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Advancements in Distributed Power Flow Control

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***Abstract*—The use of advanced power flow control functions opens up new possibilities for increasing the capacity of existing grids but also calls for a coordination of different control options enabling effective congestion management. Algorithms for distributed control have been shown to be potentially powerful and efficient in theory and simulations, but many considerations for actual implementation in real grids have been neglected in the past. This is why this paper first breaks down these neglected considerations into seven research questions. To address these questions, the paper then proposes a concept for an agent-based power flow control system, considering a holistic view including necessary hardware components, the control algorithm, monitoring of underlying distribution grids, communication technology and protocols, as well as the interface with the grid operator's control center. The presented system utilizes distributed power flow controllers and flexible power from underlying grids.**

***Index Terms* — Load flow control; Flexible AC transmission systems; Multi-agent systems; Flexible power; Power Systems Operation and Control**

I. Introduction

Due to the increasing substitution of large conventional power plants with Decentralized Energy Resources (DER) power generation is shifting from the transmission to the distribution level. As a result energy is upstreaming from Distribution Grids (DGs) to transmission and Subtransmission Grids (STGs), which subsequently face increasing congestion problems. Today's operational practice is focused on the proactive identification of grid situations in which a simple failure of certain circuits or power plants would lead to unacceptable high loads on other circuits in the grid, so-called violations of (n-1)-security. For preventing such situations, preventive power flow control is required to ensure the system in a secure operational state after being subjected to a fault/disturbance. For this purpose, preventive grid and market-related measures are used almost exclusively. As electrical power systems are commonly operated under the constraint of the (n-1)-criterion, it is evident that not all of the transmission equipment is loaded to its capability limit. For enabling a higher-utilization of existing equipment, operational processes allowing curative congestion management strategies are addressed as substantial research question by industry and grid operators. The application of curative congestion management strategies demands not only the adaption of system operator's decision making processes over all stages from long-term planning over operational planning to operation, but also requires fast and flexible transmission equipment as well as generation and load.

The research project *Impedance Controllers and Decentralized Congestion Management for Autonomous Load Flow Control*[1] (IDEAL) takes into account innovative resources and flexibilities that offer additional degrees of freedom to curatively control power flows. Here, flexibilities describe innovative control options such as Flexible AC Transmission Systems (FACTS) as well as measures that contribute to the flexibilization of load and generation in the overall system. These include products from aggregators or virtual power plants or, for example, demand side management of loads, which are hereinafter subsumed under the term Flexible Power Units (FPUs).

This paper presents the system which is being developed in the course of the aforementioned project, which aims to demonstrate the distributed coordination of power flow control actions for alleviating subtransmission line overloads. The system is conceptualized in a holistic manner in order to bridge the current scientific gap between mere software simulations of decentralized power flow control systems and implementations in real grids. This holistic concept includes the interplay of distributed control algorithms, communication paths and protocols, as well as interactions with the control center. To control power flows, the presented system makes use of Distributed Power Flow Controllers (DPFCs) and FPUs of underlying grids.

The remainder of the paper is structured as follows: Section II gives an overview of related works and a delimitation to the IDEAL project and research questions are derived. This is followed by the description of the methodical approaches used in the IDEAL project in section III. In section IV the concept of the developed agent-based power flow control system is explained in detail. Section V concludes the paper.

[1] Original name in German: *Impedanzregler und Dezentrales Engpassmanagement für Autonome Lastflussregelung*

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II. Related Works, Delimitation and Research Questions

The ongoing development towards a future smart grid pushed innovative technologies like FACTS, high-voltage-direct current lines, virtual power plants, flexible power generation, demand side management, energy storages or overhead line thermal monitoring in the focus of global research and practical applicability. As an innumerable amount of publications propose control schemes for such devices, holistic control concepts incorporating the whole set of power flow coordination possibilities for power system operation from a conceptual, mathematical, operational and technological viewpoint is rare and subject to ongoing research. As research provides promising approaches considering (semi-) automatic coordination systems based on advanced sensing, predictive monitoring and communication technologies, a brief review of selected projects in the course of distributed or autonomous power flow control in the context of the German Energiewende as well as a delimitation to IDEAL and research questions followed in this paper is given.

