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Challenges of TSO-DSO Voltage Regulation Under Real-Time Data Exchange Paradigm

MERKEBU ZENEBE DEGEFA [1], HENRIK LUNDKVIST [2], SANTIAGO SANCHEZ-ACEVEDO [1], AND KRISTOFFER N. GREGERTSEN [2]

[1]SINTEF Energy Research, 7465 Trondheim, Norway
[2]SINTEF Digital, 7465 Trondheim, Norway

CORRESPONDING AUTHOR: MERKEBU ZENEBE DEGEFA (e-mail: merkebuzenebe.degefa@sintef.no)

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ABSTRACT As conventional power generation units are being replaced with distributed energy resources, operational practices such as voltage regulation and congestion management are expected to be challenging. To address these challenges, regular and automated intercontrol center operational coordination will be needed between transmissions and distributions system operators (TSO and DSO). In this study, the data exchange required for the near-real-time operational coordination is investigated for a reactive power management use case. A realistic ICCP/TASE 2 protocol is implemented in a laboratory environment where the physical network is simulated in a real-time simulator while optimal set-points are communicated from the control centers to simulated assets being communicated through the IEC 60870-5-104. In addition, the sufficiency of the common information model (CIM) and common grid model exchange standard (CGMES) is evaluated for TSO-DSO network data exchange. The results from the cyber-physical test setup show that the detailed DSO grid model knowledge by the TSO results in lower system losses. Such data can be difficult to prepare, exchange, and compute. However, results show that simplified equivalent models can be acceptable if they are properly tailored to the specific use case. The experiences from the CIM implementation with the CGMES profile are found out to be sufficient for such operational data exchange.

INDEX TERMS Data models, power distribution control, power distribution testing, power system modeling, power transmission control, power transmission testing.

I. INTRODUCTION

For a sustainable society, it is necessary to transition into renewable forms of energy resources. Important renewable forms of energy resources such as solar and wind are characterized by their highly variable generations, inducing new dynamics in the energy system. High penetration of distributed energy resources (DERs) may increase transmission network voltages due to reverse power flow and may even saturate onload tap changing transformer (OLTCs) at boundary buses [1]. Traditionally, the nonrenewable-based conventional generation connected to the transmission system has been providing inertia and system services to the power system. As the conventional generation phases out, while being replaced by DERs connected in the distributions system, transmissions system operators (TSOs) will start to look for ancillary services from distributed energy resources connected in the distributions system operators (DSO) network [2]. Hence, operational level coordination between TSO and DSO will be more frequent and is going to be characterized by large amount of network model, measurement data as well as control signals exchange in real-time. The exchange of information will increase the requirements on the communication and the computational power of the operational planning systems that make use of it. The appropriate level of coordination should therefore be identified, in terms of what information to be exchanged and to what level of detail. Moreover, practical methods for exchanging the relevant information shall be identified and established.

The models of coordination between TSO and DSO are evolving, a recent review can be found in [3]. The main management models are classified as TSO-managed, DSO-managed, and TSO-DSO hybrid-managed models. Although a range of optimization algorithms can be used to optimize the coordinated operation for all the management models above, specific solution can suit more to one model than the other. Coordination is commonly considered in terms of a market for ancillary services, where different market models can be considered for the TSO-DSO coordination. In the SmartNet project, five different market models were considered, with different roles for TSOs and DSOs [4]. A cost-benefit analysis shows that it is feasible to implement different market solutions, including a common market or a shared balancing responsibility model. It is concluded that the European Union regulations are not addressing all the topics, such as the timing of the market, which may lead to fragmented solutions across Europe.

Coordination in the context of European regulations and practices is further treated in [5]. The need to standardize the information exchange in terms of the type, frequency, and granularity of data to be exchanged is described. The types of data can be classified into real-time, scheduled, and structural data. There is a need to handle the different abstract models of the data in different systems, in particular, common information model (CIM), IEC 61850, and TASE 2 standards. The frequency and granularity of the data exchange depend on the use case. This article contributes to the analysis of the information exchange with a detailed study of coordinated voltage control. In [6], it is proposed to use a model-driven methodology to identify how to exchange information between TSO and DSO, with the smart grid architecture model (SGAM) framework as the basis. A common model of business and system roles and a common ontology should be used to identify the information that needs to be exchanged. In [7], a model-based approach with a domain analysis of DSOs is used to derive the requirements for CIM profile and middleware for DSO applications. Both [5] and [6] point out that design principles and solutions developed for the Internet of Things (IoT) are beneficial to apply also for smart grids. For example, an evolution from traditional client-server models toward a publish–subscribe principle, which is more centered on the information to exchange than the communicating devices, can be advantageous also for the smart grid. In this article, we are starting from the existing protocols for electricity grids to validate that they are sufficient in real-world scenarios. Similar to [7], we conclude that the existing CIM standards can be used for the complementary use case of coordinated voltage control.

There are a number of distributed generation and load types connected at medium voltage (MV) and low voltage (LV) part of the power system. Load models can generally be divided into two main groups: static load models and dynamic load models [8]. While static load models suit loads such as resistive loads, dynamic load models suit for loads such as induction motors. Depending on the availability of the distribution network model structure, two modeling methods can be followed: a black-box approach and a grey-box approach. In [9], a grey box approach is presented for finding an equivalent of an active distribution network by the use of certain connectivity information.

