PREPRINT

A methodology for improved TSO-DSO coordination in grid operation planning

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Abstract— The pan-European electric grid evolves towards a network with a wide diversity of (micro-)energy systems spread throughout all voltage levels. At the transmission level, this poses new challenges for cross-border energy exchange. At the distribution level, small-scale generation, storages and controllable loads offer flexibility available for provision of ancillary services. Meeting the EU energy supply policy while optimally operating the network under these conditions needs advanced TSO-DSO collaboration schemes. Taking this into account, this paper proposes a methodology which combines application of local flexibility management and control with central grid operation planning in order to meet planning criteria for future network operation. We discuss motivation and methodology process, and present results of a proof-of-concept where the methodology was applied to a synthetic benchmark grid model.

Index Terms—Ancillary Services, Flexibility, Grid Operation, transmission-distribution interface

I. INTRODUCTION

The pan-European transmission and distribution grids currently move towards a wide diversity of energy systems. As has been acknowledged by ENTSO-E [1], a growing share of decentralized and fluctuating generation as well as implementation of stationary and mobile distributed storages poses challenges for distribution system operators (DSO). At the transmission system operator (TSO) level, regional availability of fluctuating renewable energy sources (RES) poses challenges for cross-border energy exchange. On the other side, controllable RES and storages together with demand response offer flexibilities that could be used for ancillary service provision. However, advanced collaboration schemes between TSOs and DSOs are needed to meet the European Union (EU)'s energy supply policy and ensure stable and secure grid operation.

These demands and opportunities are being addressed by different European network codes and set forth by national application rules. As part of the European Clean Energy Package, directive (EU) 2019/944 [2] highlights the relevance of demand response and provision of ancillary services by DSO-level flexible distributed energy resources (DER). Usage of such flexibility can improve grid operation and security of supply [3], [4]. Hence, regulation more and more demands to put control schemes for DER into practice, e.g. for mitigating grid congestion cases and balancing [5], [6]. Practical application demands integration of consistent grid operation planning schemes across voltage levels and grid operation control zones. It is widely accepted that this needs strong organizational, technical and informational collaboration between TSO and DSO [7].

In view of this, the EU Horizon 2020 project INTERPLAN was set to develop an integrated operation planning tool towards obtaining more standardized technically oriented solutions for grid operation planning in the 2030+ pan-European network. As main result, the project has proposed a methodology, which combines application of local flexibility management and control with central grid operation planning in order to meet specific operation planning criteria.

This paper is structured as follows. In section II, we elaborate the problem relevant for this work, and summarize the current state of the art. Section III outlines how the INTERPLAN methodology generally addresses the problem. Section IV introduces the methodology in detail. Section V reports findings from a first proof of concept where the methodology was applied to an example scenario. Section VI concludes with a summary and outlook.

II. PROBLEM STATEMENT AND STATE OF THE ART

A. *Problem Statement*

The key goal of the methodology proposed herein is to provide a process and a set of tools for the operation planning of an integrated electric network from the perspective of a TSO and/or DSO aiming at efficient and effective usage of flexibility of intermittent RES, storage, demand response (DR) and electric vehicle (EV) charging at all network control levels. Special focus is on the transmission-distribution interface. The methodology is generally applicable for various planning time periods, but development of the tools is mostly taking day-ahead operation planning into account.

In order to formalize this goal, the methodology defines (i) a set of operation planning criteria which are typical for the 2030+ pan-European network, and (ii) a set of key performance indicators (KPIs) which quantify how well the planning criteria are met. As such, the problem addressed is to optimize the KPIs for a given set of planning criteria while fulfilling the requirements posed by stable and secure grid operation.

B. *Current regulation and standards*

As part of the INTERPLAN project, an analysis on limitations of ENTSO-E network code families in terms of integration of emerging technologies was performed in 2019 [8]. It was found that most codes cover connection standards, operation and market integration of RES. However, according schemes were mostly missing for storage, EV charging stations and DR. The need for detailing implementation guidance documents as well as national energy and climate plans regarding grid integration of storage and DR technologies was identified.