A. Related Works and Delimitation

The work in [1, 2, 3, 4] combines the expertise of power and communication engineering, statistics and computer science in order to design coherent Wide Area Monitoring, Protection and Control applications based on the latest progress of the disciplines involved. Besides others, decentralized as well as centralized automatic power system monitoring and control functions have been developed in these papers. In contrast to this, the algorithms for power flow control used in IDEAL are not exclusively decentralized or centralized, but complemented to a hybrid structure in which the central entity continuously checks the plausibility and condition of the decentralized control systems and, if necessary, corrects or disables them in last consequence.

The German funding programme Smart Energy Showcases - Digital Agenda for the Energy Transition (SINTEG) aims to set up large-scale showcase regions for developing and demonstrating model solutions that can deliver a secure, efficient and environmentally compatible energy supply with electricity being generated to a large extent from volatile renewable sources. The programme focuses on building smart networks linking up the energy supply and demand sides, and on the use of innovative grid technology and operating strategies. In contrast to SINTEG, IDEAL is taking operational flexibility of active distribution grids into account for curative congestion management purposes that shall be utilized to relieve stressed situations in STGs. Aspects of availability and security of such flexibilities is not in focus of IDEAL, but the coordination of autonomous multi-agents across voltage-levels utilizing such flexibility is strongly focused.

New procedures for grid monitoring and congestion management in the transmission grid in order to better exploit existing transmission capacities and reduce the need for grid expansion in the transmission grid are developed in [5]. In a two-stage process, manual grid operation management will be supported first, followed by mechanisms for fully automated congestion management. This work firstly combines the capabilities of advanced distributed power flow control based on multi-agent technology with supportive tools for power system operators in a control center environment. Here, a MAS-like system was applied for providing control proposals to the control room staff. Therewith decision making in highly stressed power system conditions has been improved. While the cited work elaborates on innovative control functions and assistive tools for prospective congestion management based on simulations, IDEAL is going a step further and implements selected functions in the field and in laboratory environment.

B. Research Questions

As discussed in the outstanding publications of IEEE Power Engineering Society's MAS Working Group [6, 7], several questions and challenges need to be overcome before a distributed power flow control system based on MAS could be applied in practice. On the basis of these questions, a consortium consisting of academics, industrial partners and grid operators are seeking answers to the following questions in the IDEAL project. *(i)* What benefits for power system operation are offered by MAS? *(ii)* What differentiates MAS from existing systems and approaches? *(iii)* To what sort of control problem can MAS be applied and how should agents be coordinated? *(iv)* How should MAS be designed and implemented? *(v)* Are there any special considerations for the application of MAS in power engineering? *(vi)* How can innovative power flow control measures, like DPFC and flexibility from active distribution grids be considered in a MAS based power flow control environment? *(vii)* To which extend should an autonomous MAS be supervised by a central control system with full system observability?

III. Methodical Approach

The IDEAL project aims to address the aforementioned research questions. Our methodical approach for developing an environment in which we can find answers to the formulated questions is described in the following.

A. Distributed Control Algorithm

Today, the setpoints of power flow controlling devices are attuned preventively to avert line overloads before they can occur. The IDEAL project shifts this paradigm by allowing DPFC setpoint combinations which do not need to be secure for every (n-1)-case. This can only be permitted if overloads occurring in a contingency situation can be alleviated immediately. For this a control algorithm is necessary which can quickly determine and adjust setpoints of power flow controlling devices during live grid operation. Using a decentralized control algorithm for this is advantageous for several reasons. First, the calculation of sensitivities the algorithm needs is computationally expensive and can be executed faster by distributing the task onto multiple devices. Second, the algorithm should be robust to disturbances. In a decentralized system the failure of a single unit does not bring the overall system to a halt. Also, if a single unit is isolated from the rest of the system, it may still perform local control actions to ensure security for the grid devices in its immediate surroundings. Third, a distributed system does not necessarily need a full view of the entire grid to perform effectively [8]. A well-researched and effective way of implementing a distributed control algorithm is the use of a MAS. In the IDEAL project the authors build on the foundation set in past projects (cp. section II) in the area of MAS.