TSOs and DSOs only have information about their own grid and the neighboring areas are usually represented by grid-equivalent models [10], [11], [12]. Operational coordination are not common to such extent that grid models are exchanged. Hence there is a research gap on understanding the impact of the different level of knowledge of the neighboring grids in the control center's optimal power flow (OPF) tools. The lack of sufficient operational coordination and data exchange between TSO-DSO may result in frequent operational challenges for the DSOs following operational measures in TSO network. Also, TSOs will have limited alternatives/oversite to respond to congestion and voltage problems. A concrete example can be a scenario where the TSO wants to tap to flexibility resources in the DSO area and have limited information regarding the connectivity and capacities of the distribution network. This will result in inefficient activation of flexibility which may increase losses or even power quality problems toward the distribution network.

The EU Commission Regulation 2017/1485 is the guiding document for national grid codes [13]. The regulation establishes guidelines on electricity transmission system operation. Although the regulation encourages the coordination of system operation and operational planning, it does not prescribe details of the inter-control center data exchange configurations. It largely leaves it up to the TSOs and DSOs to agree on the amount of details in data exchange. This study highlights the data exchange needs and challenges with a realistic simulation environment.

In this study, three levels of equivalent models are prepared for a test distribution network and for a use case of coordinated TSO-DSO reactive power management to study the impact on system performance. The three equivalent grid models are assessed for their impact on the optimization outputs as well as the overall resulting network losses for the use case of TSO-DSO coordinated management of reactive power flow. Also, based on the use case, the sufficiency of the IEC 61970 CIM standard and the common grid model exchange specification (CGMES) profile is evaluated for real-time TSO-DSO data exchange. A cyber-physical test system is built upon an existing testbed for advance distribution management system (ADMS) to include the TSO-DSO intercontrol center communication platform [14].

The main contributions of this article are summarized as follows.

1) Establish a realistic cyber-physical test system to study TSO-DSO operational coordination.
2) Evaluate the operational impact of three types of DSO grid representation seen from TSO control room perspective.
3) Assessment of sufficiency of the CIM data modeling for operational data exchange under the use case of coordinated TSO-DSO reactive power management.

The rest of this article is organized as follows. In Section II, the inter control center communication for the specific use case of voltage regulation. Section III reviews CIM and the requirements on exchange profiles for operational coordination, then the voltage control use case is introduced in Section IV and the testbed in Section V. The results are described and discussed in Section VI. Finally, Section VII concludes this article.

II. INTERCONTROL CENTER COMMUNICATION FOR VOLTAGE REGULATION

Reviews of the challenges in voltage control in smart grids which cover both TSO and DSO perspective are published in [1] and [15]. For the voltage control at the TSO the estimation of Thévenin equivalent from measured data is considered as a key challenge, where measurement noise and load variations make it necessary to find a tradeoff between timeliness and accuracy. An automated decentralized solution for primary voltage control is proposed in the Electra project [16], where a local control receives setpoints from a postprimary voltage control which implements a system wide optimization. The local voltage regulation needs to estimate the grid impedance in order to determine the best control strategies for active and reactive power. With a complete model of the grid impedance, estimation is simplified. The alternative is to use flexible resources to generate P and Q and observe the voltage changes. Hence, the exchange of grid models between DSOs and TSOs is preferable for voltage control. Between system operators, the information exchange should give sufficient information about the current status of the grid, which includes measurements of voltage, impedance, active and reactive power, setpoints for capacitor banks, and positions for tap changers. In [17], an optimization method is proposed which takes the cost of available flexibility resources including reactive power compensators and network constraints as inputs to find feasible operation points that fulfill constraints on different maximum flexibility cost levels. The result is presented as a map that illustrates the possible operation points in terms of active and reactive power that can be selected with the appropriate choice of contracted flexibility resources. The solution is implemented by integration of forecasts and SCADA/DMS systems and demonstrates good results with low computational complexity. A similar solution of using a PQ chart to characterize the available flexibility of the distribution network is proposed in [18]. The DSO provides the TSO with the PQ chart, and the TSO can determine which flexibility resources to activate and send new set-points back to the DSO. By using piece-wise linear functions to characterize the PQ chart this can be made in a computationally efficient manner. While these methods may optimize the performance and complexity of the system, they require new information formats to exchange the available flexibility in the reactive power settings. In contrast, the exchange of grid models is possible with existing protocols. In [17], the performance is evaluated in terms of computational complexity, it is therefore not comparable with the results here that are focused on the power losses for different equivalent grid models. In [19], voltage control is implemented using smart inverters connecting PV in the distribution network in Norway. Six different voltage control methods for the inverters are considered, which demonstrate the possibility to reduce the voltage difference and the total energy loss by taking into account both the TSO and DSO losses in the control strategy. The proposed control strategies are implemented locally at each inverter without any coordination between TSO and DSO. The results are complementary to this study where the focus is on coordination of the control, and the DER types are different.

A. SMART-GRID STANDARDS AND COMMUNICATIONS PROTOCOLS

The most relevant standards for the use case and their roles are described in this section.

