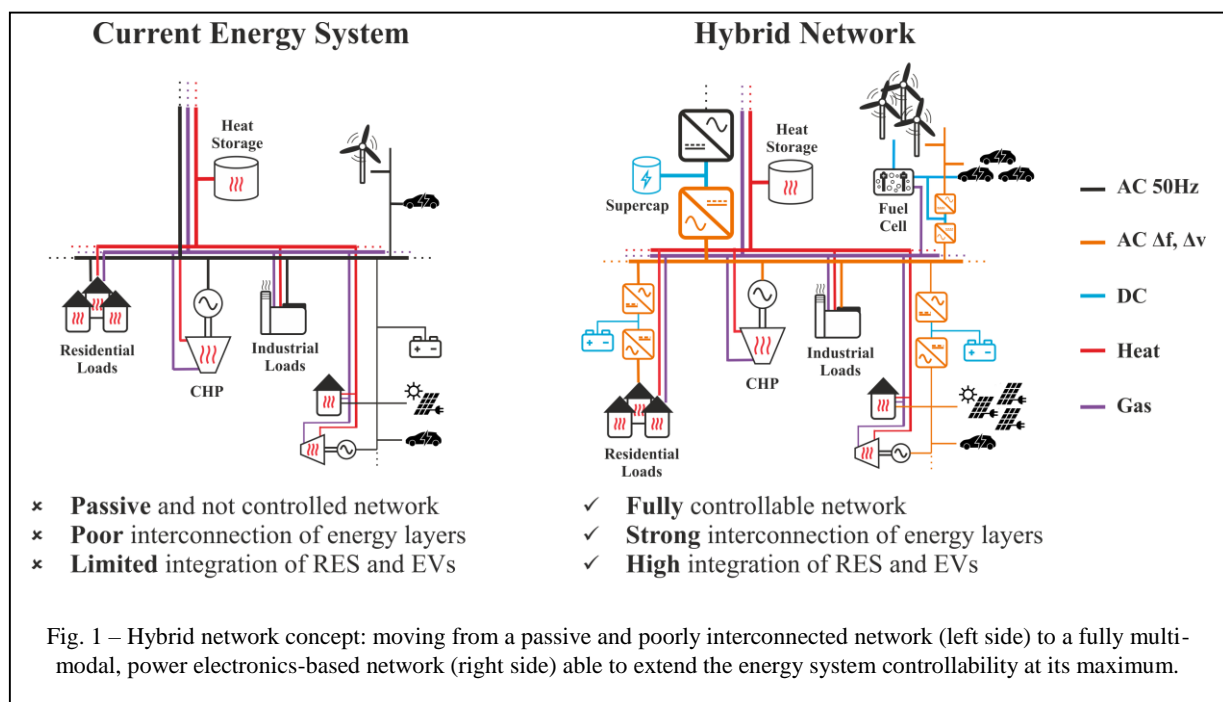# Dr.-Ing. Giovanni De Carne

Helmholtz Young Group Investigator proposal

Hybrid Networks: a multi-modal design for the future energy system

Summary of the proposal:

This Young Investigator Group will develop the Hybrid Network concept. Hybrid Networks, as shown in Fig. 1 on the right side, consist of a close interconnection of multiple energy carriers and are mandatory to balance volatile generation and fluctuating loads. This requires a massive integration of power electronics and control adoption in multi-modal networks. From a passive and poorly interconnected energy system (Fig.1, left side), we will develop a fully interconnected and controllable Hybrid Network (Fig.1, right side). This includes a power electronics-based non-synchronized connection with the main network, that enables a smart control of the fed electrical network, and multi-modal controllers, that permit the coordinated use of more energy layers. This topic fits perfectly to the Helmholtz Program "Energy System Design", where, in the initial external review of the program, it was explicitly requested to think "out-of-the-box", and to focus on cross-sector interactions, on power electronics solutions, and on non-synchronized grids. As a unique experimental setup, a multi-modal hardware in the loop will be realized for the first time to validate the proposed approaches. The main outcome of the project are design guidelines, validated control solutions and several experimental benchmarks for Hybrid Networks. KIT Energy Lab 2.0 is the ideal laboratory for this investigation because of the existing multi modal energy infrastructure including a 1 MVA PHIL Lab and many other technologies for sector coupling. Two major industrial players in this area, OPAL-RT Technologies Inc. and MR Maschinenfabrik Reinhausen GmbH, have ensured their support in the project, that shows a strong industrial interest in the proposal.

Fig. 1 – Hybrid network concept: moving from a passive and poorly interconnected network (left side) to a fully multi-modal, power electronics-based network (right side) able to extend the energy system controllability at its maximum.

Index

1. Research Goals and Expected Outcomes

Currently, the energy system operators are looking for higher controllability. Due to the increased power variability introduced by renewables in the electrical layer, the operators are in need for multi-modal energy solutions. Interconnecting different energy layers allows to shift the energy between layers and store it in different energy forms. As an example, power-to-gas plants, connecting the electrical and gas networks, have been considered as an optimal solution for long-term storage, while the installation of thermal energy storage systems between the electrical and heating networks is seen as medium-term (i.e, days) storage solution. Electrical storage or direct load control can enhance further the system controllability, offering fast dynamics energy provision for hours and minutes, respectively. However, a comprehensive energy system design that includes, coordinates and optimizes all the aforementioned technologies together with the control potential of power electronics is currently missing.

This Young Investigator Group aims to develop the Hybrid Networks concept (Fig. 1), to design, build, operate, and experimentally validate multi-modal energy systems. The Hybrid Network comprises a power electronics-based network areas decoupling, i.e. no longer synchronous with the mains, and multi-modal controllers, that permit the coordinated use of more energy layers (e.g., gas, heating networks). The novelty introduced by this Young Investigator Group consists in increasing the system controllability by combining power electronics-based advanced features, such as the voltage/frequency control of non-synchronized networks, together with high-energy multi-modal components, and by validating the proposed solutions by means of a novel multi-modal hardware testing introduced in this proposal.

Such ambition research goals require a research environment with multiple backgrounds and large research infrastructure. For this reason, this project fits perfectly in research facilities such as the Karlsruhe Institute of Technology and programs such as "Energy System Design" of the Helmholtz Association. The newly developed Energy Lab 2.0 infrastructure, with the presence of several multi-modal resources (gas turbines, fuel cells, electrolyzers, multi-modal houses "Living Labs") and the large real time simulation and power hardware in the loop testing facilities, represent the perfect environment to perform the research activities of this proposal. Furthermore, the involved institutes in the Energy Lab 2.0 (see Section 3 for more details) can offer a large knowledge spectrum, from system to component, from modelling to control layers, that can elevate the research at top-notch levels.

Considering the need to address in comprehensive way the modelling, control, protection and experimental validation of Hybrid Networks, this Young Investigator Group proposal is organized using a *5S* framework:

S1. **System integration in real time**: to understand the potential for Hybrid Networks in future energy systems, the modelling of their multi-modal components is of vital importance. The use of digital real time systems helps the understanding of the real system dynamics, giving the possibility to interface real hardware with realistic simulated conditions. This Young Investigator Group will develop an optimized modelling approach of multi-modal Hybrid Networks components, focusing on the trade-off between the computational time constraints of real time simulators and accuracy of the models with respect the real devices. To underline the importance of this topic, industrial (OPAL-RT) and academic (Prof. Benigni – FZ Jülich) cooperation have been set, in order to perform top-notch research in the field.

S2. **Smart control**: the increased power variability, caused by intermittent energy producers like renewables, and the need for interfacing energy layers of different nature (e.g., electricity, heat, and gas) calls for smart control strategies able to optimize the energy system as a whole. This Young Investigator Group will propose innovative smart control approaches, based on the advanced power electronics capability and their interactions with multi-modal resources (e.g., gas and heat networks). The Hybrid Network, not anymore a passive component, but a fully controllable resource, will be able to provide network services, such as primary frequency control, to enhance the system stability.

S3. **Safe operations**: non-synchronized networks can ensure high safety standards to the connected loads. The fast dynamic power controllability of the converters enables to clear faults faster than any mechanical actuators. Despite these advantages, the power electronics cannot provide full fault current to let the classical protection system operate properly, representing a bottleneck for the implementation of these networks. This Young Investigator Group will investigate the future protection requirements for non-synchronized networks, and introduce flexible power electronics-based protection strategies, to guarantee, and eventually to increase, the electrical system safety. This topic, of great interest for industry, due to the large-scale market potential of non-synchronized networks, will be addressed in cooperation with Maschinenfabrik Reinhausen, a well-known manufacturer of grid-forming converters.

S4. **Sector-coupling energy solutions**: higher power variability by the increasing share of renewables requires faster and larger energy reserves for an extended time window. While electrochemical storage or load control offers fast response to power unbalances, they have limited energy availability. The use of sector coupling solutions can help to overcome this limitation, offering energy for longer time windows. This Young Investigator Group will develop new energy control strategies, that in coordination with the Hybrid Network power electronics, will coordinate the multi-modal resources in different energy layer (e.g., fuel cells, electrolyzers), guaranteeing a variety of services (e.g., secondary and tertiary voltage/frequency control), under a larger spectrum of dynamics (from minutes to days).

S5. **System validation**: a key factor in developing and commercializing new technologies is the validation of their performance in realistic grid conditions. However, field tests are constrained by the possible impact on system customers, and simulations may not be always accurate. The Power Hardware In the Loop system enables the laboratory testing of new technologies in realistic conditions, coupling

the hardware under test with large-scale simulated networks by means of a power amplifier. This Young Investigator Group will introduce a new multi-modal hardware in the loop testing approach, involving in the test not only the single electrical layer, like in the current state of art, but also the heating and gas energy layers. This setup, one-of-a-kind, will enable the performance assessment of multi-modal components (e.g., gas turbines or Living Labs, see description of Energy Lab 2.0 in Section 3) in a more realistic way. Starting from the large testing facility of the Energy Lab 2.0, with a 1 MVA power hardware in the loop setup, new interface algorithms will be introduced to guarantee stable and accurate testing of multi-modal components.