B. Control Center

It is of vital importance not only to validate the functional requirements of a multi-agent congestion management standalone system, but also to investigate gaps and challenges between decentral and central controls running in parallel. Therefore, a digital replication of the MAS will be embedded in a state-of-the-art network control system of type PSIcontrol. With this replication functional and non-functional requirements and properties of the MAS-based control will be evaluated and comparatively assessed. Further, the control behavior and capabilities of the MAS will be modeled for central curative optimal power flow (OPF) calculations. Herewith, it will become possible to analyze the impact of a MAS in an open-loop network control system environment. Moreover, visualization and decision-support tools are needed, which give operators a clear and easy to perceive understanding of the MAS' current state and its prospective activities. This enables the acceptance or denial of agents' proposals as well as the possibility to schedule them to perform certain actions or to stop the entire MAS system. As a result, contributions to questions *(i)*, *(iii)*, *(vi)* and *(vii)* can be expected.

C. Communication Technologies and Protocols

The fast response on critical grid conditions highly depends on the availability and reliability of information exchange between DG state estimation, DPFCs, agents and the control center. Therefore, reliable operation of the MAS requires adequate communication technologies. Previous work on FACTS and MAS either did not take communication latency and reliability into account [9] or only on an analytical level and not based on extensive simulative or real-world results of actual communication networks [10].

This work evaluates a holistic communication architecture for the control and regulation of the STG and DG by considering different communication links in real-world scenarios (Fig. 1). The results of the latency and reliability analysis of the different links will be taken into account when analyzing the overall system.

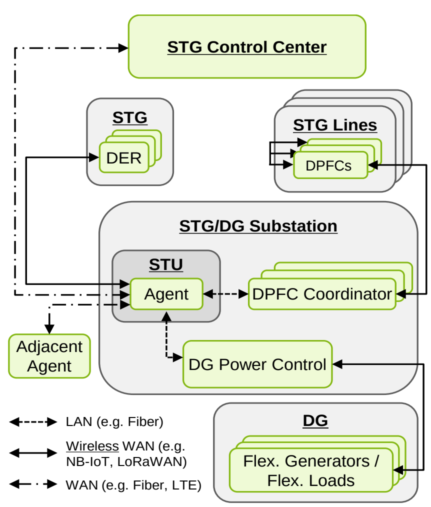

Figure 1: Overview of communication links between system components

D. Distributed Power Flow Controllers

The technology used by the developed MAS for altering the power line reactance consists of a fleet of DPFCs. Each device has the capability of injecting a certain degree of inductance or capacitance into the line. Coordinated control of these devices opens up flexible grid-based control options by shifting power flows according to Ohm's Law when installed in series with the line. The technology has been first introduced in 2006 at Georgia Tech [9]. First field installations were demonstrated in 2012 and 2013 with up to one hundred devices called Distributed Series Reactors (DSRs) [11]. DSRs are mounted directly on the conductors themselves. The DSRs are capable of injecting up to 50 μH of inductance on command and may be switched on sequentially to provide the required level of impedance at any time.

Just recently more powerful models of the DSR-type and a Static Synchronous Series Compensator-type (SSSC) were introduced [12]. The SSSC can alternatingly push power away from the overloaded line or draw power onto a weakly loaded line. By coupling a leading or lagging 90° voltage into the line the SSSC can provide the functionality of a series reactor and a series capacitor. All these devices are installed on the line towers, or are grouped on special towers or support structures at the substation. The modular design of all DPFC models allows rapid installation, customized configuration and grouping as well as re-deployment on other power lines when load conditions alter durably.