These findings were confirmed by expert interviews conducted in 2021 [9]. The interviews aimed at assessing the current practice as well as shortcomings in regulatory and market frameworks, and involved 15 experts from grid operation and standardization fields. Regarding the latter topic, experts reported a lack of technical standards and shared definitions for KPIs related to technologies that are to be grid connected. In particular in the case of EV charging, a lack in standardized testing, qualification and certification procedures was expressed. Experts from grid operators indicated that European regulation should define a framework generally applicable to different regions, that framework and regulations regarding data exchange should be improved, and legal aspects should be reviewed. Although there is currently no real market demand for flexibility at residential and commercial levels, flexibility markets were named as a recurring topic in regulation especially in Germany. However, use cases and information flows in the integrated system are not yet agreed.

C. *Current practice*

The utilization of flexible assets at the DSO level for provision of ancillary services towards the TSO level has been researched since several years. The need for stronger TSO-DSO collaboration is well acknowledged in research, by standardization bodies and grid operators [1], [4], [7]. There are several options for organizing this collaboration. One important aspect is the design of ancillary service markets. Totally centralized TSO-operated markets and highly decentralized DSO-driven markets are competing schemes [10], [11]. The DER control scheme is closely related; here we find concepts ranging from centralized control and service activation by the TSO to decentralized control by the DSO. Furthermore there are options which involve new market players. The selection of an option at this point directly affects the distribution of responsibilities and the need for information transmission between involved parties [12].

While the 2017 ENTSO-E policy seems to favor a centralized market driven by the TSOs [3], there is currently no agreement on a common European market and control design to facilitate DER for ancillary services. It seems likely that such design will depend on national and regional conditions.

Related to the current practice, the interviewed grid operators (cp. section II.B) reported that they currently use different tools for different planning criteria and use cases, and expressed a demand for standardized and integrated tools that foster TSO-DSO collaboration. Flexibility provision and congestion management were named as most important use cases. Experts expressed a lack of systemic approaches for agreeing upon future scenarios and representative simulations, and identified the need for introducing mature markets for standardized ancillary service and congestion management products. The need for grid equivalents with improved accuracy regarding power flows at the TSO-DSO interface as well as standard data exchange frameworks was identified. The particular case of the German “Redispatch 2.0” [13] highlights that integration of DSO assets into existing congestion management processes causes very high efforts at both DSO and TSO sides, and gives rise to new platforms supporting grid operator collaboration (cp. e.g. https://netz-connectplus.de). The requirement for standard grid data exchange has been answered by the Generation and Load Data Provision Methodology (GLDPM) [14].

All in all, this confirms that there is continued need for an integrated and standardized grid operation planning process and adjacent toolset.

III. SOLUTION APPROACH

The INTERPLAN methodology approach generally focuses on the description of a process for operation planning of an integrated grid from the perspective of TSO or DSO through efficient and effective handling of emerging technologies such as DER and RES. As mentioned under section II, the goal is to optimize a set of KPIs for a given set of planning criteria. This is obtained through a set of so-called control functions, which represent algorithms for grid operation planning as well as grid asset and DER control for different use cases. The assessment is performed by simulations of different types. The simulation type depends on the planning criteria in question.

Although there is some diversity in our use cases at that point, the general assumption is that there is no single grid operator (i.e. TSO) who can perform operation of DER throughout all voltage levels. Thus, the methodology is best applicable to a decentralized market and control scheme. Consequently, grid equivalenting is a key tool in order to allow

TSOs and DSOs to simulate their networks with mutual usage of simplified and non-confidential models for the peer grids.

The methodology has several strong points. First, it is responsive to meet the critical needs of grid operators in addressing a wide range of operation challenges covering all network levels and to increase TSO-DSO cooperation. It thus provides a framework for an integrated planning tool considering all network levels. The intrinsic generation of grid equivalents using the related grid equivalents library allow for simplifying certain parts of the grid while keeping its relevant characteristics. The methodology is flexible to be adapted to current and future grid scenarios. Finally, despite currently being at TRL 5, it is feasible for application in real practice and according tools could be transformed into a Python-based toolbox interfacing with e.g. PowerFactory.

On the downside, market considerations have been out of scope so far. This means that despite the methodology was applied to a number of use cases [15], the optimal selection of DER flexibility bids was not considered. Hence, for this work, the assumption is that DER flexible resources are being contracted, and conditions for service provision are agreed between DSO and DER operators.

