Flexible Connection Concept and Planning Studies for its Piloting in a Transmission System

Antti Kuusela, Lauri Ala-Mutka,
Antti-Juhani Nikkilä, Suvi Peltoketo
Fingrid Oyj
Helsinki, Finland
antti.kuusela@fingrid.fi

Tuomas Rauhala
Faculty of Information Technology and Communications Sciences
Tampere University
Tampere, Finland

***Abstract*—This paper presents a flexible connection concept and planning studies required for its piloting in a transmission system. The proposed concept utilizes a short-term rating of power system components and operational flexibility of market-based resources. In case of congestion, the short-term rating of power system components provides inherent technical flexibility. This allows a time frame to utilize active power control of flexible resources to maintain system security. The active power control of flexible resources is activated on-demand through a redispatching order at the balancing market. The proposed method enables rapid and cost-efficient grid integration of renewable energy resources without physical grid reinforcements while providing an increase in liquidity into the balancing market. This paper presents more in detail the planning perspective to prove the technical feasibility of the concept and to enable a pilot project rollout in the Finnish transmission system.**

Keywords—on-demand flexibility, flexible connection agreement, short-term rating of components, grid integration

I. Introduction

Evolution towards a carbon neutral energy system is progressing globally, EU member states among multiple nations shall be carbon neutral by 2050 [1][2]. Finland is aiming towards carbon neutrality by 2035 [3]. On top of the political agenda, renewable energy sources (RES) have become commercially lucrative investment even without subsidies [4]. The political and economic outlook sets an agenda for a rapid increase in RES integration into the power system. In addition, the carbon neutral transition changes energy production and consumption patterns. Variations in the intermittent power production will affect the energy market price and subsequently price sensitive energy consumption. Therefore, the amount and magnitude of short-term power variations in a high-voltage transmission system will likely increase as well [5]-[9].

The need for large scale RES integration and the transition towards a carbon neutral energy system challenges transmission and distribution system operators (TSOs and DSOs) especially from the planning perspective, which has been widely presented in the literature [9-11]. Increasing demand for new grid connections and the need to balance short-term power variations requires continuous grid reinforcements and development as well as tools for power system operation and management. Grid development from planning to operation takes from a few years to decades [12], where an onshore wind power plant may be typically built within 6 to 24 months from an investment decision. Therefore, power system planning and grid development shall be performed under a great uncertainty on a rather quick pace. Due to the challenges, new methods for power system planning should be developed.

This paper presents a novel flexible connection concept and considerations for its piloting in a transmission system. The proposed concept combines technical flexibility of power system components with operational flexibility of flexible resources, which are activated on-demand through a redispatching order at the balancing market. In addition, the elements required to enable utilization of market-based flexibility have been identified and resolved for piloting and are presented in this paper. The market-based operational flexibility provides an increase in liquidity into the balancing market that a system operator may utilize for redispatching, countertrading and balancing. The concept targets to produce a tool for mid-term (2-5 years) power system planning to increase rapidly and cost-efficiently RES grid integration capability within the existing power system.

Beyond presentation of the concept, this paper focuses on regional power system planning perspective to prove the concept technical feasibility and to enable a pilot project rollout in the Finnish transmission system. A set of planning studies is a must to ensure that the system security is always maintained, thus it sets a limit to the maximum amount of on-demand flexibility to be utilized. The planning studies presented in this paper take into consideration three interdependent aspects: 1. Grid stability, 2. Amount and controllability of flexible resources, 3. Short-term rating of the system components.

Flexible connections, i.e. non-firm connections, have been publicly introduced [13] and pilot projects have been deployed in recent years in the UK [14-15]. The latter method relies on Active Network Management (ANM) system which can control flexible resources directly in or near real-time. The ANM system is utilized in distribution systems to ensure a stable operation of the grid and availability of flexible resources is secured with flexible connection agreements. The concept presented in this paper secures availability of flexibility with a flexible connection agreement as well. However, the concept differs from the formerly presented since it is implemented in a transmission system, it utilizes a short-term rating of system components, and the active power control of flexible resources is activated on-demand through a balancing market.

The paper is organized as follows: Section II presents flexible connection concept and considerations of its piloting, Section III presents planning prerequisites and methodology, Section IV presents simulation results, Section V discusses findings and Section VI compacts conclusions.

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II. Flexible Connection Concept and its Piloting

A. Definition

In this paper the flexible connection concept is considered as a combination of inherent short-term technical flexibility of power system components and use of operational capability of market-based flexible resources to adjust active power production on-demand after perturbation, while maintaining instantaneous stability and providing support for long-term security of supply.