All models of DPFCs make use of the same control and communications framework: The DPFCs on a power line are linked among each other by radio remote control and are allocated to a controller interface which communicates via IEC 60870-5-104 protocol with the grid control system. In the course of the IDEAL project the DPFCs are controlled remotely by the MAS. This allows coordinated and rapid changes of line impedances in a meshed grid with many branches.

E. Flexible Power of Underlying Distribution Grids

Flexibility of underlying distribution systems may be used only in cases where DPFCs cannot remove all grid congestions. To determine the flexibility potential of a DG voltage amplitude and voltage angle have to be known precisely. The system state is estimated by a state estimation based on the weighted least square approach considering the partly low observability of typical DGs. Based on the estimated system state injection and load of FPUs are varied simulatively and considering grid restrictions feasible setpoints of the DG are determined. These setpoints will be determined for particular and future times and sent to the responsible agent.

F. Simulation and Demonstration

To answer the research questions mentioned in section II the proposed system components will be tested in different ways. First, the MAS will be tested in a software environment. A dynamic grid simulation executed in DIgSILENT PowerFactory will be coupled with the MAS implemented in Java. By quantifying the performance of the algorithm in this manner and comparing results to centralized control systems, research questions (i)-(iii) can be answered. To address questions (v)-(vii) pure software simulations are not adequate, due to the need to analyze the interplay between the different system parts described in this section. Instead, a power-hardware-in-the-loop simulation will be executed. This type of simulation allows for the coupling of real hardware devices into software simulations. Selected parts of a system can be implemented on hardware which interfaces with the rest of the system remaining in a software environment. This is especially useful for prototype testing of small parts of a very large overall system, such as control devices in a STG. The parts of the overall system to be implemented on hardware are a small number of agents and DPFCs. Different communication technologies between the system components will be tested as well. Additionally, a control center demonstrator will be set up, using PSI hardware components and software. To test the functionality of the algorithm for assessing the flexible power of underlying grids under real conditions, it will be implemented on a hardware device and undergo a field test in a real DG. By providing the grid operator with information about the current degree of flexibility in the grid the authors expect insights into availability and responsiveness of FPUs, as well as the applicability of the algorithm for power flow control.

IV. Concept of the Overall IDEAL System

To address research question (iv) the following section depicts the overall system developed in the IDEAL project connecting the different approaches explained in section III. The IDEAL-system is visualized in Fig. 2. This graphic is structured as follows: the overall system is decomposed into two columns, showing the system's hardware components and the flow of information, and three layers: Control Center, STG and DG. In the bottom layer, two separate exemplary DGs are shown. In the left grid a flexible generator and a flexible load are connected. Another flexible generator is located in the grid on the right. Both DGs are connected to an exemplary STG via transformers. This is a simple meshed grid with four nodes and five lines. To explain the system's functionality the left subtransmission line is assumed to be overloaded.