IV. THE INTERPLAN METHODOLOGY

A. *Methodology Steps*

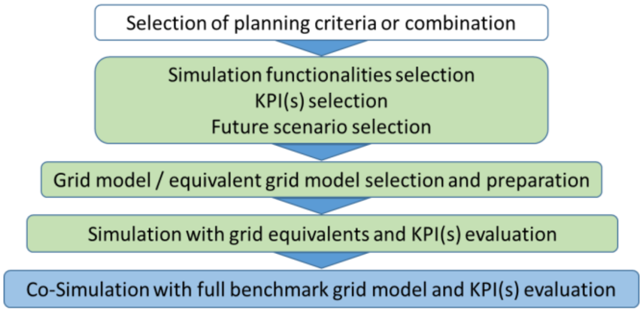

Figure 1: High-level overview of INTERPLAN methodology

The INTERPLAN methodology (cp. Fig. 1, 2) consists of three main stages: (1) Simulation functionalities, key performance indicators (KPIs) and scenario selection, (2) Grid model selection/preparation, (3) Simulation & Evaluation. The typical user is a TSO or a DSO, but also collaborative usage is possible. As a prerequisite, the user first selects the primary planning criteria to be considered for the network operation planning. This selection is based on a pre-defined list of standard planning criteria, such as minimizing losses, maximizing share of RES, mitigating grid congestion, assuring transient stability, optimizing TSO/DSO interaction, assuring voltage stability, and minimizing energy interruption. Under stage 1, the user selects the simulation functionality (e.g. Optimal Power Flow (OPF), Load Flow Sensitivity, Stability Analysis Functions, and Reliability Assessment), the KPIs and the operating future scenario. All named selection items are predefined and standardized by the methodology, and the possible selection is presented to the user based on the previous selection of planning criteria.

Stage 2 of the methodology is dedicated to grid model selection and preparation. Under this stage, the user selects the grid model for the simulation phase in the next stage. The grid model is then adapted to the scenario selected under the previous stage. If a grid equivalent model is required for the simulation phase, for instance when the operation challenge under investigation is related to TSO-DSO network portions, the user can select it from the grid equivalents library consisting of a list of pre-defined grid equivalents, or generate a grid equivalent model through a generation procedure which is part of the standard methodology toolset. When the grid model is selected, it is then mapped to the scenario selected under stage 1 through the scenario adaptation procedure.

Finally, stage 3 is dedicated to the simulation and evaluation phase. Under this stage, the user performs the simulation by using one of the control solutions according to the operation challenge under investigation, and the choices done in the previous stages. The simulation phase is followed by an evaluation through calculation of the previously selected KPIs. If the user is satisfied with the KPI(s) found, the evaluation and grid operation planning is complete. Otherwise, the user can decide to investigate further solutions addressing the same operation challenge under the same planning criteria. In this latter case, the process restarts from stage 1.

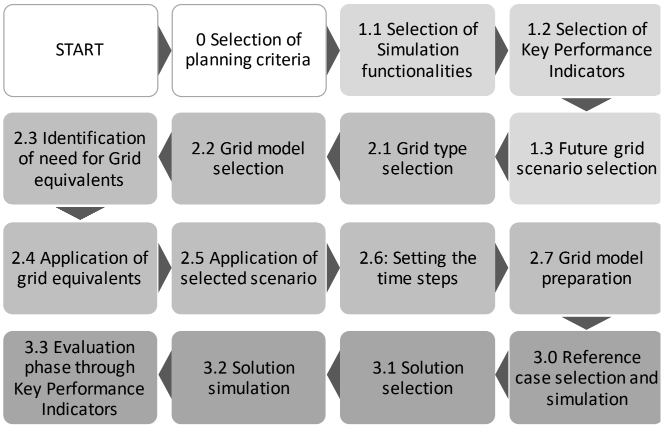

Figure 2: INTERPLAN methodology stages 1-3

The result of stage 3 is a complete set of control functions and grid operation plans that meet the selected planning criteria with adequate quality as assessed by the associated KPIs, thus a practical operation plan for DER and flexibility usage.

