms and required actions in the outage planning process.

The use of flexibility mechanisms should be non-discriminative by the TSO, i.e. the same flexibility mechanisms should be utilized in similar conditions. Planned outage cases may be very diverse, and the durations, amounts, locations, and probabilities of flexibility need vary highly depending on the case. Therefore, also the suitability of a flexibility mechanism may need to be analyzed individually for each planned outage case to find an optimal solution. However, basic principles and guidelines to assess the feasibility of flexibility mechanisms and to select the most cost-efficient solutions are needed in the outage planning process of a TSO. The high-level factors identified in the Tables I and II for each analyzed flexibility mechanism can be utilized as a tool that will enable more systematic utilization of flexibility mechanisms in the longer term.

One main difference between the analyzed technical and market-based mechanisms comes from the activation time. The analyzed technical flexibility mechanisms are suitable for flexibility needs that require immediate actions, i.e. in less than seconds, and exceed the short-term thermal ratings of grid components. The analyzed market-based flexibility mechanisms are suitable for flexibility needs that do not require immediate activation, and activation within 15 or 12.5 minutes is sufficient. As presented in the Table I and Table II, several flexibility mechanisms may be capable of providing only a partial solution if the amount of flexibility need is high, i.e. the short-term ratings of grid components are exceeded, causing a need for either immediate actions or preventive actions (e.g. curtailment or activation of down-regulation in advance). Although the analyzed market-based mechanisms are not suitable for immediate activation, these mechanisms may provide a partial solution if both the short- and long-term ratings of grid components are utilized, and market-based mechanisms are combined with other mechanisms.

TABLE I. FACTORS AFFECTING THE FEASIBILITY OF TECHNICAL FLEXIBILITY MECHANISMS

Factors	**Technical flexibility mechanisms**			
	Investment	***Special protection scheme***	***Temporary switching arrangements***	***Dynamic rating of grid component***
Number of CPs	Several or/and few large customers	One – several	One – several	Not applicable
Amount of flex. need	Moderate – very high, expected to be recurring	Small – very high	Small – very high	Very small – very high, and dependent on weather conditions
Activa-tion time	Not applicable	Less than second	Not applicable	In seconds (inherent)
Specific factors	Flex. need recurring in the future. Investment decision needed well in advance.	Case-by-case solution. Must be non-discrim-inative.	Option, if technical issues (e.g. stability) do not prevent its use. Must be non-discrimina-tive.	May be only partial solution depending on the amount of flex. need and its weather-dependency.

V. COMBINING FLEXIBILITY MECHANISMS TO SOLVE REGIONAL CONGESTIONS DURING PLANNED OUTAGES

If both, the short- and long-term thermal ratings of grid components are exceeded in a case of N−1 condition during a planned outage, the solution may consist of several flexibility mechanisms. If scheduling and temporary switching arrangements are not technically possible or otherwise efficient mechanisms to solve the grid congestions, possible

TABLE II. FACTORS AFFECTING THE FEASIBILITY OF MARKET-BASED FLEXIBILITY MECHANISMS

Factors	Market-based flexibility mechanisms			
	mFRR special regulation	***Tender process of bilateral contracts***	***Regional flexibility auction***	***Flexible connection***
Number of CPs	few – several	few – several	few – several	few – several
Amount of flex. need	small – very high, partial solution if flexibility need exceeds the short-term thermal ratings of grid components	small – very high, partial solution if flexibility need exceeds the short-term ratings of grid components	small – very high, partial solution if flexibility need exceeds the short-term thermal ratings of grid components	small – very high, partial solution if flexibility need exceeds the short-term thermal ratings of grid components
Activa-tion time	full activation in 15 min. (12.5 min)	full activation in 15 min. (12.5 min)	full activation in 15 min. (12.5 min)	full activation in 15 min. (12.5 min)
Specific factors	Option if there are suitable mFRR bids available during a planned outage. Activation of flexibility in a case of N−1 during planned outage.	Bilateral contracts are market-based if procurement phase is public and transparent. Activation of flexibility in a case of N−1 during a planned outage.	Organization of auction in advance. Activation of flexibility in a case of N−1 during a planned outage. Activation: 1) obligation to offer mFRR during a planned outage, activated as special regulation or 2) activation done by other manner agreed in the contract.	Can be utilized for new connecting parties, decision on flexible connection needed well in advance. Activation of flexibility as mFRR special regulation for congestion management in a case of N−1 during a planned outage.

solution could be to combine the technical flexibility capability of grid components (i.e. short- and long-term thermal ratings and dynamic rating if available), curtailment, and market-based flexibility procurement to prepare for N−1 condition during a planned outage and to guarantee regional and local system security. Two examples to combine these three mechanisms are discussed in the following Sections V.A. and V.B. In addition, as an example of other alternative approach, the Section V.C. discusses possibility to implement special protection scheme via market-based tender process to enable immediate activation of flexibility in a case of N−1.