1) ICCP/TASE 2

The IEC 60870-6 standard specifies a method to interconnect SCADA systems from multiple domains for exchanging time-critical data between control centers. It is therefore also known as intercontrol center communications protocol (ICCP) or telecontrol application service element (TASE 2). The message exchange follows a client-server architecture and consists of requests for information and control signals.

2) IEC 60870-5-104

Protocol used for communicating between the field devices and the SCADA human machine interface (HMI) at the control center. This protocol is used for metropolitan or wide area network communication.

3) IEC 61970 CIM

In order to facilitate interoperability among different asset and energy management tools it is important to have a standardized information model that defines names, attributes, and relations for the entities in the system [20]. The IEC61970 common information model is a standard defined in UML that defines such a model. The whole model includes a wide variety of aspects, so CIM also encourages the use of *profiles* for defining a subset of the standard for different purposes. For instance, in many cases the physical assets themselves are not of interest in the model, but rather the function they perform in the energy system. One example is the CGMES profiles that are defined for the exchange of grid models among European TSO's by ENTSO-e.

4) IEC 61850

The communication of field devices at the process level is carried out with the support of devices that handle the multiple protocols defined in the IEC61850 standard. Current and voltages at the substations are streamed to intelligent electronic devices with sampled values. Control and protection signals are carried with GOOSE messages. Besides, correct synchronization of field devices can be achieved by precision time protocol (PTP).

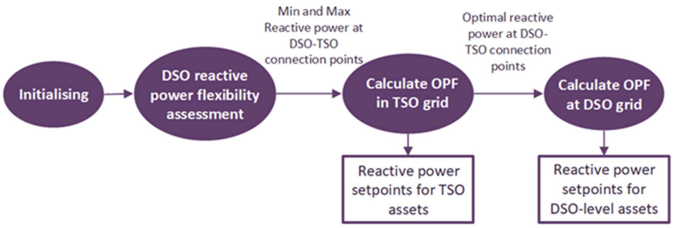

FIGURE 1. TSO-DSO coordinated voltage/reactive power control.

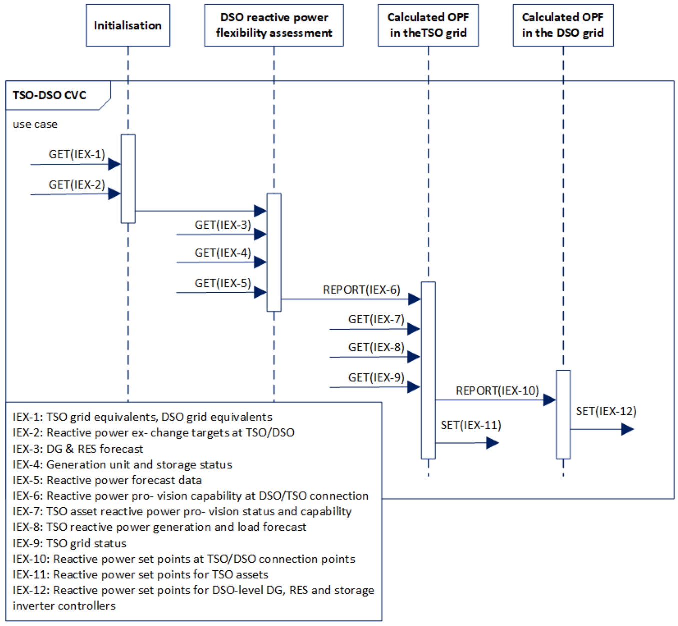

FIGURE 2. Sequences diagram for the use case of coordinated TSO-DSO reactive power management.

III. CIM FOR OPERATIONAL COORDINATION

CIM can be used to share digital models of the respective grids between adjacent system operators. The CGM used by European TSOs covers use cases such as day ahead congestion forecast, planning, and system extension studies. For efficient communication of the model CGMES is divided into multiple parts which are transferred in separate files, to allow for different controlling entities of the devices and different update intervals.

Multiple use cases for TSO-DSO coordination are analyzed in [2] to identify information that is missing in the CGMES. Since the article is attempting a general approach to address a range of different use cases, CIM would not be sufficient without several extensions. For example, it is proposed to add flexibility with dynamic requests for selected CIM information between system operators, such as measurements from a specific observation area. This article rather proposes to use ICCP for the exchange of the dynamic measurement information, which avoids the need for extensions of CIM. What information to include in the grid model exchange is determined in advance to define a static CIM profile.

For the voltage control coordination use case, the parts of the CGMES that are used are the equipment, topology, and state variables files. The topology is used in the formulation of the OPFs that will be solved by the system operators. By replacing part of the grid with a network equivalent the complexity of both the OPF and the CIM models to be exchanged is reduced. As proposed in [2] the equivalents package can be used to exchange the network equivalent models. However, while [2] proposes to extend the CGMES with validity time information and status information to achieve a more flexible dynamic behaviour, this is avoided in our simpler approach by using a periodic update interval. Considering that the typical current grid operation uses fixed update intervals of, for example, one hour or 15 min, this is a sufficient solution which can match the operation with available planning information.