Up to now, researchers have considered these "*S*" aspects singularly, or matching them in coupling at time, in order to reduce the complexity of the problem (see Literature review in Section 4). However, this choice leaves out a comprehensive view of the Hybrid Networks potential, limiting the understanding of Hybrid Networks benefit for the future energy systems. In this proposal we target to consider all the aforementioned "*S*" aspects, and, thus, to develop models, control algorithms, protection strategies, and experimental validation approaches that will help the integration of Hybrid Networks in the energy systems. To achieve our goal, this work is structured in 5 work packages:

1. **Real time modelling of Hybrid Networks**, targeting a realistic evaluation of multi-modal system performances.
2. **Smart demand control**, that can transform the Hybrid Networks in fully controllable resources.
3. **Hybrid network protection** strategies for Hybrid Networks, that can guarantee fast and safe handling of fault scenarios.
4. **Sector-coupled energy solutions**, able to guarantee the energy independency of Hybrid Networks, providing energy services in the large spectrum of dynamics.
5. **Multi-modal hardware in loop systems**, offering the testing of hardware under several energy layers and the validation of new control solutions in realistic networks.

The expected outcomes target 4 different groups (see also the Communication Plan in Section 7.3):

- **Researchers**: can receive new inputs and ideas from the "out of box" strategies developed during the project. The development of strategies that transform the network in a fully-controllable resource can pave the way to consider any grid device as controllable and fully exploitable. New protection strategies will support a larger integration of non-synchronized networks, such as islanded microgrids. New stability and accuracy analysis methods for power hardware in loop system will enable a faster and safer performance evaluation for hardware testing. The libraries, models, and strategies developed in this project will be made available to the public, under open-source software form, giving the possibility to future young researchers to use them as starting point of their research.
- **Manufacturers**: benefit from the investigation of Hybrid Networks component requirements and control possibilities, that can be transferred to any of their commercial products. The gained power hardware in the loop experience will support the industry needs for more complete and accurate system analysis of their components. Consultancies for stable and accurate power hardware in loop setups will be provided from the knowledge developed in this project.
- **Network operators**: can understand the increased control capability derived from the Hybrid Network concept to improve the network management, avoiding large network infrastructure replacement (e.g., new cables or substations). Starting from the outcomes of this project, further pilot projects can be planned to implement the Hybrid Networks concept at distribution system level. Single solutions developed within the Hybrid Networks framework can be separately employed to optimize the current energy system infrastructure.
- **General public**: transparent representation of the results for general public can increase the awareness of the Hybrid Networks contribution in the energy change. Open to public showcases, participation of national and international conferences and fair, and real lab demonstration will help the understanding of the Hybrid Networks benefit to non-specialized public.

2. Relation to Helmholtz Mission and Programme

This Young Investigator Group proposal directly contributes in the Helmholtz program Energy System Design[1], realized in the Research Field "Energy" and set to start in 2021, in the Topic 2 "Digitalization and System Technology".

The goal of the Helmholtz program "Energy System Design" is to "*tackle key energy system design challenges for the energy transition in Germany and worldwide*"[1]. In particular, as highlighted in the first notification of the program, "*the topic 2 team is also encouraged to thing radical and "out of the box", e.g. impact of power electronics / non synchronized grids, DC grids, etc…*", that, revolutionizing the common practice, can address the questions on how to operate future energy systems. These solutions, based on power electronics control, non-synchronized grids, and sector-coupling will be addressed in this Young Investigator Group proposal. This proposal will directly follow the "Energy System Design" program indication in developing ambitious research programs that analyses the future interactions of individual technologies from a systemic standpoint.

As the Topic 2 aims to "*develop models, methods and tools for optimization-based design, scheduling and control of energy systems and demonstrate the technical feasibility of different hardware and software solutions in smart energy system labs (e.g. Energy Lab 2.0 at the KIT,[…])*", this Young Investigator Group proposal will introduce new network architectures (non-synchronized and power electronics-based), new control and protection strategies (flexible and multi-objected oriented), and new realistic testing procedures (inclusive of more energy layers). This project fills the knowledge gap in Topic 2, introducing new energy control solutions and system technologies that have to be tested in "close-to-real-word environments", such as the Energy Lab 2.0 at KIT.

This project is built on my previous research experience (see Section 4.1), to perform cutting-edge research with potentially high scientific impact, which is particularly fitting with the Helmholtz Research programme. The goal of this Young Investigator Group is to claim a leading global position in the future energy systems design, contributing significantly to the success of the energy system transformation. The results are expected to have a strong impact also at industrial level. Considering the interest of industrial partners (see attached letter of interests), like OPAL-RT in the real time modelling and in the stability analysis tools for power hardware in the loop systems, and Maschinenfabrik Reinhausen in the development of future protections strategies for non-synchronized networks, the technology transfer of the project outcomes to industrial solutions is already considered and planned.

The Young Investigator Group will address the comprehensive future energy system design, that includes the integration and modelling of future hybrid energy networks (Work Package 1), advanced control (Work Package 2), protection (Work Package 3), and energy management (Work Package 4) solutions, to achieve a smooth shift towards greener energy supply and consumption. Important focus of this Young Investigator Group is the full-size validation of multi-modal approaches in laboratory (Work Package 5), by means of a multi-modal hardware in loop, unique in its kind and of strategic importance within the "Energy System Design" program.

3. Relation to Research Programme of ITEP and KIT

The Young Investigator Group is planned to be established at the Institute for Technical Physics (ITEP) at the Karlsruhe Institute of Technology (KIT). The group will work closely with several institutes of KIT, in particular with Prof. Veit Hagenmeyer at the Institute of Applied Informatics (IAI), due to the existing close collaboration within the Energy Lab 2.0 framework. Further collaborations are planned with the Institute of Electrical Engineering (ETI – Prof. Marc Hiller), the Institute of Electric Energy Systems and High-Voltage Technology (IEH – Prof. Thomas Leibfried), and Institute for Micro Process Engineering (IMVT – Prof. Roland Dittmeyer). The involvement of these five institutes, with a large variety of backgrounds and know-how, is the ideal condition to tackle such inter-disciplinary research

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[1] Proposal for the Helmholtz Research Program – Energy System Design (ESD) 2021-2027.

project. This collaboration is further strengthened in common projects: Energy System 2050 Helmholtz Initiative, that targets holistic solutions for managing the energy transition in the future German grid; the BMBF-funded Kopernikus Project ENSURE (new energy network structures for the energy transition); the Energy Lab 2.0 project, that aims to study, develop and test the components of the future energy systems. Of particular interest for this proposal, the Energy Lab 2.0 offers a large set of experimental facilities (3 multi-modal buildings "Living Labs", 1.5MW Lithium-ion and 900kW Redox Flow batteries, 1MVA photovoltaic power plant, the industrial Bioliq facility, a combined fuel cell-electrolyser system, 3kW and 100kW gas turbines). In the Energy Lab frame, the work group, that I scientifically coordinate, has recently brought in operation a 1MVA power hardware in the loop setup, that offers a flexible component-testing platform for research institutes, grid operators and industries. I have currently applied as early stage principal investigator for a DFG Graduate School proposal "Energy Status Data", aiming at the integration and exploitation of the data analysis in the electrical network. The project has received an initial positive evaluation, with a final evaluation in May 2020. The details of these collaborations with KIT and other research/industrial partners are described in Section 7.

The KIT Department for Electrical Engineering and Information Technology offers a wide research spectrum in designing, control and development of energy technologies, including power electronics and sector-coupling, and their applications. I will promptly apply to become a KIT Associate Fellow of the Department, to be able to supervise doctoral students and participate in their evaluation. In addition, I will offer in the winter semester 2020 the course "Energy Storage and Network Integration" for electrical engineering students, introducing storage technologies and their integration in energy systems.

4. Current Status of Research

The goal of the "Energy System Design" program of the Helmholtz is to create a future energy system that is defossilized, decentralized, digital and diverse. This goal can be met with a clear shift of the energy production, from centralized and fuel-based to decentralized and renewable-based energy sources. Like in the German case, the renewable power production is able to cover up to 38% of the consumed power[2], making a first step to the desired "energy transformation" or "Energiewende". In addition, pushed by the decreasing costs of battery energy storage and the need for pollution reduction in urban districts, the electrification of the transportation system is exponentially intensifying. Starting from private cars and moving up to heavy trucks, it aims in the next years to reach 35% of vehicles sales by 2030[3]. The fast integration of these resources has, however, impacted on the existing energy system. It has been originally thought for centralized and scheduled production, shifting towards a distributed and intermittent power production direction[4]. Germany is a perfect example of this change. Increasing the share of RES and phasing out nuclear and coal power plants, the system inertia, defined as the ability of a system to oppose changes in frequency due to resistance provided by kinetic energy of rotating masses, strongly decreased in the last years. This will lead to larger frequency deviations during power imbalances[5]. In an ENTSO-E study on Nordic countries, it has been foreseen that the inertia may drop down of 18% with respect to 2020 values in just 5 years, endangering the system stability[6].

To accommodate the largest amount of greener resources, new control solutions have to be proposed, thinking not only to marginal technological upgrades but to a complete redesign of the future energy system. The achievement of the new future energy system designs passes through 5 fundamental points: **model**, **control**, **couple**, **protect**, and **validate** the future energy systems. This section organizes the current state of art around the 5S approach described in Section 1.