A. Example A: combining technical and market-based flexibility with curtailment (short-term rating)

In the example A, technical flexibility, curtailment, and market-based procurement are combined and the process can be divided in two steps:

1) Step 1: Curtailment by the TSO in advance as a preparation for N−1 condition during a planned outage to avoid congestions due to overloading of grid components. The amount of curtailment is defined based on the short-term ratings of components and on the impact of dynamic rating if available. The curtailed amount is informed by the TSO to the connecting parties well in advance prior to the planned outage following the pro rata principle.

2) Step 2: The remaining flexibility need, i.e. the need between the short- and long-term ratings of the grid components, is procured in a market-based way and activated in a case that N−1 condition occurs during a planned outage causing regional or local congestion. Market-based flexibility could be procured either from mFRR as special down-regulation (if suitable bids available), from regional flexibility auction (organized in advance) or from a public tender process of bilateral contracts (organized in advance).

B. Example B: combining technical and market-based flexibility with curtailment (long-term rating)

In the example B, technical flexibility, curtailment, and market-based procurement are combined and the process can be divided in two steps:

1) Step 1: Curtailment is done by the TSO as a preparation for N−1 condition during a planned outage to avoid congestions due to overloading of grid components. Curtailment of connecting parties is done according to the flexibility need calculated based on the long-term thermal ratings of grid components and on the impact of dynamic rating (if available). The curtailed amount is informed to the connecting parties well in advance and pro rata principle is followed by the TSO.

2) Step 2: The connecting parties are given an opportunity to reduce the amount of curtailment if they offer mFRR down-regulation during the planned outage. The curtailed amount in total can be decreased by mFRR bids of the connecting parties only by the amount of flexibility need that is between the short- and long-term ratings of the grid components. The mFRR bids of the connecting parties are selected based on the price of the bid and its impact on the congestion. Flexibility is ordered as mFRR special down-regulation if grid congestion is caused by N−1 condition during a planned outage.

C. Example C: special protection scheme via tender process

If special protection schemes have not been implemented nor agreed in advance in the terms and conditions of the connecting parties in the region, a TSO could implement special protection schemes afterwards for a required number of connecting parties to guarantee regional N−1 compliance during a planned outage. In a case that there are several connecting parties which have impact on the grid congestion, a non-discriminative selection process shall be applied by a TSO to decide which parties are connected to special protection scheme, i.e. to lower security of supply level during a planned outage. In such cases, as an example, a public tender process of bilateral contracts of special protection schemes could be organized by a TSO. The connecting parties selected in the tender process would receive financial remuneration due to the risk of being disconnected from the grid by a TSO in a case of N−1 condition during a planned outage. A tender process would require bids from several participants to be a competitive and cost-efficient option. To avoid strategic bidding, a TSO should determine maximum price level of the financial compensation and how it is defined in advance, and if the bids are above the determined price level, other flexibility mechanisms are used. If special protection scheme is applied as a flexibility mechanism, curtailment of connecting parties in advance can be avoided.

VI. Discussion

There are several options on how flexibility mechanisms can be combined. The two examples presented in Section V to combine the technical flexibility capability of grid components, curtailment, and market-based flexibility procurement represent two possibilities. The tender process of system protection scheme presented in Section V represents an example of an alternative approach. The feasibility of each flexibility mechanism and combinations of mechanisms needs to be further evaluated to find the most cost-efficient and practical solutions. Power systems with a high share of variable, renewable production, changing consumption patterns and a large amount of connecting parties capable to provide flexibility may get the most advantage from market-based mechanisms as there is enough liquidity.

As presented by [21] addressing and solving all different elements from prior- to post-delivery (demand, planning, procurement, data management & forecasting, activation & trading, verification & remedial actions, settlement & remuneration) is crucial to enable the systematic and wide-scale utilization of market-based flexibility mechanisms. The Tables I and II of this paper addressed factors affecting the feasibility of flexibility mechanisms and decision-making in the planning phase. Decisions taken in the planning phase highly impact the other elements of the process.

N−1 conditions during planned outages are extremely unlikely and it is even more unlikely that N−1 condition would occur during a period of maximum power flows in a region causing the highest possible flexibility need. However, the probability of flexibility need as well as its amount and variability are dependent on the characteristics of the region, the grid of the TSO and the nature of the planned outage case. Based on the analysis of N−1 conditions during a planned outage, if there is no immediate risk of system security, the probability of congestion and the probability of N−1 condition are both identified to be extremely low, decision not to utilize preventive actions may be considered as an option by the TSO especially if there is lack of feasible flexibility mechanism.