The additional stage 4 represents applying this result to the full physical network. However, since INTERPLAN does not include a field test, this stage was replaced by a co-simulation capable of using the full physical grid model and modelling individual control centers of all involved stakeholders as independent subsimulations. The difference to the previous simulation in stage 3 is that in stage 4, grid equivalents are no longer used. For evaluating stage 4, the same KPIs as defined for stage 3 are used. If a validated grid model is used for stage 4, it can thus be assessed which performance can be expected from the selected solutions if applied to the physical grid when compared to the performance as expected by the grid operation planning. However, this requires that the full physical grid model is available to the methodology user or an external party that offers to participate in the co-simulation.

B. *Grid equivalents and control functions*

As outlined above, two methodology main tools are grid equivalenting with the related grid equivalents library, and the control functions. The grid equivalenting allows simplifying certain parts of a grid model while keeping its relevant characteristics. This is considered an essential tool for TSO-DSO interactions, especially when utilizing flexibility from DER, which can be used to address operational challenges occurring at all network levels. Equivalents allow for simplified simulation of flexibility provision, as well as help to determine requirements for operational data exchange between grid operators. As part of the methodology development, methods for automatic grid equivalent generation were researched and a library of grid equivalents was established, strongly focusing on the low voltage level. There are three types of equivalents differentiated:

- Basic – simple representation of the grid, preserving voltage, active and reactive power characteristics;
- Advanced – representation considering an extended set of voltage levels and grid areas;
- Dynamic – basic or advanced grid equivalents suitable for transient stability studies.

As second main tool, the control functions are defined for specific elements of the network such as RES and loads in order to reach the goal of the grid operator. They define concrete algorithms for utilizing DER flexibility, addressing very specific operational challenges such as coordinated voltage/reactive power control, grid congestion management, inertia management, frequency restoration control, power balancing at DSO level, etc.

On the other hand, the control functions also allow to address a combination of the operation challenges defined above, thereby representing typical cases the grid operators may need to consider for operation planning purposes, such as low inertia systems, effective DER operation planning through active and reactive power control, TSO-DSO power flow optimization, optimal energy interruption management, etc.

V. PROOF OF CONCEPT

A. *Aim and User Story*

The main goal of the proof of concept is to provide a first demonstration case for the INTERPLAN methodology, applying it to a fictional scenario which represents one of the project’s showcases. The showcase was selected such that a high number of the developed tools could be used, especially including a subset of the control functions, grid equivalents, simulation with equivalents, co-simulation and assessment of results using the KPIs as defined by the methodology.

This is put into the framework of a user story which involves a TSO and a DSO who are collaborating in such that they both use the methodology. In practice, this could involve grid operation engineers from both stakeholders who mutually process the stages and agree on decisions made in each stage. For the selected showcase, the TSO’s goal is to facilitate flexibility for tertiary reserve, utilizing both TSO and DSO resources while striving for minimal grid losses at all times. The DSO aims at providing flexibility to the TSO with the goals of minimizing both power losses and transformer loadings at the TSO-DSO interconnections. Optimization at the TSO resp. DSO side consistently uses grid equivalents for calculating day-ahead grid operation plans.

B. *Scenario*

For the demonstration, we prepared a small synthetic benchmark grid model derived from the SimBench benchmark dataset [16]. The grid represents the region of North-Eastern Germany and includes 238 buses with low (LV), medium (MV), high (HV), and extra high (EHV) voltage levels. The EHV portion of the model was modified according to German network development plans to represent an example future scenario. Still the model is by no means a verified scenario as it is only used for the methodology proof-of-concept rather than quantitative assessment of the control function performance. Time series for generation and loads were synthetically generated for the INTERPLAN 2050 “small and local” scenario, which is characterized by a high share of DER. Generators and loads in the model are mostly concentrated. Table 1 shows the installed generation capacity and the generator asset count. There is mostly solar and wind generation due to regional characteristics of the area. The number of loads sums to 225. There were no controllable loads considered in this example, but full controllability of all renewable sources was assumed.