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[2] Umweltbundsamt "Erneuerbare Energien in Deutschland – Daten zur Entwicklung im Jahr 2018", Februar 2018, in German.
[3] ENTSO-E, "Power Facts, Europe 2019".
[4] P. P. Barker and R. W. De Mello, "Determining the impact of distributed generation on power systems. I. Radial distribution systems," 2000 Power Engineering Society Summer Meeting, Seattle, WA, 2000, pp. 1645-1656 vol. 3.
[5] A. Ulbig, T. S. Borsche, and G. Andersson, "Impact of Low Rotational Inertia on Power System Stability and Operation", IFAC Proceedings Volumes, vol. 47, no. 3, pp. 7290-7297, 2014.
[6] ENTSO-E, „Future system inertia".

Real Time modelling of future energy system: Modelling and analysing the future energy systems in real time allows a realistic evaluation of the components performance. The current state of art in modelling energy systems sees two main directions. The first focuses on developing electrical components models for real time systems applications[7,8]. The goal is to achieve good accuracy with respect to real systems, keeping low the needed computation time. The second direction is instead to develop complex, large multi-modal networks in simulation[9,10], or co-simulation[11] environments. While the first direction allows to simulate in real time more complex and accurate electrical devices (like the case of multilevel modular converters for HVDC applications[8]), it misses still their counterparts in the other energy layers, such as the heating and gas networks. In the second direction, work has been done to include this modelling in the optimal power flow problems[10,12], but still few has been done for the modelling of these energy layers in real time simulators for dynamic purpose.

To my personal knowledge, no (or little) effort has been done to implement multi-modal networks in real time simulators.

Smart demand control: employing the electric load to control the grid is an attractive solution. Its geographical distribution and the overall energy handled makes it a perfect resource to substitute (or at least support) the conventional generation-based approaches[13]. The control is usually performed via communication, aiming to increase the system controllability for voltage[14] or frequency[15,16] control purpose. However, in the proposed approaches, only the electrical layer of the network is considered, avoiding to address innovative control solutions offered by power electronics. In the last years, the attention has moved to multi-physics demand control[3]. In particular, the **Sector Coupling** offers the possibility of shifting and storing energy among electrical and other energy layers (e.g., heat, gas)[10] to target grid situations with high penetration of renewables[17,18,19]. As example, an optimal use of Power-to-Gas allows an 85% integration of renewables in a German scenario[20], and cost savings deriving from full use of wind energy and reduction of electrical congestions[12].

[7] W. Li and J. Bélanger, "An Equivalent Circuit Method for Modelling and Simulation of Modular Multilevel Converters in Real-Time HIL Test Bench," in *IEEE Transactions on Power Delivery*, vol. 31, no. 5, pp. 2401-2409, Oct. 2016.

[8] K. Ou *et al.*, "MMC-HVDC Simulation and Testing Based on Real-Time Digital Simulator and Physical Control System," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 2, no. 4, pp. 1109-1116, Dec. 2014.

[9] X. Chen *et al.*, "Increasing the Flexibility of Combined Heat and Power for Wind Power Integration in China: Modeling and Implications," in *IEEE Transactions on Power Systems*, vol. 30, no. 4, pp. 1848-1857, July 2015.

[10] P. Mancarella, "MES (multi-energy systems): An overview of concepts and evaluation models", Energy, vol. 65, pp. 1-17, Feb. 2014.

[11] S. R. Drauz, C. Spalthoff, M. Würtenberg, T. M. Kneikse and M. Braun, "A modular approach for co-simulations of integrated multi-energy systems: Coupling multi-energy grids in existing environments of grid planning & operation tools" *2018 Workshop on Modeling and Simulation of Cyber-Physical Energy Systems (MSCPES)*, Porto, 2018, pp. 1-6.

[12] S. Clegg and P. Mancarella, "Integrated Modeling and Assessment of the Operational Impact of Power-to-Gas (P2G) on Electrical and Gas Transmission Networks," in *IEEE Transactions on Sustainable Energy*, vol. 6, no. 4, pp. 1234-1244, Oct. 2015.

[13] D. S. Callaway and I. A. Hiskens, "Achieving Controllability of Electric Loads," in *Proceedings of the IEEE*, vol. 99, no. 1, pp. 184-199, Jan. 2011.

[14] K. Christakou, D. Tomozei, M. Bahramipanah, J. Le Boudec and M. Paolone, "Primary Voltage Control in Active Distribution Networks via Broadcast Signals: The Case of Distributed Storage," in *IEEE Transactions on Smart Grid*, vol. 5, no. 5, pp. 2314-2325, Sept. 2014.

[15] C. Zhao, U. Topcu and S. H. Low, "Optimal Load Control via Frequency Measurement and Neighborhood Area Communication," in *IEEE Transactions on Power Systems*, vol. 28, no. 4, pp. 3576-3587, Nov. 2013.

[16] K. Samarakoon, J. Ekanayake and N. Jenkins, "Investigation of Domestic Load Control to Provide Primary Frequency Response Using Smart Meters," in *IEEE Transactions on Smart Grid*, vol. 3, no. 1, pp. 282-292, March 2012.

[17] D. Böttger, M. Götz, M. Theofilidi, T. Bruckner, "Control power provision with power-to-heat plants in systems with high shares of renewable energy sources", Energy, vol. 82, pp. 157-167, Mar. 2015.

[18] T. Nuytten, B. Claessens, K. Paredis, J. Van Bael, D. Six, "Flexibility of a combined heat and power system with thermal energy storage for district heating", Applied Energy, vol. 104, pp. 583-591, Apr. 2013.

[19] A. Sternberg, A. Bardow, "Power-to-what? – Environmental assessment of energy storage systems", Energy Environmental Science, vol. 8, pp 389-400, 2015.

[20] M. Jentsch, T. Trost, M. Sterner, "Optimal Use of Power-to- Gas Energy Storage Systems in a 85% Renewable Energy Scenario", Energy Procedia, vol. 46, pp. 254-261, 2014.

Currently, only limited investigation of control approaches has been developed on coordinating load control and the sector-coupling to increase the system controllability on a wide spectrum of dynamics.

Network safe operations: with the introduction of distributed generators, the protection strategies have been revised in the electrical networks to cope with new challenges[4]: higher short circuit levels, reverse power flow, and false tripping are only some of them[21,22]. In the last years, with the introduction of the electrically decoupled networks, such as Smart Transformers[23,24] and Islanded microgrids[25,22], the protection concept is again under scrutiny. The grid-forming converter, that forms the voltage in these networks, is also the main source of short circuit current during faults[25]. However, as semiconductor-based device, its limited short circuit current contribution cannot be compared with the traditional AC connections, leaving open questions on the management of these grids under grid faults. Classical breakers, that are dependent on high current thresholds to open the circuit, cannot operate rapidly if these current levels are not met, while fuses do not represent a feasible solution for a fully digitalized and electronic-based energy system. Currently, a IEC working group SC 8B on "Microgrids – Part 3-1: Technical requirements – Protection and dynamic control[26]", where I am member, is working on protection settings in non-synchronized networks, writing a IEC recommendation report. However, this report is still at guideline level, leaving outside technical details on the protection requirements for grid-forming converters.

Concluding, the protection problem for non-synchronized networks and grid-forming converters is addressed only at conceptual level, without giving clear indication on how to manage the protection system under lower short circuit current.

Full-scale power hardware in loop validation: real time simulators are rapidly growing in these years, both in hardware, with increased computational capability, and software, offering new electrical component models, such as the multilevel modular converters[8]. In particularly, the power hardware in loop applications are spreading in academia and industry, due to the advanced feature to validate any electrical device performance in realistic simulated environment[27,28]. As mentioned in a large amount of publications, the stability of these loops is a source of concerns for engineers[29,30,31,32]: measurement delays, power amplifier response time, and transfer function ratio between software and hardware part have been found to be cause of stability issues. Several algorithms have been developed to improve the

[21] R. C. Dugan and T. E. McDermott, "Distributed generation," in *IEEE Industry Applications Magazine*, vol. 8, no. 2, pp. 19-25, March-April 2002.

[22] H. Nikkhajoei and R. H. Lasseter, "Microgrid Protection," *2007 IEEE Power Engineering Society General Meeting*, Tampa, FL, 2007, pp. 1-6.

[23] G. De Carne, M. Langwasser, R. Zhu and M. Liserre, "Smart Transformer-Based Single Phase-To-Neutral Fault Management," in *IEEE Transactions on Power Delivery*, vol. 34, no. 3, pp. 1049-1059, June 2019.

[24] R. Zhu and M. Liserre, "Control of Smart Transformer Under Single-Phase to Ground Fault Condition," in *IEEE Transactions on Power Electronics*, vol. 35, no. 2, pp. 2034-2043, Feb. 2020.

[25] A. Gkountaras, S. Dieckerhoff and T. Sezi, "Evaluation of current limiting methods for grid forming inverters in medium voltage microgrids," *2015 IEEE Energy Conversion Congress and Exposition (ECCE)*, Montreal, QC, 2015, pp. 1223-1230.

[26] IEC SC 8B – Decentralized Electrical Energy Systems, "Microgrids – Part 3-1: Technical requirements – Protection and dynamic control", proposed stability date 2023.

[27] G. F. Lauss, M. O. Faruque, K. Schoder, C. Dufour, A. Viehweider and J. Langston, "Characteristics and Design of Power Hardware-in-the-Loop Simulations for Electrical Power Systems," in *IEEE Transactions on Industrial Electronics*, vol. 63, no. 1, pp. 406-417, Jan. 2016.

[28] C. S. Edrington, M. Steurer, J. Langston, T. El-Mezyani and K. Schoder, "Role of Power Hardware in the Loop in Modeling and Simulation for Experimentation in Power and Energy Systems," in *Proceedings of the IEEE*, vol. 103, no. 12, pp. 2401-2409, Dec. 2015

[29] W. Ren, M. Steurer and T. L. Baldwin, "Improve the Stability and the Accuracy of Power Hardware-in-the-Loop Simulation by Selecting Appropriate Interface Algorithms," in *IEEE Transactions on Industry Applications*, vol. 44, no. 4, pp. 1286-1294, July-aug. 2008.