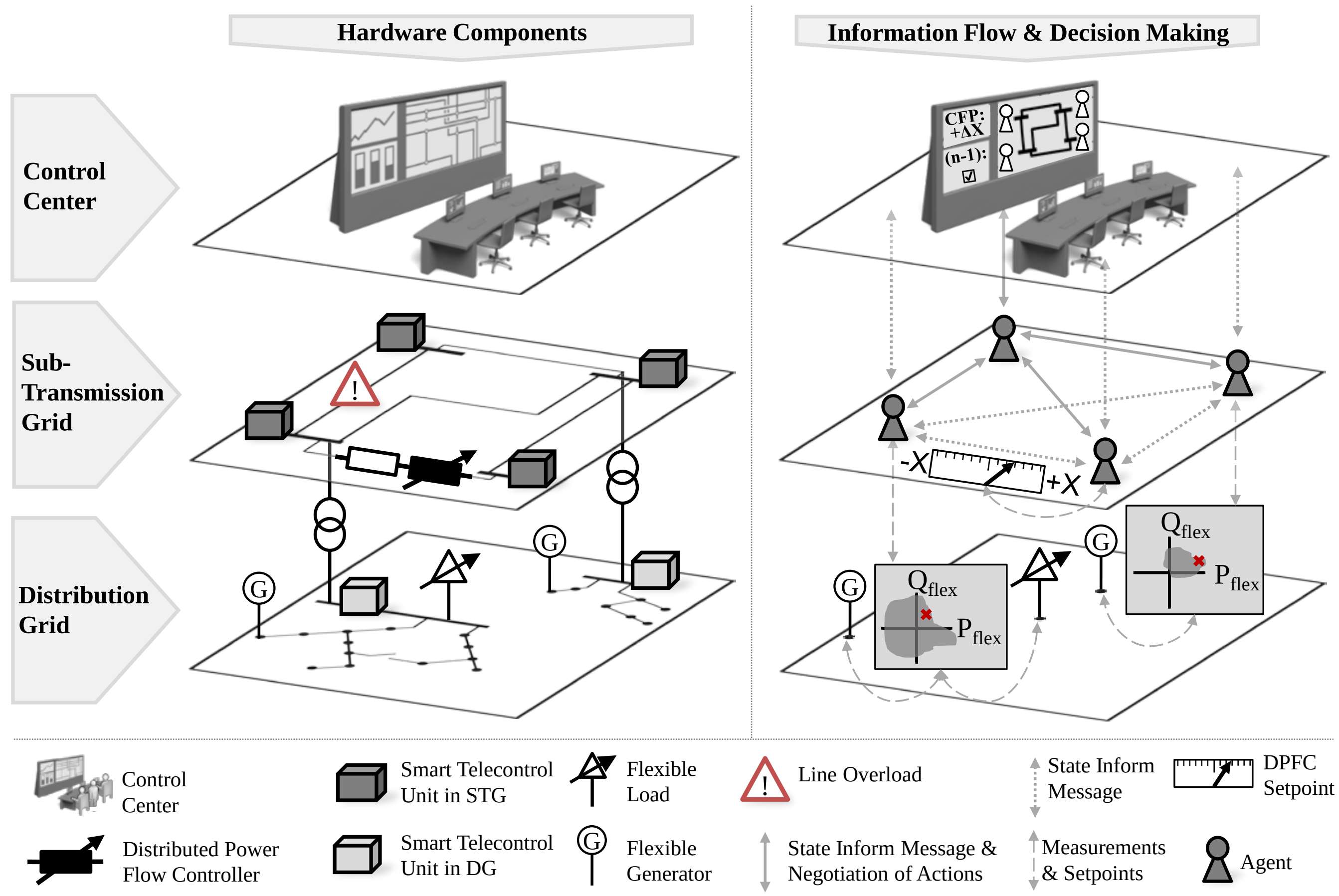

Figure 2: Overview of the System Concept of the IDEAL-Project

A. Hardware Components

For the proposed system, Smart Telecontrol Units (STUs) are installed at every substation: An agent-hosting STU at the subtransmission side, and a STU for carrying out state estimation and analysis of flexible power at the distribution side. These devices can receive and analyze measurements and communicate with other devices. In the shown STG there is a DPFC (or rather a set of DPFCs) installed on the bottom line. As the symbol for the DPFC indicates, this power flow controlling device can only influence the reactance of the line it is installed on. For implementing the proposed system, no additional hardware is needed in the control center, making it easy to integrate the system into existing control center infrastructure. All of this is shown in the left column of Fig. 2.