	Fossil	**Solar**	**Wind**	**Hydro**	**Biomass**
P_{inst} [MW]	222	2098	2590	25	13
Assets	4	164	28	2	18

TABLE I: GENERATION IN THE BENCHMARK GRID MODEL

For testing purposes, we assumed that the TSO simulates an operation plan with sixteen different target levels for tertiary reserve provision, occurring every 4th quarter hour between 7:00 and 22:00 of a one-day time interval. This time interval is called "on-hours" in the following, while the remaining time is called "off-hours". The target values for tertiary reserve were randomly chosen between -80 and +80 MW. Note that this is a purely synthetic scenario designed for investigating the methodology process, rather than representing a practically valid use case.

C. Stages 1 to 3

According to the methodology (cp. Figure 2), four of the predefined planning criteria are selected: (1) minimizing grid losses, (2) maximizing share of RES, (3) optimize TSO/DSO interaction and (4) maximize DER contribution to ancillary services. In stage 1, this results in the proposal of a number of appropriate KPIs [15] as well as two control functions which refer to (i) tertiary reserve provision and (ii) balancing power flows at the TSO/DSO connections. Also, a scenario is selected, in this case "INTERPLAN small and local" for the target year 2050. This scenario features a high share of distributed generation.

In stage 2, application to both transmission and distribution networks is selected to cover the interests of both TSO and DSO. Since we assume that the grid operators do not want to exchange full grid models due to confidentiality, the need for mutual usage of grid equivalents is identified. Preparation and exchange of these models is carried out as a manual task. The same is the case for preparation of DSO-and TSO-level grid models. In the proof of concept, these steps are carried out by automatic time series generation and semi-automatic preparation of simple Thévenin equivalents for the used radial benchmark network. Finally the time frame of consideration is set to one day with a 15 minute interval size and time series for the network are generated accordingly.

In stage 3, users select a base case with no control functions as a reference for KPI comparison. The proposed solutions for the planning problem consist in the two control functions with according grid operation planning schemes, one of which controls DSO-level assets, the other controlling TSO-level assets. Both solve a generally non-linear optimization problem with the respective planning criteria as requirements. The showcase defines that the operation planning is carried out in three steps: first, the DSO calculates the range of DER active power flexibility available at the three TSO-DSO connection points for all times within the planning timeframe. Second, the TSO performs an OPF which results in optimal operation points at the TSO-DSO connections, taking the tertiary reserve targets into account. Lastly the DSO performs an OPF-based optimization to provide the requested active power while minimizing losses, transformer loading, and RES curtailment. Note that all this was done using grid equivalents for the respective peer network, and using perfect forecast for generation and loads.

With that, all necessary input data for simulation, calculation and assessment of a grid operation plan is selected and the planning phase is carried out. During the on-hours, the full algorithm as outlined above is executed. During the off-hours, no tertiary reserve provision is assumed, hence only the DSO-side OPF for minimizing transformer loading and RES curtailment is performed. The obtained active power operation plans are simulated and compared to the base case in terms of expected KPIs. The simulation was carried out on a single computer and controlled by a Python script with functions attributed to TSO and DSO actions respectively.

The simulation results show that during the on-hours the optimization was able to achieve its primary objective, which is reaching the tertiary reserve power targets. Multiple additional KPIs were calculated. As examples, the KPIs "Transformer loading" as percentage of the average transformer nominal power and "Level of losses", referring to active energy losses relative to the total amount of active energy injected into the network, are shown in Fig. 3 and 4. The optimization ("control case") did not consistently reduce these KPIs since this was not a primary objective of the control function for tertiary reserve provision.