B. Identified Elements and Considerations for Piloting

During the development of the flexible connection concept, it was recognized that the concept requires addressing of seven different elements. The elements are necessary for power system planning and operational processes as well as for agreeing on a flexible connection between a system operator and a connecting party. Identified elements to be resolved to enable market-based flexibility utilization are presented in the Fig. 1.

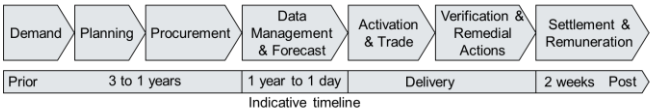

Fig. 1. Identified elements to be resolved to enable market-based flexibility utilization, presented on an indicative timeline from prior to post delivery.

From the piloting point of view the identified elements in Fig. 1 are handled shortly in following subsections. It has been recognized that if the concept is to be scaled as a system-wide planning solution, the elements should be further studied, and development needs should be addressed to ensure scalability of efficient and secure flexibility utilization.

1) Demand

Identification of a demand for the flexible connection concept is widely presented in Section I, the main drivers are: demand for new RES grid connections, need to manage balance variations with market-based methods and to produce higher overall economic efficiency. The major demand for the pilot project is a need to integrate RES rapidly into a regional grid where the grid capacity is fully occupied. In addition, a shortage of down-regulation capacity at the balancing market needs a remedy while an economic benefit of an investment deferral is an additional perk.

2) Planning

Technical planning studies shall ensure that the system security is always maintained. This is a technical paramount, which dictates the maximum amount of on-demand flexibility to be utilized. Planning shall take into consideration three aspects: 1. Grid stability, 2. Amount and controllability of flexible resources, 3. Short-term rating of system components. This paper presents in Section III and IV the planning phase and its results by using the pilot project as a case example.

3) Procurement

To utilize operational flexibility as a tool for power system planning, availability of flexibility shall always be ensured through procurement. There are multiple alternatives to ensure flexibility availability [13]. In this pilot project, a flexible connection agreement is applied since a demand for flexibility is created by a new power plant project and it is technically capable to deliver the demanded flexibility. The connecting party subject to the flexible connection agreement shall provide its power plant capacity to the balancing market, in order to be capable to deliver the flexibility whenever operational. In case of local congestion, an agreed reference price cap for the down-regulation is applied to hedge the system operator against strategic bidding of the connecting party.

4) Data Management and Forecast

Data management and optimization of flexible resources as well as a reliable forecast system is necessary for efficient and secure flexibility utilization. In the future, there is a need for a common market platform for market participants to bid, procure, activate, coordinate, form agreements and to optimize flexibility utilization by a resource and location [7]. The planned flexible connection pilot project is limited to a certain grid area and only a few power plants are subject to the pilot. Necessary agreements are custom made for piloting purpose and operational actions are handled through SCADA and balancing market terminal manually according to predefined instructions. A data management and forecast system was not within the scope of the pilot. If the system was more complex, novel tools should be developed.

5) Activation and Trade

Flexible resources at a balancing market may be activated for redispatching, countertrading or balancing. Technically activation performance requirements are the same regardless of a use case. In case of local congestion, the resources at the balancing market are utilized to redispatch power generation. TSO shall order down-regulation at the balancing market from the flexibly connected resource in order to retain local system security. To maintain the control area balance, the TSO shall order matching amount of up-regulation outside of the congested grid area. The activation and ramping times for manual frequency restoration reserve (mFRR) product at the balancing market have been recently standardized throughout Europe and shall be accommodated to a common Manually Activated Reserves Initiative (MARI) platform by 2024 at latest [16-17]. The activation time for mFRR direct full activation is 12.5 minutes.

6) Verification and Remedial Actions

Verification of flexible resources' activation is necessary for operational purposes as well as for balance settlement and remuneration. A grid operator shall monitor in real-time flexibility delivery, i.e. down-regulation in case of this concept, in order to ensure system security locally. In case of a non-delivery, remedial actions such as disconnection of the flexible resources shall be executed. Therefore, a real-time monitoring is a necessity.

7) Balance Settlement and Remuneration

Flexible service provider's (FSP) energy balance shall be corrected to its balance responsible party's (BRP) balance sheet according to the verified activated energy per delivery period. The correction shall be made to avoid imbalance settlement costs for BRP. FSPs shall be remunerated according to the verified active energy delivery for down- or up-regulation at the balancing market.