[30] I. D. Yoo and A. M. Gole, "Compensating for Interface Equipment Limitations to Improve Simulation Accuracy of Real-Time Power Hardware In Loop Simulation," in *IEEE Transactions on Power Delivery*, vol. 27, no. 3, pp. 1284-1291, July 2012.

[31] S. Lentijo, S. D'Arco and A. Monti, "Comparing the Dynamic Performances of Power Hardware-in-the-Loop Interfaces," in *IEEE Transactions on Industrial Electronics*, vol. 57, no. 4, pp. 1195-1207, April 2010.

[32] G. Lauss and K. Strunz, "Multirate Partitioning Interface for Enhanced Stability of Power Hardware-in-the-Loop Real-Time Simulation," in IEEE Transactions on Industrial Electronics, vol. 66, no. 1, pp. 595-605, Jan. 2019.

system stability and the accuracy in reproducing in hardware the simulated phenomena[27,28,29]. However, as can be noted from Fig. 2, where the power hardware in the loop setup power is related to the simulated network size (in terms of bus number), the existing works refer to simplified cases, where the hardware is a simple impedance, and the validation is performed with low-power setups[33,34,35]. These conditions lead to not realistic evaluations, particularly where the hardware is a power electronics converter of at least hundreds of kilowatt [36,37,38], or the simulated grid involves thousands of nodes[39].

Currently, the performance and the stability of hundreds kilowatt-range power hardware in loop systems have not been investigated. Furthermore, at my personal knowledge, the possibility to interface more energy layers to a real-time simulated network (i.e., a multi-modal hardware in loop system) has been barely considered, leaving uncovered a large spectrum of questions regarding power interface technology, accuracy, and stability of such systems, where more energy layers are involved.
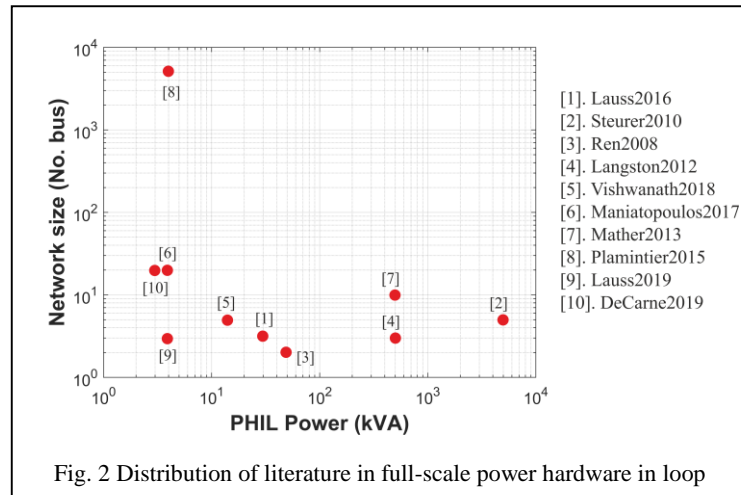

Fig. 2 Distribution of literature in full-scale power hardware in loop

4.1. Previous relevant work of Dr. De Carne

My research background covers a large variety of aspects of the network modelling, control, protection and experimental validation, focusing particularly on new power electronics-based technologies, and it is built on important industrial work (projects and patents).

During my PhD, I focused on integrating a new (and possible breakthrough) network technology, that is the Smart Transformer[40], a low/medium voltage power electronics-based transformer. In particular, I addressed the system level control features that it can offer, like the possibility to evaluate how the load consumption varies under different voltage and frequency values [J18] (see attached list of publications for reference), and use this information to shape the load consumption and provide services to the grid: soft load reduction [J11], that is an alternative to firm load shedding; reverse power flow control [J10][J16], that limits the impact of renewables on the voltage profile; overload control [J15], that avoids dangerous hardware overload conditions; primary frequency regulation [J6], that supports the generators during large frequency deviations; dynamic fault management [J5], that reduces the impact of single-phase faults in Smart-Transformer fed networks. This concept has been extended to higher voltage grids in the Kopernikus project ENSURE (see attached CV), where, together with ABB, we developed a

[33] G. M. Vishwanath and N. P. Padhy, "Power Hardware in Loop based experimentation on DFIG wind system integrated to isolated DC microgrid," 2018 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), Chennai, India, 2018, pp. 1-5.

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[35] G. De Carne, G. Buticchi, M. Liserre and C. Vournas, "Real-Time Primary Frequency Regulation Using Load Power Control by Smart Transformers," in IEEE Transactions on Smart Grid, vol. 10, no. 5, pp. 5630-5639, Sept. 2019.

[36] J. Langston et al., "Power hardware-in-the-loop testing of a 500 kW photovoltaic array inverter," IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society, Montreal, QC, 2012, pp. 4797-4802.

[37] M. Steurer, C. S. Edrington, M. Sloderbeck, W. Ren and J. Langston, "A Megawatt-Scale Power Hardware-in-the-Loop Simulation Setup for Motor Drives," in IEEE Transactions on Industrial Electronics, vol. 57, no. 4, pp. 1254-1260, April 2010.

[38] B. A. Mather, M. A. Kromer and L. Casey, "Advanced photovoltaic inverter functionality verification using 500kw power hardware-in-loop (PHIL) complete system laboratory testing," 2013 IEEE PES Innovative Smart Grid Technologies Conference (ISGT), Washington, DC, 2013, pp. 1-6.

[39] B. Palmintier, B. Lundstrom, S. Chakraborty, T. Williams, K. Schneider and D. Chassin, "A Power Hardware-in-the-Loop Platform With Remote Distribution Circuit Cosimulation," in IEEE Transactions on Industrial Electronics, vol. 62, no. 4, pp. 2236-2245, April 2015.

[40] G. De Carne, "Analysis of Smart Transformer features for electric distribution", doctoral dissertation, 2018

control strategy to help HVDC systems in the provision of primary frequency control in weak networks [C3]. The aforementioned control concepts have been submitted as three pending patents[41,42,43], aiming to transfer research ideas in market solutions.

Of particular importance in my research has been the modelling of power electronics devices depending on the power systems phenomena under study. In [J3], I led a joint effort with several ENSURE partners in developing a guideline, that addresses the study accuracy against the required modelling complexity: depending on the studied power systems phenomena, the modelling complexity has to match the power systems dynamics to perform accurate studies. This concept has been applied to protection of HVDC networks, where we developed together with ABB a simplified numerical tool, that allows to estimate accurately the short-circuit current in DC grids with significantly reduced computational time [J7].

On the experimental side, I worked with power hardware in loop systems, with a clear focus in validating power electronics devices, such as the Smart Transformer. For this purpose, I developed a current-type power hardware in the loop setup in Kiel University [C19], that allows the validation of power electronics hardware in non-synchronized networks. My focus was mostly related in understanding the stability and accuracy limitation of the current-type power hardware in loop system [C21][C18], less studied than the voltage-type one, but of great interest for non-synchronized networks analysis. I am currently collaborating at international level in increasing the industrial and academic awareness of the power hardware in the loop testing advantages, participating in international committee (IEEE P2004, see attached CV), and publishing technical articles with experts in the field [J1].

5. Work Packages

In this section the five Work Packages (WP), which this Young Investigator Group is composed of, are described. Each work package is following divided in Work Steps (WS), that describe in detail the activities that each resources (PhD or Post-Doc) shall pursue, and the relative Deliverables (D) with the assigned Project-Month (PM) dates. The project milestones (M) together with time plan of each work package are summarized in Section 6. The structure and interdependencies between work packages are described in Fig. 3, where the project topics are divided in two main areas, System and Control.

The WP 1 "Real time modelling of Hybrid Networks" will focus mainly at system level, with the goal of developing Hybrid Networks models for real time simulation purpose. In parallel with WP 1, the WP 2 "Smart demand control" will develop intelligent demand-shaping strategies for transforming the Hybrid Networks in controllable resources. These two work packages will work closely together and their output will be provided to the work packages WP 3 "Hybrid Network flexible protection strategies" and WP 4 "Sector-coupled energy solution". These work packages, focusing on the Hybrid Network protections and energy management, respectively, will work on the system and control area, interfacing with WP 1 and WP 2 for system and control solutions. The work package WP5 "Multi-modal hardware in the loop" will cover the entire duration of the project, to develop a

Fig. 3 Structure of the Work Packages

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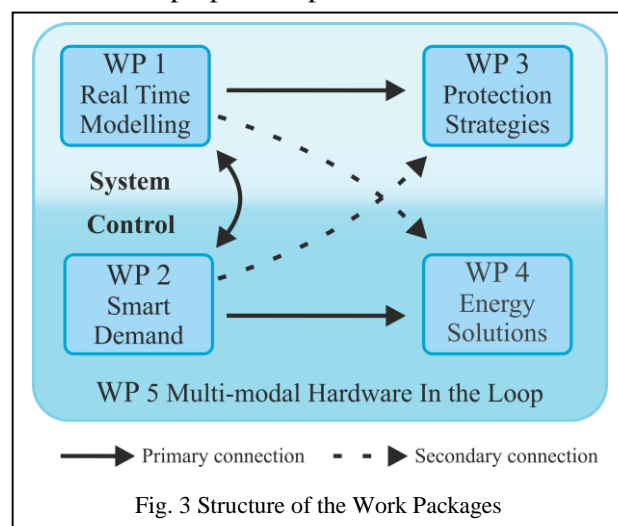
[41] G. De Carne, G. Buticchi, M. Liserre, C. Vournas, "Method for operating an electrical power supply grid, computer program, power electronics device and power supply grid", WO2018069390A1, 2016, pending.