B. *Information Flow & Decision Making*

In the right column on the bottom layer of Fig. 2 the information flow on the distribution level is depicted. The STU installed at the distribution side of the substation receives data from measuring devices and FPUs in its grid. It analyzes this data and performs a state estimation to determine which combinations of FPU setpoints can be realized without violating any DG restrictions. From this information it derives a range of active and reactive power that can be physically exchanged with the STG and forwards this information to the STU at the subtransmission level. The STU at subtransmission level can order the STU of the underlying DG to signal FPUs to change their setpoint and thus alter the power exchange with the STG accordingly.

At the subtransmission level there is an agent implemented on a STU at every substation. An agent is assigned a set of power lines connected to its substation and any DPFCs connected to these lines. The agents monitor their assigned assets and can change DPFC setpoints. They forward line current and voltage measurements together with the line impedances and ratings to all other agents in the grid and to the control center. This is depicted by the dotted arrow lines in Fig. 2. Each agent performs a topology analysis to derive a grid state. In the example shown in Fig. 2 the line on the left is overloaded. This line is assigned to the top left agent. The agent perceives it as overloaded and sends out a message to all other agents, consisting of the power flow on the line, the line's rating, and a call-for-proposals (CFP) flag. This is shown in Fig. 2 as the full arrow lines. The agents then perform sensitivity analyses to calculate how a change of setpoints of their assigned flexibilities could alleviate the overload (cp. [8, 13]). They propose the results of this analysis to the agent which originally sent out the CFP. This agent then chooses the best proposal, or set of proposals. The MAS can run in two different modes: If the system runs fully autonomously the agent can order the respective agents to execute the chosen proposals. At the same time it informs the control center about this. In semi-autonomous mode the agent proposes the chosen proposals to the control center and only orders the agents to execute, if the control center accepts. The integration of a MAS-based power flow control as well as DPFCs in state of the art control systems requires extensive adjustments in the control center's model database as well as in the process database and SCADA system. For instance, the control capabilities as well as physical properties of new equipment like DPFCs need to be adequately modeled for enabling fundamental grid calculations like state-estimation, power flow calculation, OPF, short-circuit calculation and so on. New picture variables for the supervisory system need to be defined and integrated as well as the innovative control functions need to be harmonized with conventional control measures. Therefore, special parametrization and visualization tools are required. In the following, some preliminary results are highlighted.

For performing grid calculations with new equipment types in the control system, it is imperative to integrate adequate physical models. Since multiple DPFCs may be mounted on each phase of a power line, it may be challenging to supervise the full set of DPFCs in the supervisory system. Line impedance $\underline{Z}_L$ may be changed in a discrete way according to the equation: $\underline{Z}_L = R_L + j \cdot (X_L + i \cdot \Delta x)$. Here, i is the tap position of the controllable reactance Δx of a DPFC. Shunt elements are neglected for simplicity.

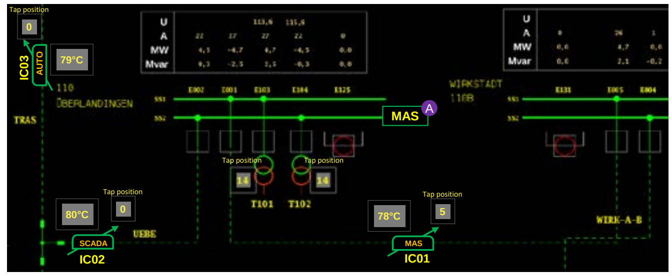

Figure 3: Process visualization of MAS and DPFCs embedded in an exemplary 110 kV grid in PSIcontrol

As each device can increase or decrease a line's reactance discretely, we propose to use an aggregated representation of all the DPFCs' discrete impedance change capabilities in a single substitute. Therewith, condensed information is shown to the operator, while the full detail-depth is considerable in grid calculations. Fig. 3 shows the supervisory process visualization of DPFCs and MAS in SCADA. It should be noted, that both, the MAS as well as the DPFCs may change operational modes. For DPFCs, an automatic [AUTO], a MAS-Controlled [MAS], a SCADA controlled [SCADA], failure [F] or out of operation [OFF] mode is considered. The agents may be in autonomous mode [A], in decision-support mode [S], failure [F] or out of operation [OFF] mode.