III. Planning Prerequisites and Methodology

A. Planned Pilot Project and Planning Cases

1) Planned Pilot Project

The planned pilot project is located in a regional grid comprising of a 110 kV meshed transmission system.

Production capacity in the grid comprises of synchronous generators and power park modules. A simplified presentation of the planned grid is presented in Fig. 2.

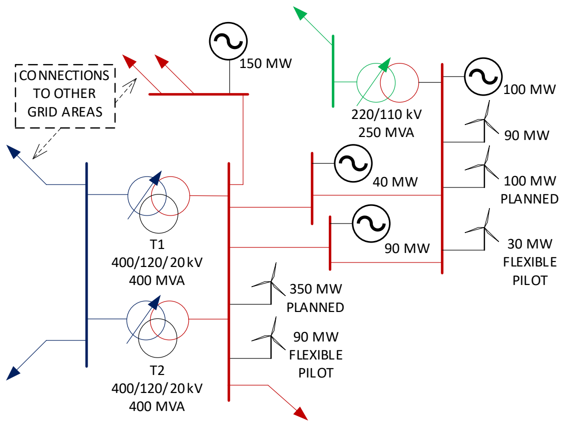

Fig. 2. A simplified presentation of the planned grid. The 110 kV transmission system is connected to the main transmission system through two 400/120 kV 400 MVA transformers and one 220/110 kV 250 MVA transformer. The synchronous generators are hydro and thermal units with total capacity of 380 MW. The prevailing wind capacity within the area is 90 MW and the planned capacity is 570 MW of which 120(90+30) MW is planned to be integrated subject to the flexible connection agreement.

2) *Planning Cases*

Planning cases for simulations were formulated by analyzing historical data for the existing generation and load within the area for the past two years and eight months. The defined time period was chosen to be representative since the operational production capacity in the area remained unchanged. Based on the historical data analysis it was decided to form two cases (summer and winter) for contingency analysis. Preconditions of the chosen planning cases are presented in the following Table I.

TABLE I. PRECONDITIONS OF CHOSEN PLANNING CASES

Preconditions of Chosen Planning Cases	**Case**	
	Winter	***Summer***
Synchoronous generation (MW)	347	300
Wind generation, existing (MW)	90	90
Wind generation, planned (MW)	450	450
Wind generation, planned flexible connections (MW)	120	120
Regional minimum load (MW)	160	100

B. *Planning Process and Methodology*

Power system planning is based on N−1 stability criterion, where an intact power system shall be able to recover to a stable operational equilibrium after a dimensioning fault [18]. Thus, any physical disturbance in the transmission system shall be managed without causing system-wide effects and it is enforced by a grid code within EU [19]. The power system shall recover to a stable equilibrium within 15 minutes after a disturbance. The given time constraint sets a limit for operational actions which may be applied to retain stability.

The presented planning process in this paper is focusing on stability of the regional grid. Thus, static voltage stability, power flows, and dynamic thermal rating of system components are analyzed. Dynamic stability studies of the power system are not within the scope of this paper.

The planning process in this paper takes into consideration three key aspects: 1. Grid stability, 2. Amount and controllability of flexible resources, 3. Short-term rating of the system components. The three aspects are interdependent and are further elaborated below.

1) *Grid Stability*

Grid stability analysis is based on load-flow and N−1 contingency analysis, performed with PSS/E planning software for the simulated planning cases by utilizing well-known Newton-Rhapson iteration [18]. Voltage stability violations and long-term thermal rating power flow violations are reported as a result of the N−1 contingency analysis. The flexible resources are down-regulated in each violated case in order to retain long-term rated limits. If the long-term thermal rating operational limits are met by down-regulation, the short-term rating of the violated components shall be analyzed in time domain simulations.

2) *Amount and Controllability of Flexible Resources*

The concept presented in this paper pursues to activate flexible resources through balancing market, which time frame was chosen as the fixed planning baseline for the pilot project. Short-term rating of the system components is analyzed in two variations: 1. Ideal activation and 2. Remedial disconnection. In the first case the full activation time of flexible resources is 12.5 minutes (2.5 min initial delay to activation and 10 min for ramping) according to the mFRR requirements 2024 onwards [16]. In the second case the activation of flexible resources fails and a remedial disconnection is executed at 30 minutes. The remedial disconnection case was chosen as a safety precaution for the pilot since the piloted control actions may not operate as planned during the first trials. In both cases the amount of flexible resources is 120 MW.