[42] G. De Carne, R. Zhu, M. Liserre, "Method for controlling a grid-forming converter, computer program and grid-forming converter", EP18181659, pending.

[43] M. Liserre, G. De Carne, G. Buticchi, "Electrical power supply grid and method for operation thereof", WO2018167226A1, 2017, pending.

stable and accurate power hardware in loop system, that is able to power-interface more energy layers in the same facility, and to validate "in-the-loop" multi-modal components.

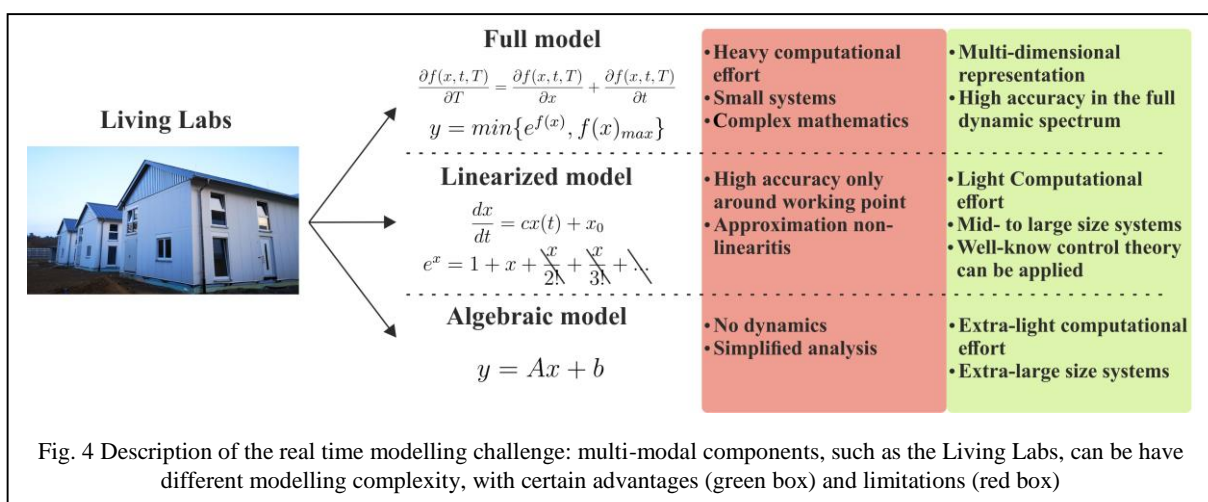## 5.1. WP 1: Real Time Modelling of Hybrid Networks

The energy system is undergoing rapid changes due to the green turn in the energy production and the extensive electrification of the transportation. With the production and consumption changes, new challenges arise and thus new control requirements will be demanded from the network operators, to achieve a safe management. In order to address these challenges, a proper modelling of multi-modal components is needed. Particular focus shall be given to real time applications, due to the increasing needs of industry for validating new technologies in realistic grid conditions. While commonly the modelling has been addressed mostly at mathematical level, fewer works tackle the issue to fit the model complexity to the investigated energy phenomena. This work package will address the need for accurate, although low-complexity, multi-modal models, investigating their modelling for real time applications of Hybrid Networks. The focus lies on the system point of view, identifying the current and future network challenges, and to model properly the solutions that can address them.

WS 1.1 Network requirements and future challenges

This work step focuses on investigating the network challenges, that will arise in the next 10 to 30 years, considering the evolution of the electrical networks, and which requirements may the network assets respect in the future. This activity will develop several possible future scenarios, where the network intelligence level varies, depending on the presence of communication infrastructure (faster and widespread), integrated technologies (with particular reference to power electronics), and presence of asset-owned control points (e.g., centralized heating storage systems, power-to-gas stations). A concrete result is for example the development of a large electrical network benchmark in real time simulators, that shall be coupled with other energy layers, such as heating and gas networks. This benchmark will consider multiple coupling points between the networks, allowing the energy shift among the energy layers. The network benchmark will be used as starting point for this Young Investigator Group activities and it will be physically realized with the real time models developed in WS 1.2, and validated with the multi-modal hardware in loop system in WS 5.1.

WS 1.2 Multi-modal networks modelling

This work step offers the basic understanding of Hybrid Networks, which modelling requires working with different energy carriers, dynamics and network issues. The modelling complexity can vary greatly depending the targeted problems and dynamics. System phenomena with faster dynamics shall be addressed with a more detailed component modelling. However, if more energy layers are considered, their transient dynamics can strongly differ. As an example, thermal transients may last minutes, while electrical transients lie in the milliseconds range.

| **Full model** | • Heavy computational effort
• Small systems
• Complex mathematics | • Multi-dimensional representation
• High accuracy in the full dynamic spectrum |

Living Labs

$$\frac{\partial f(x,t,T)}{\partial T} = \frac{\partial f(x,t,T)}{\partial x} + \frac{\partial f(x,t,T)}{\partial t}$$
$$y = min\{e^{f(x)}, f(x)_{max}\}$$

Linearized model
$$\frac{dx}{dt} = cx(t) + x_0$$
$$e^x = 1 + x + \frac{x}{2!} + \frac{x}{3!} + \ldots$$

• High accuracy only around working point
• Approximation non-linearitis

• Light Computational effort
• Mid- to large size systems
• Well-know control theory can be applied

Algebraic model
$$y = Ax + b$$

• No dynamics
• Simplified analysis

• Extra-light computational effort
• Extra-large size systems

Fig. 4 Description of the real time modelling challenge: multi-modal components, such as the Living Labs, can be have different modelling complexity, with certain advantages (green box) and limitations (red box)

Dr.-Ing. Giovanni De Carne

This work step aims not only to model the Hybrid Networks components, but also to introduce a modelling approach for digital real time simulator, aiming for a reduction of the computational time, while keeping high the accuracy of the studied models. To achieve such a task, for each multi-modal component (e.g., micro-gas turbine, Living Labs, fuel cell and electrolyzer present at KIT), the frequency characterization profile, in magnitude and phase for each considered energy layer, will be obtained and compared with models of higher complexity (e.g., comparing the linearized model with the full model of Fig. 4) and, when possible, with hardware experiments. As a final outcome of this activity, for each realized model, the dynamic range, in which the behaviour accuracy is respected, the system phenomena, that are accurately represented, and its relative cost in terms of computational time, will be clearly assessed. This work step will represent the corner stone for the following system and control analysis, and it will be realized in close cooperation with Prof. Andrea Benigni, FZI Jülich, considering his expertise in multi-modal modelling (see the attached letter of interest). Considering the importance of the modelling in this proposal, we have established a strong cooperation with the digital real time simulator company OPAL-RT (see the attached letter of interested). OPAL-RT, already collaborating with us in other project proposals on real time simulation and power hardware in the loop area, will support this Young Investigator Group in improving the real time modelling of the Hybrid Networks components, in order to achieve high modelling accuracy under reduced computational time. As deliverable from this work step, a library of Hybrid Networks components for real time systems will be realized and made available in an open source environment.

WS 1.3 Large-scale modelling of Hybrid Networks

Following the work done in WS 1.2, this work step focuses on expanding the real time modelling approach to very large-scale problems, such as the integration of Hybrid Networks in large-scale systems, such as at National and European level. A computational time of each model, that can be consider acceptable for small-scale systems (e.g. urban distribution grid), can result unacceptable in very large systems, such as the European Network, where thousands (or millions) of resources are involved. In particular, this work step will address the reduction of dynamic range accuracy, connected to the simplification of the models (e.g., employing algebraic or simplified linear models, as in Fig. 4) in exchange of a lower computation time. For this reason, we will work closely with the Helmholtz Young Investigator Group of Tom Brown in IAI, offering this group our technological background and receiving from them advanced modelling knowledge for large-scale systems. The goal is to realize simplified models, with reduced complexity, that can fit large-scale networks real time simulation, while pointing out the limitations of the simplified models in representing accurately system phenomena.

Deliverables

D1.1	PM 6	Report on future energy networks requirements and network benchmark for digital real time simulation
D1.2	PM 30	Open source library of real time models of multi-modal components and report on Hybrid Network benchmark development
D1.3	PM 36	Models library extension for large scale analysis

5.2. WP 2: Smart demand control

The electrical decoupling in Hybrid Networks offers advanced control capability, due to the faster power electronics dynamics. An innovative feature is the possibility to shape the load consumption by means of controlled voltage and frequency variations, acting on the load intrinsic nature to change its consumption under non-nominal voltage and frequency values. This concept, that I introduced in my previous works with the name of load control [J10],[J11], enables a rapid power control in the network, limiting the need for additional power/energy reserve. The load control, developed for the Smart Transformer case, addresses, however, only simplified cases, without analysing the dependency of different load classes (e.g., industrial, residential, commercial) to voltage and frequency, and only considering voltage and frequency once at time, and not under a combined control. This work package

aims to take a leap forward in the development of such concept, analysing the behaviour of real loads to voltage and frequency variations, and develop smart demand controllers that, exploiting the voltage and frequency dependency of the loads, are able to increase the system controllability. In particular, the focus will be on low- and extra-low inertia grids, that are seen as future electrical system scenario.