IV. USE CASE OF TSO-DSO VOLTAGE REGULATION

The details of the use case used in this study can be found in [21], however, we provide a brief illustration of the main processes focusing on DSO-TSO interaction in Fig. 1. The use case starts by preparing forecasts of load and generation in both TSO and DSO premises for the defined time window of operation, such as every 15 min. Also, the initialization process prepares TSO and DSO grid equivalents and any other contractual agreements for reactive power exchanges. The process continues by estimation of maximum and minimum reactive power exchange potentials at DSO-TSO interconnection point by DSO control room. The DSO control room communicates the interconnection point reactive power limits to the TSO control room which runs OPF to define the optimal exchange reactive power amount and setpoints for voltage regulating components under TSO premises. In the end, the DSO control room uses the TSO-communicated optimal reactive power to run another OPF for identifying optimal setpoints for voltage regulating components in its premises. The sequence diagram illustrating the information exchange process is presented in Fig. 2. In this use case, TSO and DSO are coordinating in the secondary voltage control process to optimally compute set-points for the primary controllers of capacitor bank, on-load-tap-changing transformers and a converter connecting a wind turbine.

A. TEST NETWORKS

In the implementation of the use case a modified CIGRE high voltage (HV) network is used as a TSO system and a modified CIGRE MV network as DSO system. The modifications on the CIGRE HV network include: the removal of all capacitor banks except from the one connected on Bus-6 and the removal of the generator, and the transformer connected at Bus-12. The modifications on the CIGRE MV network include: the high voltage side of the transformers are set with 220 kV to make them connectable to the CIGRE HV network; all DER units are removed and only the wind turbine at Bus-7 is kept; all 20 kV buses have loads and the network is operating radially with the switch between Buses 8 and 14 is open.

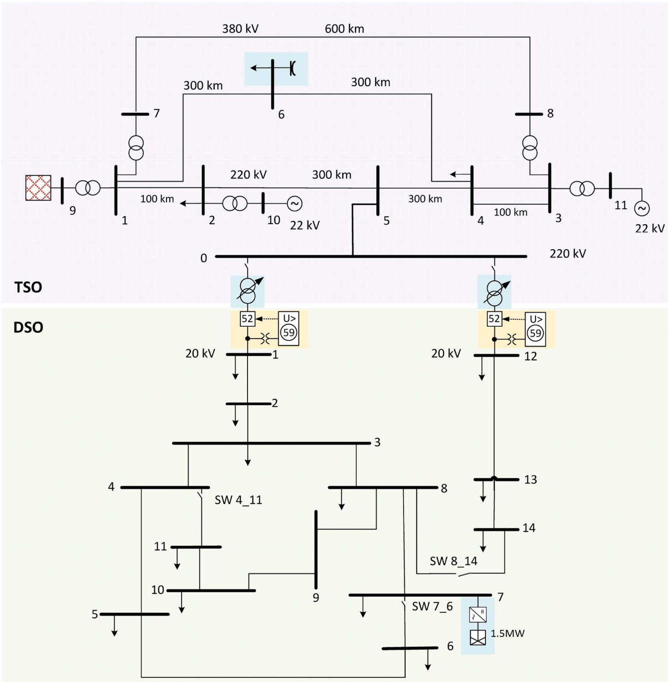

FIGURE 3. TSO-DSO network made of modified versions of CIGRE HV and MV test networks.

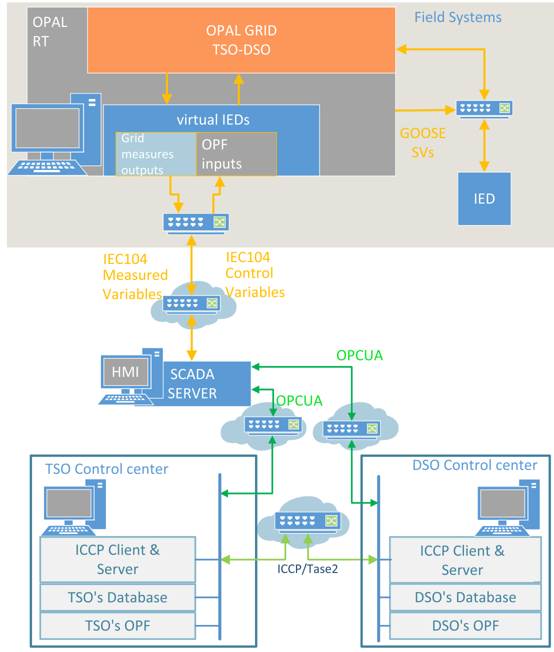

FIGURE 4. Architecture of laboratory setup.

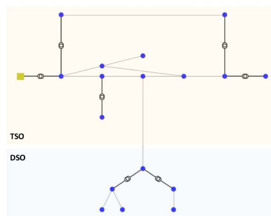

FIGURE 5. Case-Full.

The two networks are connected and have two HV/MV transformers with OLTCs at the connecting bus. In addition to the two OLTCs, there is a capacitor bank in the transmission network and a wind turbine with converter in the medium voltage network which can receive set-points from the respective TSO and DSO control centers. The controllable parameters (set-points) are reference voltages for OLTCs, reactive power setting for the capacitor bank, and the intercept of the Q-V droop characteristics curve of the converter connecting the wind turbine. The optimal power flow is implemented in pandapower with powerflow solver PYPOWER with the objective to minimize losses. The internal solution of PYPOWER uses the interior point method [22]. The TSO-DSO test network is illustrated in Fig. 3.