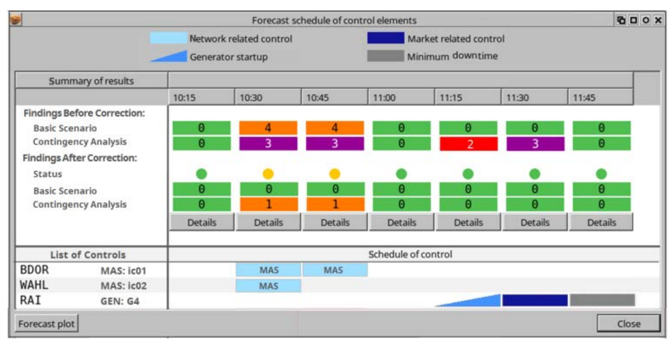

Figure 4: Exemplary Snapshot of Control Actions under Consideration of DPFCs and MAS in PSIcontrol

One goal of IDEAL is to analyze the requirements and prospective advantages of a combined central and MAS-based control. Here, it is expected, that the autonomous control capabilities of MAS may be advantageous to be considered in predictive grid security optimizations, i.e. the MAS-based control of DPFCs is considered as grid-related measures either for optimizing the economic dispatch or curative congestion management. Putting the focus on curative congestion management, the IDEAL-MAS could be preferable to market-based measures due to its low-cost nature. For taking decisions, the operators obviously need a clear visualization of the predictive grid status as well as the proposed measures. Fig. 4 shows exemplary the control schedule of prospective controls. Here, the status and number of violations of operational limits are displayed either before or after executing an appropriate OPF aiming for alleviating such violations. It should be noted, that market-based and grid-based controls are under consideration, while decentral controls by the MAS are highlighted as such.

C. Communication Technology

To ensure a reliable reaction to critical situations in the energy grid, the overall state of the grid must be known. This requires suitable communication technologies and protocols. For the MAS with many decentralized units, a direct connection of these units to the agent (star topology, central approach) via cellular mobile technologies (LTE, NB-IoT) is evaluated. As an alternative to traditional mobile communication, an implementation of proprietary Low Power Wide Area Networks (LPWAN) such as Low Range Wide Area Networks (LoRaWAN) is considered as well, resulting in independence from the reliability of cellular solutions in critical conditions. Another alternative to these two static network topologies are meshed networks. In a meshed network, each node is connected to one or more others. The information is passed from node to node until they reach the destination. A meshed network topology therefore is suitable if long distances must be bridged, but the direct connection of decentralized technical units to a central instance is not feasible.

These three communication approaches will be examined and evaluated based on extensive simulative analysis and real-world deployments using MAS based use cases and established protocols such as IEC 60870-5-104 and the Foundation for Intelligent Physical Agents (FIPA)-protocol. This will result in a validation of applicability in terms of availability and reliability of an agent-based power flow control system. Communication between STU and FPUs will also be implemented using IEC 60870-5-104.

V. Conclusion

This paper derived research questions still largely unanswered by analyzing the current state of the art in distributed power flow control systems. The IDEAL project is expected to deliver insights into these questions, by asserting the effectiveness and efficiency of distributed power flow control systems beyond the mere functionality of the control algorithm. By proposing a holistic concept of the overall system this paper offers answers to question (iv) and ways to address questions (i)-(iii) and (v)-(vii). Concrete answers to these questions will be given in the course of the IDEAL project through simulations, laboratory testing and field tests. The influence of delays due to real communication channels and the interaction with the control center, which is necessary in a real grid, will be quantified. In turn, the adoptions necessary to the control center software will become evident. This way the authors will be able to make suggestions regarding the software representation of MAS as well as DPFCs in the control center. For further insights into question (vi) the authors want to analyze the advantages and disadvantages of various communication technologies for DPFC communication.

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