WS 2.1 Combined voltage/frequency sensitivity-based controller

This work step aims to develop an electrical network controller, that enables the transformation of the Hybrid Network from a passive consumer and independent producer, to a fully controllable resource. To achieve this goal, the load sensitivity to voltage and frequency of a large set of load categories has to be analysed, taking into account particularly the loads with higher sensitivity, and thus of higher interest for the voltage/frequency controller. At this regard, the research facility of Energy Lab 2.0 offers an extensive network of measurements for a large set of loads, such as the Living Labs (office installation), the Bioliq facility (industrial plant), and MW-size batteries plants (see Fig 5 and description of KIT facility in Section 3). The availability of such a set of resources allows an extensive investigation of the load response during voltage and frequency changes, that can be recorded and analysed off-line. Once these data are available, a smart demand controller will be realized, able to adapt the voltage waveform, in frequency, amplitude and phase, in order to dynamically interact with the local loads and provide services to the electrical network. The novelty with respect to my previous work [J11], will be the development of a smart controller that exploits voltage and frequency sensitivities of the loads at the same time, while providing the requested service. A multi-objective optimization software, that receives the sensitivities from the loads, and sets the new voltage and frequency set-points, will be realized, taking into account the network constraints (e.g., voltage limits at the end of the lines) and loads connection rules (e.g., voltage and frequency min/max limits and ramp rates in Germany). This software will focus on the different response dynamics of the load (e.g., frequency measurement at load point of common coupling), as well as on the interdependency of these two control variables. The added value of this activity is the use of the Energy Lab facilities, where the controller performance will be verified by means of power hardware in the loop evaluation and field experiments (e.g., Living Labs).

WS 2.2: Network stability enhancement by means of Hybrid Networks

Frequency deviations occur more frequently at European Level. Just in the last year, two major disturbances occurred in UK[44] and Continental Europe[45], due to the non-sufficient energy reserve. In UK the frequency reached 48.8 Hz, before triggering an emergency response scheme of 1.5GW, while in the Continental Europe 1.8GW of load has been shed to prevent further frequency dip.

As mentioned in WS 2.1, Hybrid Networks can transform the electrical network in a controllable resource. As an example, through voltage and frequency variations, it can shape the load consumption for providing fast relief to the power system during primary frequency control actions. This concept can be further enhanced if the multi-modal layers of Hybrid Networks are included. These layers, with slower dynamics, but higher energy capability, can
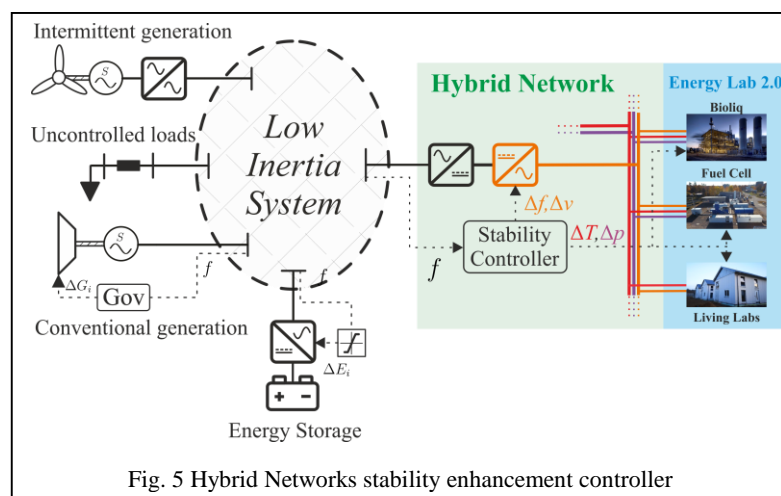

Fig. 5 Hybrid Networks stability enhancement controller

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[44] National Grid ESO, "Interim report into the low frequency demand disconnection (LFDD) following generator trips and frequency excursion on 9th August 2019", Aug. 2019.
[45] ENTSO-E, "Continental Europe significant frequency deviations – January 2019", 2019.

sustain the primary frequency control for longer terms (e.g., for 1-2 minutes), until the secondary and tertiary frequency control kick in (usually after 5 minutes).

This work step develops smart Hybrid Network controllers for increasing the electrical network stability in case of large and unexpected frequency variations, acting on the electrical demand shaping capability of the power electronics, in coordination with the high energy capability of multi-modal layers. The controller, described in WS 2.1, will be further extended, including multi-modal control degrees of freedom, such as temperature, pressure, and mass flow in heating and gas networks (Fig. 5).

To develop such complex controller, that involves components of different nature, search algorithms for artificial intelligence, such as genetic algorithms, will be employed. The stability controller shall receive the status of the network resources and load sensitivities, and, at specified time-step (e.g., every 15 minutes), the genetic algorithm-based controller computes the new control rules, to be applied in case a frequency event occurs. This work step will not be limited to the control development, but it will aim to quantify the benefit of Hybrid Networks in increasing the frequency stability in term of required energy reserve from conventional generators or transmission-based energy storage, also in low and extra-low inertia conditions (i.e., future all-renewables-based grid). This activity will be strictly connected with WP 5, where the proposed frequency control will be validated by means of multi-modal hardware in loop. The future scenarios, investigated in WS 1.1, will be used to validate the control solutions in realistic networks.

Deliverables

|		
D2.1	PM 6	Report on the load sensitivity analysis to voltage and frequency for each load category
D2.2	PM 18	Open source library of smart demand controllers
D2.3	PM 30	Open source library extension with multi-modal frequency controllers
D2.4	PM 36	Experimental benchmark for the validation of the developed stability controllers by means of multi-modal hardware in the loop

5.3. WP 3: Hybrid Networks protection

Power electronics converters are key elements in Hybrid Networks, allowing the electrical network decoupling, and the grid-forming characteristic in the fed network. However, as any semiconductor-based device, they have limited current ratings. This implies that, in case of fault in the decoupled grid, they are not able to provide full short circuit currents, as it occurs with classical AC connections. This feature can affect the whole protection system, that shall be re-thought in order to fit the lower short circuit current availability. This work package aims to understand the requirements for the Hybrid Networks protection system, in terms of fault dynamics and magnitude, and to design new protection strategies, exploiting the advanced controllability of the power electronics in the grid-forming converter.

WS 3.1: Requirements for future protection systems in Hybrid Networks

This work step investigates the protection requirements for Hybrid Networks, considering the short circuit current limitations of the grid-forming converter. This investigation will cover different levels of protection intelligence, depending on the future presence of fast communication, the integration ratio of distributed generation, and the availability of solid-state breakers on the market. The power electronics architecture of the grid-forming converter shall be considered as well, highlighting if particular architectures (e.g., two-level, neutral point clamped, modular multi-level converters) or semiconductors (e.g., Si IGBT, SiC Mosfet, GaN) are more suitable to handle fault currents. As an outcome, the requirements for future protection systems in Hybrid Networks will be determined, and benchmark for the protection strategy testing will be developed and implemented in the digital real time simulator, on the base of the network benchmark developed in WS 1.1.

WS 3.2: Power electronics-based flexible protection strategies

Knowing the requirements for future protection systems in Hybrid Networks is the first step for developing intelligent protection control strategies. In order to not revolutionize the whole protection system, just for integrating the Hybrid Networks, this work step aims to develop new flexible protection strategies for grid-forming converters, that can work together with the existing protection strategies. The goal of these strategies will be to use the advanced voltage control capability of the power electronics, investigated in WS 2.1, in the grid-forming converter, to safely and dynamically clear the electrical faults, without the need for additional hardware (e.g., fault limiters or solid-state breakers). Rapidly reducing the voltage output, the fault current can be shaped to levels that the grid-forming converter can handle. However, this affects the vertical selectivity of the protection system, where high-current protection systems are needed in the first half of Fig. 6. This work

Fig. 6 Power electronics-based protection system: higher fault current cannot be handle by the grid-forming converter (red area), thus new flexible protection strategies must be realized

package will start from my previous works [J5], and will develop a power electronics-based flexible protection strategy that will respect the existing protection selectivity and at the same time can adapt to network changes (e.g., switch from radial to meshed grids). Reaching this goal means to eliminate one of the main bottlenecks for the implementation of non-synchronized networks. These protection strategies will be validated with the power hardware in the loop setup, considering the network scenarios developed in WS 1.1 and the network requirements of WS 3.1.
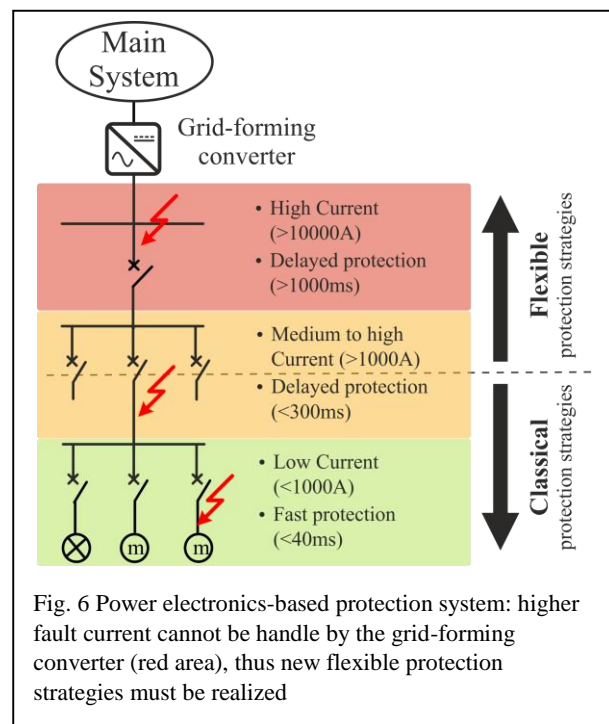
Deliverables

D3.1	PM 36	Report on protection requirements in future Hybrid Networks
D3.2	PM 60	Open source library on power electronics-based protection strategies

5.4. WP 4: Sector-coupled energy solutions

Of particular interest for increasing the system controllability are the hybrid energy storage solutions, where two or more energy storage solutions are combined to provide coordinated services in different time-scales (e.g., fast and slow transients). This work package aims to expand the work done in WP 2, that addresses short term services, such as the network frequency control, developing sector-coupled energy solutions, that can address the energy control in the full spectrum of dynamics for longer terms (e.g., secondary and tertiary controls).