B. EQUIVALENT GRIDS

For effective operational coordination between TSOs and DSOs and also to guarantee the system security, TSOs need to have a sufficiently detailed knowledge of the behavior of active distribution networks [23]. Nevertheless, the availability of detailed information as well as the computation of large networks undermines the implementation of such information exchange between TSOs and DSOs. Equivalent grid models for the distribution network can be sufficient in many cases to establish tighter operation coordination between TSOs and DSOs.

Currently the use of aggregated distribution network grid models among the utilities is nonexistent [24]. In [24], two main categories of equivalent grid model development techniques are presented for active distribution networks. The first category is system reduction techniques which aggregates and eliminate some components of the detailed model of the system through modal analysis or coherency based aggregation methods. The second category is called system identification technique which develop models using simulated data or measurement at the boundary bus. The equivalent grid model development technique tested in this study falls under the system reduction technique.

In this study, three DSO network equivalents are developed and tested with the laboratory setup presented in Fig. 4. The laboratory setup shown in Fig. 4 represents a cyber-physical power system testbed, which is described in the next section. The first equivalent is crudely assuming the DSO grid as a P-Q bus with net load-generation in the DSO network updated at each iteration (Case-Bus, see Fig. 7). The second is an equivalent grid formed by clustering with respect to voltage level, generation technology, and control type (Case-TCA, see Fig. 6). The third is the assumption that the TSO control center have full knowledge of the DSO network (Case-Full, see Fig. 5).

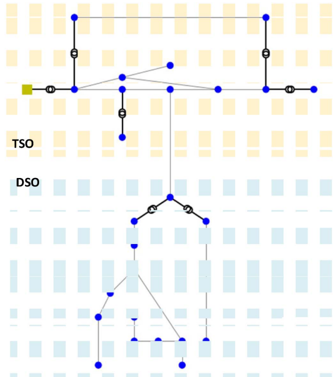

FIGURE 6. Case-TCA.

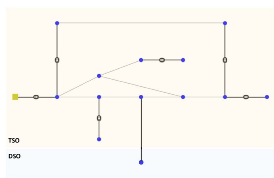

FIGURE 7. Case-Bus.

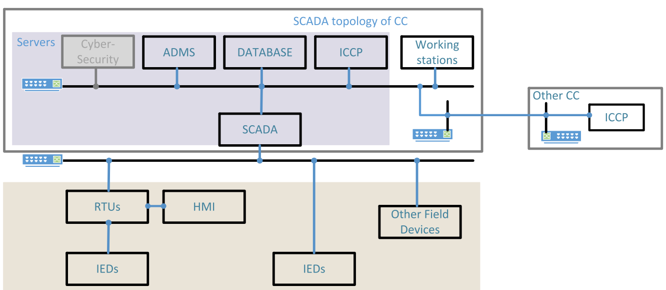

FIGURE 8. SCADA infrastructure for control centers (CC) communications.

V. CYBER-PHYSICAL POWER SYSTEM TESTBED (CPPS-TB)

Laboratory based validating and testing of complex power system control functions in realistic setup is very important to avert the cost prohibitive and inflexible full-fledged physical demos in the real world. Fortunately, with the wide accessibility of advanced real-time simulation platforms, powerful simulation techniques such as hardware-in-the-loop (HIL) are being applied for demonstrating advanced control schemes. Liu and Ochoa [25] show an advanced control scheme for active distribution networks. This work uses a validation setup with a real-time simulator (RTS) and a control room with SCADA and DMS. In [26], the authors present a power hardware-in-the-loop topology for evaluating advanced distribution management systems. In this study, a CPPS-Tb is set up to implement the aforementioned use case with the HIL strategy in the National Smart Grid Laboratory in Trondheim, Norway [27].

The CPPS-Tb in Fig. 4 presents the main components used in the task of voltage regulation with TSO and DSO communication. Field devices and the dynamic power system is highlighted at the top in Fig 4. A real-time simulator (OPAL-RT) has been used for simulating the transmission and distribution networks, emulation of virtual intelligent electronic devices (IED) used in power systems substations and it links physical devices. Additionally, the real-time simulator has high computational capabilities for simulating complex systems like transmission and distribution networks. Besides, OPAL-RT handles multiple smart grid protocols and standards which enables hardware-in-the-loop tests with integrated field devices such as IEDs. In this article, OPAL-RT represents field devices and it communicates to the SCADA control center via IEC 60870-5-104. Internal substation communication has been handled with IEC 61850 GOOSE and measurements of voltages and currents use sampled values (SVs). The links between field systems and control centers is handled by the SCADA server. Besides, each control center (CC) at the transmission and distribution sides communicate with its respective SCADA. Finally, communication between CCs is carried by the ICCP servers at TSO and DSO sides, respectively. In this article, the level of details needed for operational level coordination of TSO and DSO has been evaluated for the use case of reactive power management (see Fig. 4). Specifically, three levels of equivalent distribution network models are compared for their impact on the accuracy of optimal reactive power management (see Figs. 5–7). In addition, the frequency of network and measurement data exchange is characterized in a realistic simulation setup. The laboratory setup represents a cyber-physical system, the TSO and DSO control rooms with their realistic communication infrastructure and protocols. The infrastructure developed for this article follows the topology shown in Fig. 8. Besides, Fig. 8 shows the typical control center infrastructure. A typical CC has cybersecurity, EMS/DMS, database, ICCP, and SCADA servers. Additionally, the SCADA system has the field devices such as IEDs, RTUs, and HMIs. Hence, Fig. 8 shows the link between CCs based on the ICCP servers. In this article, the network model exchange is implemented as CIM models between DSO and TSO. Measurements and control signals are exchanged using the ICCP/TASE 2 protocol between the control centers of the TSO and DSO. The ICCP/TASE 2 implementation follows the minimum requirements in this case. Initially, each system operator defines the bilateral tables (BLT). Each BLT describes the data set used by the TSO and DSO for voltage regulation. A set of BLTs have been developed with Java-script object notation (JSON) files and following the configuration for the ICCP/TASE 2 protocol. At the laboratory setup, DSO and TSO communicate based on client-server links. The ICCP communication has been developed to operate on cyclic strategy, and the exchange of CIM models follow the same principle to keep the models updated. The OPCUA client-server used internally at each control center runs the server in a cyclic iteration in order to synchronize with the ICCP service. Besides, events or changes in the variables at each hour will trigger the database to store the new value used on the TSO or DSO internal communication. The values assigned in the database at the different CCs have a time-stamp that facilitates its access from the different services.