3) *Short-term Rating of System Components*

Analyzed system components are the ones which long-term rating is exceeded during congestion. The main components comprise of transformers, overhead lines (OHLs) and instrument transformers. The short-term rating is time dependent since transformers and OHLs have inherent thermal inertia [20-23]. The affected instrument transformers, which are current transformers (CTs), can bear overloading only for 10 seconds [24] and therefore short-term thermal inertia for CTs is non-existent. However, the CTs are typically dimensioned for fault scenarios with a factor of 1.2 to 1.5 overloading to the nominal rating, which allows operation on higher load during congestion.

Based on the grid stability analysis, the focus was aimed at the short-term rating of power transformers during the pilot project planning. A standardized method for evaluating a hotspot temperature of oil immersed transformers presented in IEC60076-7 [20] was utilized. The method was chosen since input parameters for the model were obtained from the original component specification and factory acceptance test results. It is essential to evaluate the transformers winding hotspot temperature during a contingency. If the hotspot temperature exceeds 140 °C with a winding insulation moisture content of about 2 %, it is likely that gas bubbles form into the insulation and dielectric strength of the transformer windings and leads insulation is lost [20]. Aging of the transformer was not analyzed since it is not a significant concern in the pilot project context, because the transformer is subject to excess loading only in rare fault cases for a short time period.

Grid stability analysis produces a load factor (K) sequence input for the time domain simulations. The load factors are changed according to the variations given in section III.*B.2*. The simulation was performed with PSCAD simulation software.

IV. Simulation Results

A. *Grid Stability in Static State*

The N−1 contingency analysis was performed for the planned simulation cases. The analysis results are comprised into the following Table II.

TABLE II. N−1 Contingency Analysis Results

N−1 Contingency Analysis Results	Contingencies in Chosen Planning Cases Causing a Violation		
	Contingency	*Winter*	*Summer*
Voltage stability	-	-	-
Long-term thermal rating (load/rated in p.u.)	T1	T2 (1.156)	T2 (1.172)
	T2	T1 (1.158)	T1 (1.175)

The contingency analysis results show that violated components in the N−1 contingency analysis were the 400/120 kV transformers T1 and T2. The highest loading compared with rated capacity was observed for the transformer T1 in T2 contingency in the summer case.

The following Table III presents load-flow simulation results for the transformers T1 and T2 in contingency cases after down-regulation of the flexible resources (120 MW). The simulation results show that the long-term rated limits are met since the long-term thermal ratings are below 1.0 p.u. Initial conditions for the components T1 and T2 to be used in time domain simulations of short-term rating are reported in Table IV.

TABLE III. Load-flow Simulation Results After Down-Regulation

Results After Down-Regulation	Contingencies in Chosen Planning Cases Causing a Violation		
	Contingency	*Winter*	*Summer*
Long-term thermal rating (load/rated in p.u.)	T1	T2 (0.977)	T2 (0.990)
	T2	T1 (0.976)	T1 (0.991)

TABLE IV. Initial Conditions for the Components T1 and T2

Initial Conditions for the Components	Case	
	Winter	*Summer*
Long-term thermal rating (load/rated in p.u.)	T1 (0.697)	T1 (0.707)
	T2 (0.670)	T2 (0.695)

B. *Short-term Rating of System Components*

The time domain simulations are presented only for the most challenging cases, which were the T1 and T2 contingencies in the summer case.

1) *Input for the Model*

In both cases the contingency of T1, and T2 respectively, occurs at 10.0. In the ideal activation case, the initial delay for activation is 2.5 minutes, thus the ramping is started at 12.5 minutes and full activation of the flexible resources is achieved at 22.5 minutes. In the remedial disconnection case activation of flexible resources fails and transformer T1, and T2 respectively, is exposed to a high loading for 30 minutes. The flexible resources are disconnected at 40.0 minutes. The total run time of the simulation is 90.0 minutes.

The load factor input for the transformers T1 and T2 in the summer case for the ideal activation and the remedial disconnection are presented in the following Table V.

TABLE V. Load Factor Input for the Time Domain Simulations

Load Factor (K) Input for the Time Domain Simulations	Time (min)	Load Factor (K) in the Summer Case			
		Ideal activation		*Remedial disconnection*	
		T1	*T2*	*T1*	*T2*
	0.00	0.707	0.695	0.707	0.695
	10.00	0.707	0.695	0.707	0.695
	10.01	1.175	1.172	1.175	1.172
	12.50	1.175	1.172	1.175	1.172
	22.50	0.991	0.990	1.175	1.172
	40.00	0.991	0.990	1.175	1.172
	40.01	0.991	0.990	0.991	0.990
	90.00	0.991	0.990	0.991	0.990

2) *Time Domain Simulations*

a) *T1 and T2, Ideal Activation*

Simulation results show that the transformer T1 winding hotspot temperature (θ_h) reaches a top value of 101.4 °C, in case of an ideal activation of flexible resources. The transformer T2 winding hotspot temperature reaches a top value of 107.0 °C respectively, which is presented in Fig. 7.