WS 4.1: Multi-modal energy management framework

This work step targets to increase the system controllability over a large dynamics spectrum. While electrical components of the Hybrid Network can target phenomena with faster dynamics, that require high power but lower energy (see Fig. 7), the Hybrid Network multi-modal components can tackle longer time constant problems, offering higher energy and power in longer terms.

In this work step, several technologies (supercapacitors, flywheels, fuel cells, water heating storage systems) will be considered and combined with the load control investigated in WS 2.1, in order to address the largest set of system phenomena dynamics. As an outcome of this work step, a multi-modal energy management framework, that targets the service provision to the network (e.g., secondary and

tertiary frequency regulation) and takes into account the resources power and energy density, response time, and lifetime, will be realized by means of a genetic algorithm-based solver. The solver will receive in real-time specific inputs from external controllers (e.g., frequency/voltage/current readings from system operator, market signals, weather forecasts, storage state-of-charge) and it will give as output the new controlled resources set-points (e.g., storage power, grid-forming converter voltage and frequency set-points). Due to the complex nature of this problem, the use of artificial intelligence algorithms is preferred to (but it does not exclude) Lagrangian relaxation methods. This concept will be proved through multi-modal hardware in loop evaluation using several electrical (batteries, super-capacitors, fuel cells) and thermal (water storage) technologies that are currently present in the Energy Lab 2.0.

WS 4.2: Hybrid Network controlled islanding

The different nature of the Hybrid Network components offers an advanced controllability of the energy flow. As can be seen in Fig. 7, faster network phenomena, such as local power unbalance, can be addressed by power electronic features, such as load control, while slower and energy-requiring transients, can be managed by shifting energy among different energy layers. This degree of freedom can transform the Hybrid Network in an energetically independent entity from the main energy system (e.g., transmission system, regional heat and gas networks), and thus it enabling its islanded control.

This work step aims to apply the multi-modal energy management framework developed in WS 4.1, to control the energy flow in the Hybrid Network in the way that it becomes independent from the main
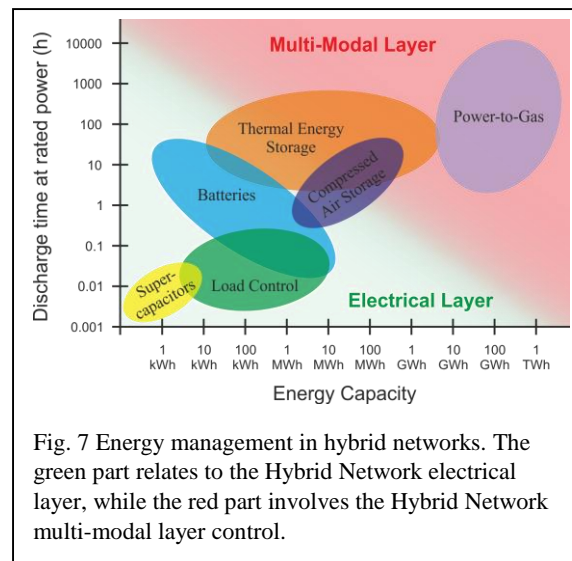

Fig. 7 Energy management in hybrid networks. The green part relates to the Hybrid Network electrical layer, while the red part involves the Hybrid Network multi-modal layer control.

energy system. In this applicative case, the optimization solver will target a zero-exchange of energy with the main energy system, fully exploiting the energy and power capability of the Hybrid Network resources to supply the internal energy demand. This feature can be used to increase the resilience of both Hybrid Network and main system. The Hybrid Network will not depend on remote energy transmission, and thus on possible disruption caused by natural phenomena (e.g., earthquakes, thunderstorms), and the main energy system will not have to consider the Hybrid Networks during restarting procedures after black-outs. These strategies will be validated using real data extrapolated from the measure reading in Energy Lab 2.0, in order to develop realistic energy scenarios and to understand benefit and limitation of each solution.

Deliverables

D4.1	PM 54	Multi-modal energy management framework software
D4.2	PM 60	Open source library on energy controlled islanding algorithms

5.5. WP 5: Multi-modal hardware in the loop validation

In literature, multi-modal systems have shown promising features in controlling the energy flow. Currently, the validation of multi-modal approaches has been proposed only in simulations or in field-tests. A power hardware in loop evaluation of multi-modal systems, that involve electrical, heating and gas networks, is missing. As example, if such multi-modal hardware in the loop system were available, a micro-combined heat and power (CHP) plant could have been tested connected to simulated electrical, heating and gas network, making the analysis of its performance complete.

This work package aims to the ambitious goal to develop a multi-modal hardware in the loop system, where the power testing is not performed only at electrical level through a power amplifier, but also at

heating and gas levels. A first attempt to develop such system has been performed at RWTH Aachen[46], with a multi-physics test bench for smart homes. However as mentioned in the work, limitations and potentials on the dynamic, power interface and stability of the system have been not fully addressed. To make a leap ahead in the research, the goal of this work package is to investigate which power interface technology can be employed for interfacing the heating and gas layers (and which are its limitations), which interface algorithms and variables can be employed to connect hardware and software sides, and which stability (and accuracy) considerations shall be taken into account, if the power interface is not electrical, but multi-modal.

WS 5.1: Multi-modal interface algorithms

This work step aims to develop a new multi-modal hardware in loop system, with the goal to interface at least two among electrical, heating and gas networks. Particular focus of this work step will be the realization of interface algorithms allowing the evaluation of components, that involve more energy layers. The algorithms shall take into account the different system's time constants, and different power interface technologies (e.g., power amplifier for the electrical network and thermal pump for the heating network). As an example from Fig. 8, instead of voltage (v^*) and current (i) signals, the heating network shall exchange signals such as temperature (T) and mass flow (dm) measurements. However, there is no standard in experimental testing, and this shall be clearly investigated. A detailed investigation of the variables that can be measured and fed back to the simulator will be performed in this work step, always considering the available actuators technology (e.g., limitation on the temperature control of thermal loads, lack of bi-directionality of heat exchangers). As an outcome of this work step, an interface algorithm library will be created, that future researchers can easily plug-and-play in their multi-modal hardware in the loop systems, speeding up the future validation of multi-modal technologies.
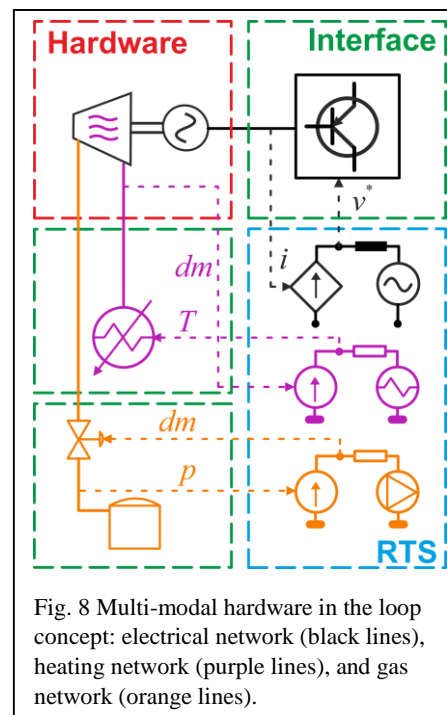

Fig. 8 Multi-modal hardware in the loop concept: electrical network (black lines), heating network (purple lines), and gas network (orange lines).

WS 5.2: Stability analysis of multi-modal hardware in the loop systems

The stability and accuracy of a power hardware in the loop system plays a fundamental role in developing and testing system technologies. As demonstrated in the literature section[27,28,29], achieving a stable and accurate evaluation is challenging, due to the presence of many interconnected components. Due to this complexity, the power hardware in loop system, stability and accuracy analysis is currently carried considering simplified setups, where the simulated grid is represented usually as an impedance, and the hardware under test with simplified controllers. Although these assumptions give us a first idea of the power hardware in the loop system stability, it may lead to unacceptable stability and accuracy assessment errors, in case of larger and more complex simulated grids and hardware under test.

This work step aims to represent the Hybrid Networks components, both hardware and software, by means of the component connection method technique[47,48]. This modelling technique allows to represent each component as an input/output model with a certain internal rule. The main advantage is the possibility to easily connect the component connection method-based blocks to perform power hardware

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[46] C. Molitor et al., "Multiphysics Test Bed for Renewable Energy Systems in Smart Homes," in IEEE Transactions on Industrial Electronics, vol. 60, no. 3, pp. 1235-1248, March 2013.

[47] Y. Wang, X. Wang, Z. Chen and F. Blaabjerg, "Small-Signal Stability Analysis of Inverter-Fed Power Systems Using Component Connection Method," in *IEEE Transactions on Smart Grid*, vol. 9, no. 5, pp. 5301-5310, Sept. 2018.

[48] R. Rosso, S. Engelken and M. Liserre, "Robust Stability Analysis of Synchronverters Operating in Parallel," in *IEEE Transactions on Power Electronics*, vol. 34, no. 11, pp. 11309-11319, Nov. 2019.

in loop stability and accuracy analysis in large and complex grids (see Fig. 9 for a complex electrical grid). This work step will focus on creating connecting blocks of different energy natures (e.g., gas turbine modelling with 3 input/output ports: electrical, heating, gas), that can be connected each other, to perform rapidly the stability and accuracy analysis of large multi-modal hardware in loop systems.