The CPPS-Tb system has links to communicate substations to the control center; where the SCADA computer is connected with the database at each control center. OPF service is part of the ADMS server shown in Fig. 8. Therefore, input values for the OPF are obtained from the database server. A real-time simulator (RTS) OPAL-RT simulates the transmission and distribution power systems with 200 us sampling time. Field values are streamed to the SCADA server with IEC60870-5-104 protocol. IEC61850 is the standard used to carry communications at the substation level. Besides, the setup has an intelligent electronic device (IED) subscribed to the sampled values (SVs) of one of the DSO substation transformers. Hence, the IED is used to reproduce one of the field devices in the laboratory setup.

A CIGRE HV network is used as a TSO system while modified CIGRE MV network is used as a DSO network. Both networks are simulated on OPAL-RT. The optimization functions of the TSO and DSO control rooms are set up on dedicated computers linked with OPC UA and exchanging network models, measurement data, and control signals using CIM and ICCP/TASE 2. Simplified illustration of the laboratory setup is presented in Fig. 4. The TSO and DSO control rooms are represented by dedicated computers with their respective OPF functions, AVEVA SCADA system, and PyCIM implementation.

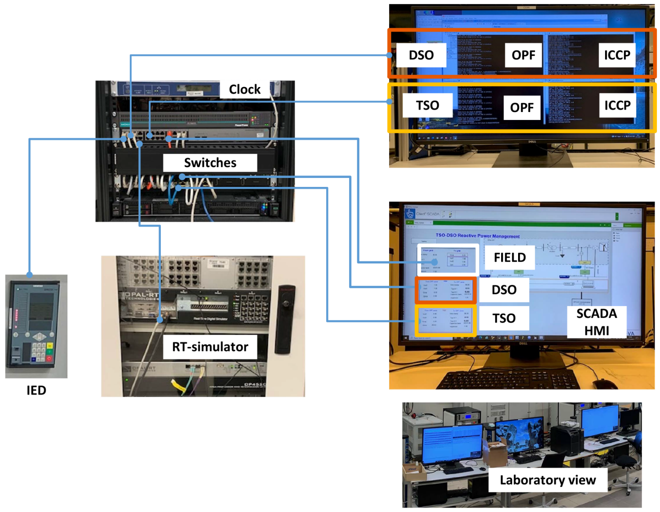

FIGURE 9. TSO-DSO laboratory environment.

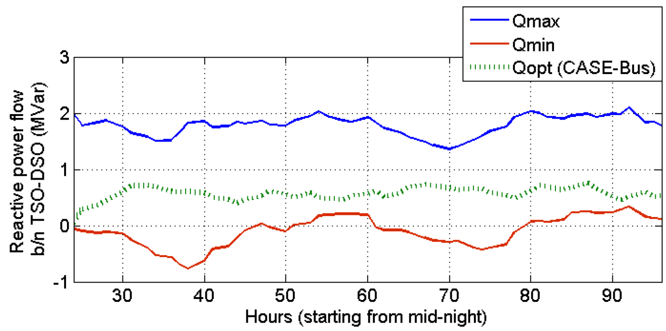

FIGURE 10. TSO-DSO optimal reactive power exchange (MVar).

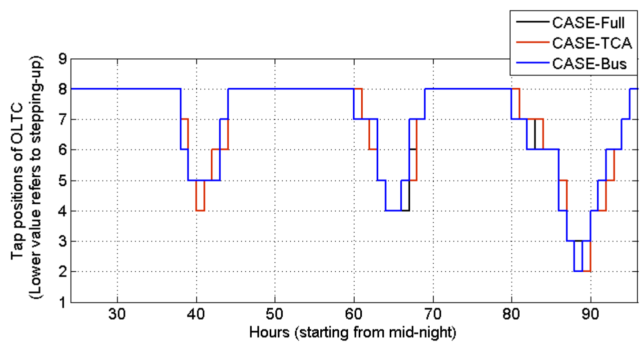

FIGURE 11. OLTC tap positions for the three equivalent grid cases.