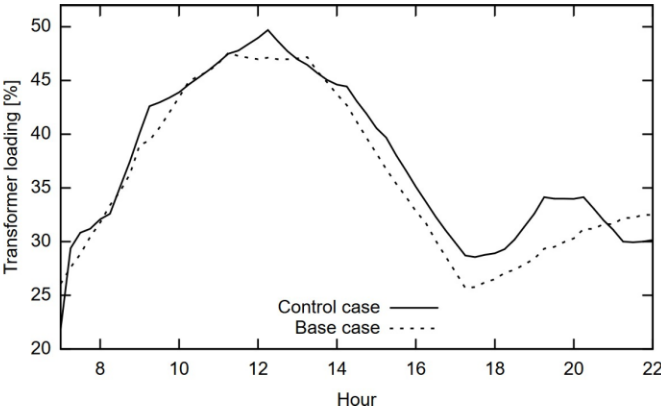

Figure 3: TSO/DSO transformer loading

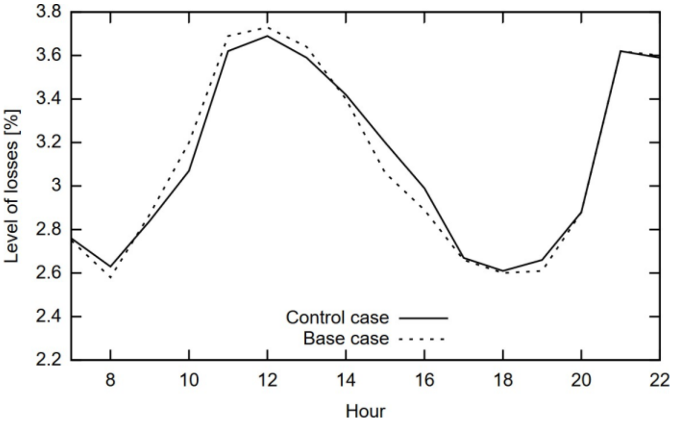

Figure 4: Active energy losses relative to total active energy injected

D. *Stage 4*

For purposes of the proof-of-concept, stage 4 consisted in a co-simulation of the grid operation using the full physical network model. The co-simulation platform OpSim [17] was used for this. OpSim is a Co-Simulation environment developed by Fraunhofer IEE and the department *e2n* of University of Kassel. It can be used for several different use cases from testing control strategies and interfaces [18] to assessing cyber security [19] and large scale simulations [20]. It was also shown to be usable to simulate the interactions between TSO and DSO with only sparse knowledge of the respective grid models. OpSim is based around a message bus, thus enabling asynchronous distributed simulations. But simulators don't need to be event driven or even aware of the distribution or synchronization at all, since OpSim uses conservative synchronization to synchronize all simulation components, thus allowing these complex setups.

In order to mimic a collaborative co-simulation between TSO and DSO using OpSim, we distributed the simulation to a total of three remote computers: (i) PC1 was used to control the simulation, (ii) PC2 was running the grid calculation and TSO control function subsimulations and (iii) PC3 was running the DSO control function. The computers were placed in networks of project partners DERlab and Fraunhofer and connected by VPN, essentially representing a TSO-DSO collaborative co-simulation. The two subsimulations combined at PC2 could also have been split to two different machines without changing the general setup, which was omitted because of resource limitations. The input for the control functions were the setpoints as obtained by the stage 3 planning phase. The PCs were connected to the OpSim Message bus. Core OpSim components were running at Fraunhofer servers. For connecting the TSO and DSO subsimulations we used web proxies which allow connections to independent external networks. Fig. 5 shows the total setup.

The results of the co-simulation were automatically evaluated and compared to the expected KPIs obtained by stage 3. It was found that most of the KPIs were met with deviations of 0.5% or less. As an example, Fig. 6 compares the level of losses as obtained from the stage 4 co-simulation with the values from stage 3 simulation (cp. "control case" in Fig. 4). In one case ("share of RES"), deviations of up to 2% were obtained. Fig. 7 shows the deviations for the active power exchange targets at the three TSO/DSO connection points. The maximum deviation here is about 2.5%. Overall, these results are considered acceptable since the deviations were attributed to the simple grid equivalenting approach that was applied for the proof-of-concept. Hence, this first test indicates that the INTERPLAN methodology using grid equivalents for TSO resp. DSO networks may be a suitable tool for grid operation planning, and could be further improved by using more sophisticated grid equivalenting methods.