VII. Conclusions

This paper presented how different types of flexibility mechanisms can be utilized in the outage planning of transmission systems to mitigate the impacts of a contingency during a planned outage and to reduce the need for preventive curtailment. Factors affecting the feasibility of the analyzed flexibility mechanisms were identified, and examples to combine different types of flexibility mechanisms were provided. This paper presented how the technical flexibility capabilities of grid components can be used as an enabler of market-based flexibility mechanisms. More extensive use of flexibility mechanisms will require the development of outage planning processes in the future.

Acknowledgment

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 957739.

References

[1] A. Akrami, M. Doostizadeh, F. Aminifar, "Power system flexibility: an overview of emergence to evolution," Journal of Modern Power Systems and Clean Energy, vol. 7, no. 5, pp. 987-1007, September 2019.

[2] O.M. Babatunde, J.L. Munda, and Y. Hamam, "Power system flexibility: a review," Energy Reports, vol. 6, suppl. 2, pp. 101-106, 2020.

[3] E. Lannoye, D. Flynn, and M. O'Malley, "Power system flexibility assessment – state of the art," IEEE Power and Energy Society General Meeting, pp. 1-6, July 2012.

[4] International Energy Agency (IEA), "Status of power system transformation 2019: power system flexibility," IEA, 2019. [Online]. Available: https://iea.blob.core.windows.net/assets/00dd2818-65f1-426c-8756-9cc0409d89a8/Status_of_Power_System_Transformation_2019.pdf [Accessed 08-Apr-2022]

[5] E. Lannoye, D. Flynn, M. O'Malley, "The role of power system flexibility in generation planning," IEEE Power and Energy Society General Meeting, pp. 1-6, July 2011.

[6] N.E. Koltsaklis, A.S. Dagoumas, I.P. Panapakidis, "Impact of the penetration of renewables on flexibility needs," Journal Energy Policy, vol. 109, pp. 360-369, October 2017.

[7] J. H. Zhao, J. Foster, Z. Y. Dong, K. P. Wong, "Flexible Transmission Network Planning Considering Distributed Generation Impacts," IEEE Transactions on Power Systems, vol. 26, no. 3, pp. 1434-1443, August 2011.

[8] J. Liu, M. Kazemi, A. Motamedi, H. Zareipour and J. Rippon, "Security-constrained optimal scheduling of transmission outages with load curtailment," IEEE Transactions on Power Systems, vol. 33, no. 1, pp. 921-931, January 2018.

[9] G. Crognier, P. Tournebise, M. Ruiz, and P. Panciatici, "Grid operation-based outage maintenance planning," Electric Power Systems Research, vol. 190, art. 106682, 2021.

[10] Y. Fu, M. Shahidehpour and Z. Li, "Security-constrained optimal coordination of generation and transmission maintenance outage scheduling," IEEE Transactions on Power Systems, vol. 22, no. 3, pp. 1302-1313, August 2007.

[11] Commission Regulation (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation.

[12] European Union, "Clean energy for all Europeans," Luxemburg: Publications Office of the European Union, 2019. [Online]. Available: https://op.europa.eu/en/publication-detail/-/publication/b4e46873-7528-11e9-9f05-01aa75ed71a1 [Accessed: 08-Apr-2022]

[13] EU Directive 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU.

[14] Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity.

[15] Morozovska, K., "Dynamic Rating with Applications to Renewable Energy", PhD dissertation, KTH Royal Institute of Technology, 2020.

[16] Commission regulation (EU) 2017/2195 of 23 November 2017 establishing a guideline on electricity balancing.

[17] Fingrid Oyj., "Terms and conditions for providers of Manual Frequency Restoration Reserves (mFRR)", Fingrid Oyj., 2020. [Online]. Available: https://www.fingrid.fi/globalassets/dokumentit/en/electricity-market/reserves/reservitoimittajien-mfrr-ehdot-ja-edellytykset_en-id-237930.pdf [Accessed: 08-Apr-2022]

[18] Entso-e, "Manually Activated Reserves Initiative (MARI)". [Online]. Available: https://www.entsoe.eu/network_codes/eb/mari/. [Accessed: 08-Apr-2022].

[19] Piclo, "Case study: storage and EVs take the lead in £14million worth of awarded UK Power Networks flexibility contracts enabled by Piclo Flex," July 2020. [Online]. https://uploads-ssl.webflow.com/6123718de4b96c44035b9af8/61e6c519f623fb46a117aad5_Piclo%20Case%20Study%20-%20UKPN%20-%20July%202020%20-%20Release.pdf [Accessed: 08-Apr-2022]

[20] O. Valarezo, T. Gómez, J. Chaves-Ávila, L. Lind, Leandro, M. Correa, D. Ziegler, David, R. Escobar, "Analysis of New Flexibility Market Models in Europe," Energies. Vol. 14, no. 12:3521, June 2021.

[21] A. Kuusela, L. Ala-Mutka, A-J. Nikkilä, S. Peltoketo, T. Rauhala, "Flexible connection concept and plannning studies for its piloting in a transmission system," accepted for presentation in IEEE PES ISGT Europe 2022, October 2022.