VI. RESULTS AND DISCUSSION

Three cases are formulated in accordance with the three equivalent DSO grids illustrated in Figs 5–7. Accordingly, the simulated cases are named as CASE-Full, CASE-TCA, and CASE-Bus.

In this study, the simulation is run using hourly time series load and generation data assuming a perfect forecasting of one hour ahead. The load and generation time series data is prepared using actual measured data and scaled to the levels as specified in the CIGRE HV and MV networks.

Using the physical laboratory setup presented in Fig. 9, the three cases are simulated. Fig. 10 presents the maximum and minimum reactive power exchange capacities between TSO and DSO as evaluated by the DSO control center for each hour. In addition, the optimal reactive power exchange for the CASE-Bus is illustrated as it is evaluated by the TSO control center. As described in the sequence diagram in Fig. 2, optimal reference voltage set-points are calculated for the two OLTCs in the test network, the capacitor bank reactive power set-point in the TSO network and the intercept of the droop characteristics curve of the converter connecting a wind turbine in the distribution network. In Fig. 11, the resulting tap stepping for one of the OLTCs in the test network is presented. One can already notice that there is a difference among the different levels of equivalent grids of the DSO network as seen from the TSO control room. In addition, in Fig. 12, the onload tap changing transformer (OLTC) secondary side voltage is presented as measured from the full power system test network running on the real-time simulator. Hence, one can conclude that the implementation of the full TSO-DSO intercontrol center coordination as depicted in Fig. 9 is functioning as expected.

After running the simulation for period of three days' load and generation profiles for the three cases, the following conclusions are deduced.

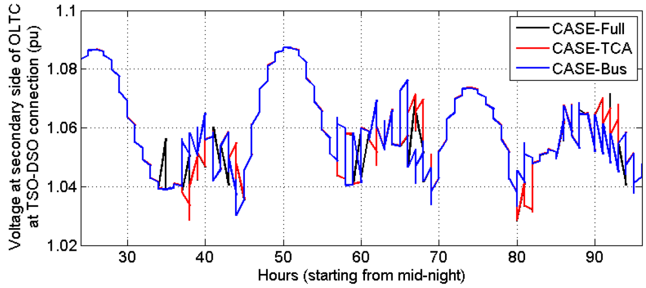

FIGURE 12. Voltage at secondary side of one of the OLTC connecting TSO and DSO.

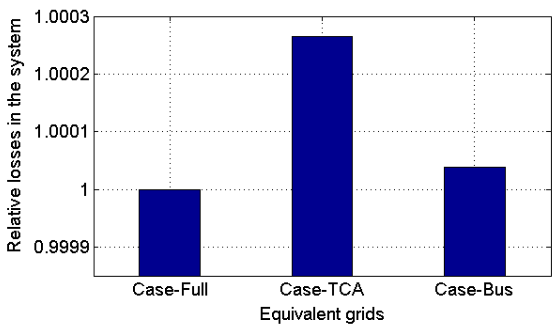

FIGURE 13. Relative total system loss under different regimes of equivalent grids. The reference is the case with full DSO grid model available to TSO.

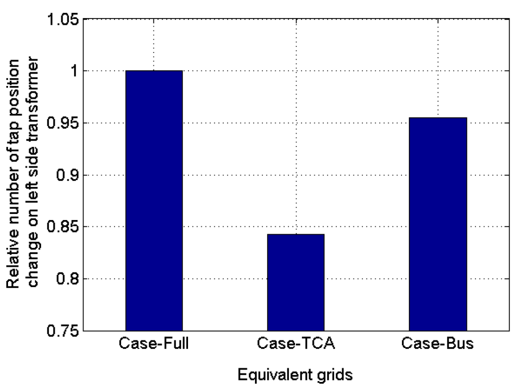

FIGURE 14. Relative number of tap position changes for the left side OLTC.

1) In general, when TSO control centers have the full DSO grid model, the optimally calculated set-points would achieve system-wide loss minimization objective. As illustrated in Fig. 13, the relative losses in both clustered loads model as well as single bus representation are higher than the full grid case. However, for the specific use case the CASE-TCA seems to perform worse than the CASE-Bus.
2) As a natural consequence, when the TSO control room have detailed DSO grid model, the assets at the TSO-DSO connection point as well as the assets in the DSO network have been used more frequently. Fig. 14 shows the number of tap-position changes in a defined period with relative values to the full grid model case.

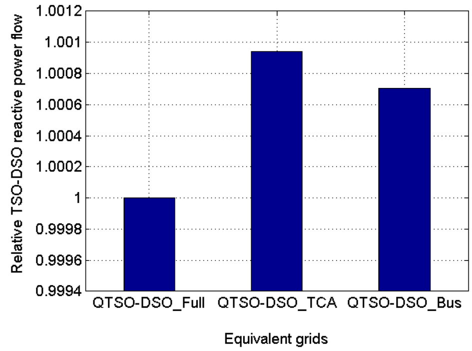

FIGURE 15. Relative reactive power exchange between TSO and DSO.

3) Matching the pattern of the system losses for the three cases, the reactive power exchange between TSO-DSO is recorded the lowest for the full DSO grid case. In Fig. 15, the relative TSO-DSO reactive power exchanges are presented.