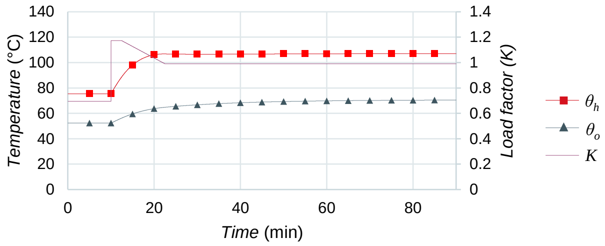

Fig. 3. Time domain simulation results for the transformer T2 in T1 contingency in case of an ideal activation. θ_h is the winding hotspot temperature, θ_o is the top-oil temperature and K is the load factor.

b) *T1 and T2, Remedial Disconnection*

Simulation results show that the transformer T1 winding hotspot temperature (θ_h) reaches a top value of 118.9 °C, in case of a remedial disconnection of flexible resources. The transformer T2 winding hotspot temperature reaches a top value of 126.6 °C respectively, which is presented in Fig. 9. Simulated temperatures are well below the allowed short-term winding hotspot temperature of 140 °C even in the remedial disconnection case.

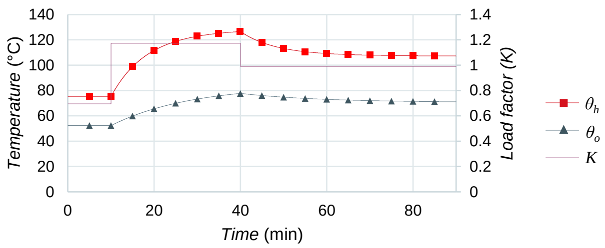

Fig. 4. Time domain simulation results for the transformer T2 in T1 contingency in case of a remedial disconnection. θ_h is the winding hotspot temperature, θ_o is the top-oil temperature and K is the load factor.

V. DISCUSSION

The proposed flexible connection concept is a novel approach and has not been presented before in a similar context. Flexible resources subject to the flexible connection agreement will provide liquidity into the balancing market that enables more versatile possibilities for a system operator to utilize resources. In the paper, the baseline of the planning studies was the technical performance of mFRR product and a remedial disconnection as a safety precaution. Other products and different time scales could be studied as well to assess more opportunities for on-demand flexibility utilization in a transmission system.

System components in a transmission system are typically operated well below their long-term thermal rating in normal conditions to ensure system security. Therefore, there is typically dynamic thermal inertia available in case of congestion. This paper analyzed the short-term loading of transformers based on the grid stability analysis for the pilot project. Similar methods are available for OHLs as well [22-23] and the presented concept could be utilized if the congested grid elements were OHLs.

The planning cases were formulated based on historical data analysis. As the future changes are uncertain, some additional margins or novel forecast methods may be required for the case formulation. Grid stability was analyzed on a regional scale while dynamic power system stability studies were neglected. Scalability of the concept to a system-wide solution is an identified development need that shall be assessed at least from the following perspectives: planning case formulation considering system level uncertainties in the future, impact of the concept on dynamic stability of the power system, needed data management and forecast systems for large scale flexibility utilization, and necessary tools for activation and monitoring of flexibility utilization.

The pilot project enables rapid grid integration of RES and shall produce higher economic efficiency as the necessary grid reinforcements may be postponed at least in the mid-term (2-5 years) time scale. Thus, the existing capital expenditure to the grid equipment will be utilized more efficiently. Annualized redispatching costs in case of local congestions are considered small, since a power transformer fault probability is very low (~1 %) [25]. Further analysis on economic benefits and costs of the concept for involved stakeholders should be performed.

VI. CONCLUSIONS

Technical feasibility of the novel flexible connection concept is proven for the pilot project based on the planning studies presented in this paper. The studies demonstrate that the regional grid stability is maintained during and after congestions. The hotspot temperature of the transformer windings does not exceed 140 °C in short-term dynamic simulations and long-term thermal limits are met after redispatching. The pilot project rollout enables rapid and cost-efficient integration of RES into the transmission system without physical grid reinforcements while providing an increase in liquidity into the balancing market.

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