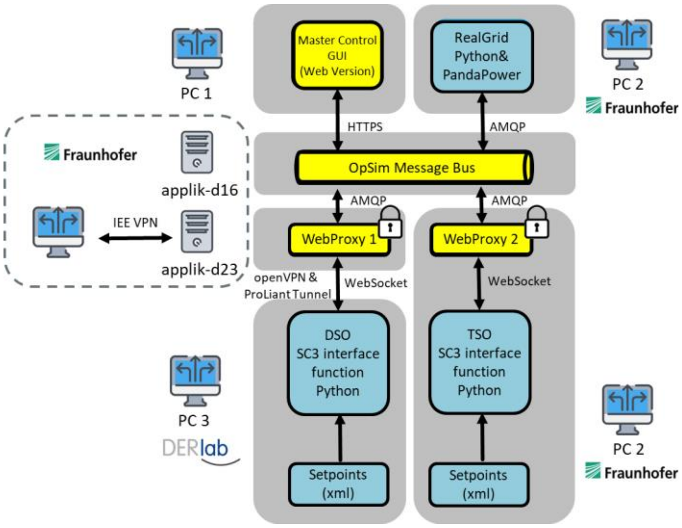

Figure 5: Co-simulation setup

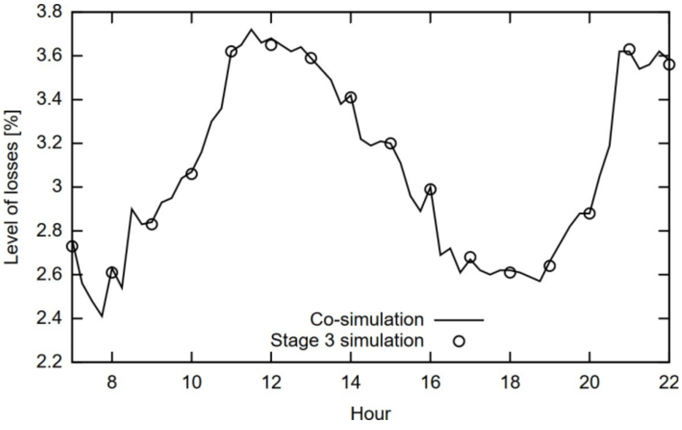

Figure 6: Level of losses – Co-simulation vs. Stage 3 simulation

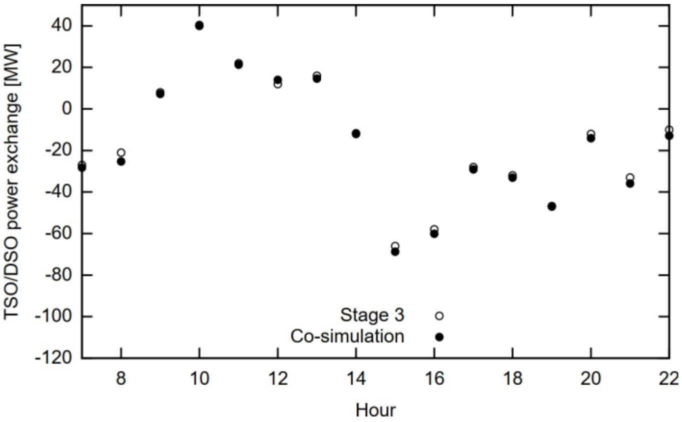

Figure 7: TSO/DSO power exchange – Co-simulation vs. Stage 3 targets

VI. CONCLUSION

As a result of regulation review and experts interviews, it was found that there is a demand for standardized and integrated tools that foster TSO-DSO collaboration and utilization of flexibility at the distribution level for grid operation planning. The methodology developed in INTERPLAN H2020 project proposes a formalized way of performing such planning with effective and efficient use of flexibility resources such as RES, EV and DR. It focuses on decentralized market models and is meant to be used across all voltage levels and grid operation control zones. Key tools are grid equivalenting, control functions, and simulation.

The primary target customer group for the methodology are TSOs and DSOs. Flexibility aggregators, regional security operators or even new market players supporting grid operator collaboration might be additional customer groups.

A first proof of concept has shown that there is good prospect for practical application of the methodology. However, although the methodology received positive feedback when presented to grid operators during the project's stakeholder workshops, it needs further testing, refinement and pilot applications in direct collaboration with the target customer group. It also needs to be set into a framework that features a user interface and allows for high usability. Interfacing to existing customer systems will be one of the biggest challenges here. A possible way for increasing the TRL would be integration into existing software systems for grid simulation and calculation. In addition, market and flexibility procurement aspects need to be integrated into the methodology. Finally, stakeholder experts have expressed that protection technology is currently missing. Definition of additional planning criteria and KPIs for grid protection may be a way to fill this gap.

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