To summarize the results show that there is a significant difference in the optimal reactive power exchange depending on the level of information exchange. With respect to the number of tap position changes the difference is smaller, but still notable. The objective of system-wide loss minimization while regulating voltage is given high priority in the simulation. Hence, one can conclude that there is clear value to exchanging more detailed grid models. However, a single bus representation of the DSO grid can also be sufficient for the use case of TSO-DSO reactive power exchange coordination use case. The technologically clustered model where the converter is represented in a separate model to the the rest of load generation mix results in higher losses but fewer tap position changes. This implies that in between simplifications of the DSO grid has to be carried out with utmost care and tailored to the specific case.

In addition, the experiments demonstrate that this can be achieved within the existing CIM specification using a subset of the CGMES together with ICCP. Hence, for this use case there is no need for extension such as those proposed in [2], if we use the pragmatic approach considered here with a periodic exchange of well-defined information elements.

Large power systems, such as the Nordic interconnected system, are characterized by the interconnection of multiple TSOs and hundreds of DSOs under them. In addition, some DSOs may have direct interconnection with each other. Hence, the data exchange paradigm shall be investigated in the view of such complexity where TSO-TSO, TSO-DSO, and DSO-DSO operational data exchange is becoming a routine near-to-real-time operational planning process. The expected challenges include a lack of common data format, lack of established communication infrastructure, data size and integrity, bottlenecks in communication of large amount of data, nonconvergence of optimizations in the operational planning processes, cybersecurity, resource sharing (e.g., DERs for voltage regulation), and interaction with third parties (such as market operators, aggregators, and balance responsible bodies).

VII. CONCLUSION

A test system for a TSO-DSO intercontrol center operational coordination is implemented in a laboratory by using the relevant communication protocols, control center functions, and power system network. The test system is used to investigate the impact of different levels of the DSO network model by the TSO control center for a use case of TSO-DSO coordinated reactive power management.

In the test system, the minimum ICCP/TASE 2 requirements are fulfilled. In addition, CGMES is used for near-real-time operational level network model and data exchange between TSO and DSO. Multiple simulations are run for three equivalent grid models for the DSO network. The results clearly show the advantage of having the full DSO grid knowledge while running optimal power flow-based functions at the TSO control center. However, simplifications should be carried out with a tailored approach for the dynamics considered in specific cases to avoid performance degradation. Otherwise, it can be sufficient to represent the DSO grid as a simplified bus to avoid loss. The use of the CGM model for exchanging different levels of DSO equivalent grids has shown its adequacy for such operational coordination.

Further investigations are needed in terms of scalability for the size of the DSO grid as well as the dimensioning of intercontrol center communication among multiple neighboring TSOs and DSOs. Furthermore, in addition to the voltage regulation use case, other systems services with varying requirement of time resolution and frequency of data exchange need to be studied. In the end, the adequacy of the communication infrastructure for intercontrol center data exchange as well as their vulnerability for cyberattacks require deeper investigation. The laboratory test system encompassing powerful real-time simulators and versatile ICCP implementation will be valuable to carry out such studies in the future.

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MERKEBU ZENEBE DEGEFA received the M.Sc. degree in electrical engineering, in 2010, and the Ph.D. degree in power systems and high-voltage engineering from Aalto University, Espoo, Finland, in 2015.

He is currently a Research Scientist with SINTEF Energy Research, Trondheim, Norway. He has authored more than 50 scientific papers. His research interests include the development of advance operational functions for active distribution systems, laboratory-based testing, the development of ancillary services, and load and flexibility modeling.

HENRIK LUNDKVIST received the M.S. degree in electrical engineering from Linköping University, Linköping, Sweden, in 1998 and the Ph.D. degree in telecommunications from KTH, the Royal Institute of Technology, Stockholm, Sweden, in 2005.

He is currently a Senior Research Scientist atwith SINTEF Digital, Trondheim, Norway. His research interests include communication systems, cyber-physical systems, and smart grids.

SANTIAGO SANCHEZ-ACEVEDO received the B.Sc. and M.Sc. degrees in electrical engineering from the Universidad Tecnológica de Pereira, Pereira, Colombia, in 2006 and 2008, respectively, and the Ph.D. degree in electric power engineering from the Norwegian University of Science and Technology (NTNU), Trondheim, Norway, in 2015.

In 2016, he joined as a Postdoctoral Research Fellow with NTNU, where he was the main academic Researcher in the project CLUDGRID for interoperability of high-voltage dc transmission systems. Since 2019, he has been a Research Scientist with SINTEF Energy Research, Trondheim, Norway, where he is involved in projects regarding power system stability, HVdc transmission systems, laboratory analysis of digital substations, validation of cyber-physical power systems, and cybersecurity.

KRISTOFFER N. GREGERTSEN received the M.Sc. and Ph.D. degrees in engineering cybernetics from the Norwegian University of Science and Technology (NTNU), Trondheim, Norway, in 2008 and 2012, respectively.

He has been with SINTEF Digital, Trondheim, Norway, since 2012, and is currently a Senior Scientist and Research Manager for the Reliable Automation Group. His research interest include embedded real-time systems, communication middleware, cyber-physical systems, robotics, smart grid, and space applications.