The outcome of this activity will be the development of a component connection method-based library of Hybrid Networks components (electrical, heating, gas), that will integrate the multi-modal hardware in loop library developed in WS 5.1, and that will be employed for verifying the stability and accuracy features of multi-modal systems. This work step will be performed in close cooperation with OPAL-RT, in particular regarding the creation of flexible stability and accuracy tools for evaluating the stability in the electrical part of the power hardware in loop (see letter of interest).
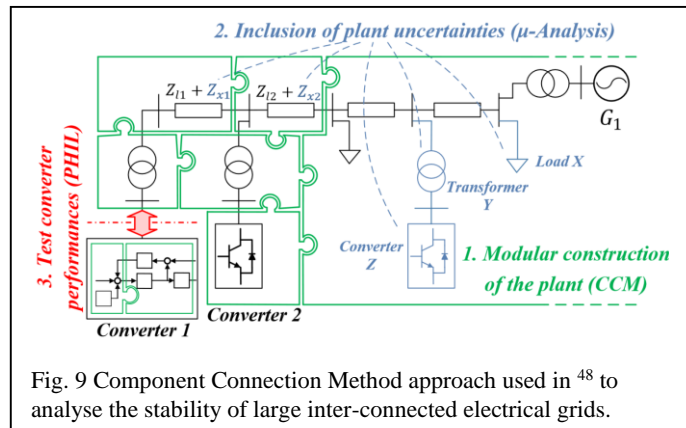

Fig. 9 Component Connection Method approach used in [48] to analyse the stability of large inter-connected electrical grids.

Deliverables

D5.1	PM 18	Open-source library and setup on multi-modal hardware in the loop interfaces
D5.2	PM 36	Experimental benchmark of multi-modal hardware in the loop
D5.3	PM 48	Experimental benchmark of multi-modal hardware in the loop stability analysis by means of component connection method
D5.4	PM 60	Experimental benchmark for multi-modal hardware in the loop stability validation

6. Work Plan

6.1. Work Package timings and milestone

This section wants to give an overview of the project timeline with the Gantt diagram shown in Fig. 10. The deliverables are listed at the end of each work package in Section 5, while the Milestones are marked in red in the Gantt diagram. The timings may be subject to changes, depending on the research progresses. Any significant deviations from the original research plan will be promptly communicated and explained to the Helmholtz Association, in order to guarantee the best outcome for the project.
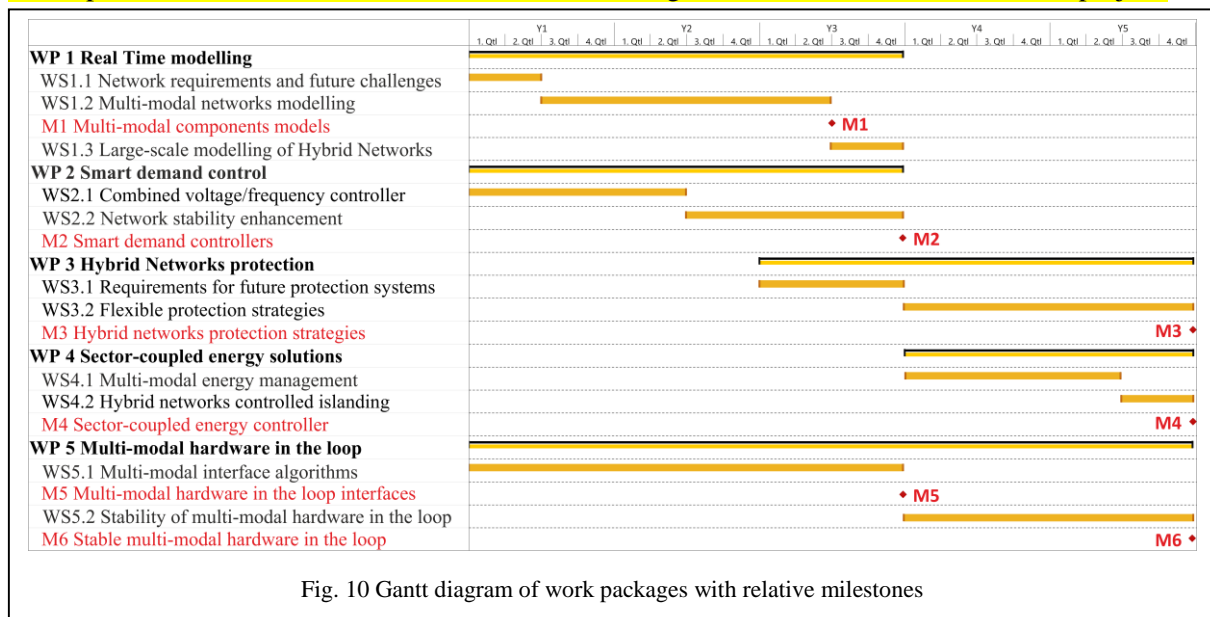

Fig. 10 Gantt diagram of work packages with relative milestones

6.2. Personnel plan

The proposed research plan is highly ambitious, covering several fields (power systems, power electronics, control, fluid- and thermodynamics) and requiring analytical, as well as experimental skills. It is planned that at any time a team leader and two PhD students will be employed in the project, with exception of the third year, where four PhD students are planned. It has been planned that 2 post-docs are employed in the project, in the first two years in WP 5, and in the last two years in WP 4.

The activities of WP 1, WP 2, and WP 3 will be carried out by PhD students, one for each work package for the duration of it, working on real time modelling, smart demand controllers, and protection systems, respectively. A post-doc will be employed to carry out the activities of WP 4, working on the

	Year 1	Year 2	Year 3	Year 4	Year 5
PhD 1 - WP1	▓	▓	▓		
PhD 2 - WP2	▓	▓	▓		
PhD 3 - WP3			▓	▓	▓
Post-doc 2 - WP4				▓	▓
Post-doc 1 - WP5	▓	▓			
PhD 4 - WP5			▓	▓	▓

Fig. 11 Personnel resources distribution in the project

system multi-modal optimization. The activities of work package 5 will be covered by a post-doc in the first two years, to develop the multi-modal hardware in the loop interfaces, and by a PhD student in the last three years, to work on stability analysis for multi-modal hardware in the loop systems.

The need for two post-docs is related to the request of specific skill sets. The post-doc in WP 4, will be specialized in multi-objective optimization, in particular of complex multi-modal systems. This profile requires large experience on artificial intelligence (e.g., with genetic algorithms), that is unlike to be found in M.Sc. students and it requires advanced studies (i.e., a PhD). The post-doc in WP 5 will be specialized on multi-modal hardware in the loop systems and their interface algorithm. Although some M.Sc. may have previous experience in power hardware in the loop, it is required for this profile a deep knowledge of heat and gas network operations, as well as laboratory experience. This is usually not available at Master student's level. As mentioned in Section 4.1, Dr. De Carne has a strong background in modelling, control and experimental validation. Additional specialized personnel on optimization algorithms and heat and gas network operations, as the two aforementioned post-docs, can further improve the research quality and enhance the young investigator group skills set.

6.3. Financial plan

The financial plan (see Annex 7) follows the indications of the DFG Personnel Rates for 2020[49], increased of 2%, to include the inflation rate for 2021. The salary of a head of independent junior research group for 5 years is included. The post-docs will be employed in the category E13 Level 3 or superior (related to the experience). The PhD students will be employed with the 75% of the E13 Level 2, as common practice in the field. No costs for investment are planned in this young investigator group, due to the existing large facility of Energy Lab 2.0. Expenses for materials and supplies are related to consumables, office materials (PC, software, etc.), conference fees and travel expenses for the group.

7. Cooperation and communication plan

7.1. Cooperation partners at KIT

The Young Investigator Group will strongly benefit from the inter-disciplinary environment developed in the "Energy Lab 2.0" facility, where the Institute for Technical Physics (ITEP), led by Prof. Noe, has strong research ties with the Institute for Automation and Applied Informatics (IAI), under the leadership of Prof. Hagenmeyer, the Institute of Electrical Engineering (ETI), directed by Prof. Hiller, the Institute for Electrical Energy Systems and High Voltage Technique (IEH) of Prof. Leibfried, and the Institute for Micro Process Engineering (IMVT) of Prof. Roland Dittmeyer.

Within the Energy Lab 2.0 framework, collaboration with IAI Prof. Hagenmeyer lab "Smart Energy System Control Laboratory" is set to fully exploit the Living Labs facility, in particular to model multi-

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[49] https://www.dfg.de/formulare/60_12/60_12_en.pdf

modal resources (WS1.2), to validate the smart demand controller (WS2.2), and to develop the multi-modal hardware in loop setup and validate it with the Living Labs facility (WS5.1). Further collaborations with IAI are planned with Dr. Brown Young Investigator Group, in developing Hybrid Networks models for large-scale simulation scenarios (WS1.3). Prof. Drittmeyer expertise will be involved in the modelling advancement of multi-modal components, such as fuel cells and electrolyzer, in WS 1.2. With Prof. Hiller ETI group, advancements in grid-forming converter protections requirements are planned (WS3.1), while with the power hardware in loop research group of Prof. Leibfried at IEH, new stability tools for power hardware in loop evaluations (WS5.2) will be studied and validated in the Energy Lab 2.0 facility.

Participation in the KIT Energy Center, which unites all the energy-related departments of KIT, is already considered, as well as the engagement with the KIT Young Investigator Network, that enables the experience exchange with young researchers and group leaders in other fields.

7.2. Cooperation partners outside KIT

The cooperation outside KIT will be carried out both at academic and industrial level. At academic level there will be the official involvement of Prof. Benigni at IEK-10 Forschungszentrum Jülich in the WP1, for the real time models development of Hybrid Network components (see letter of interest). This topic fits particularly the expertise of IEK-10 in Jülich, and it will further strengthen the collaboration between the two Helmholtz centres, within the joint projects Energy Lab 2.0, Living Lab Energy Campus, and the planned infrastructure High Power Grid Lab. Academic partnerships will be pursued with my former institute at Kiel University with Prof. Liserre, in the development of smart controllers for Hybrid Networks (WP 2), and with Prof. Vournas at National Technical University of Athens, in the network requirements and system challenges (WP 1), both internationally recognized scientists in their fields.

At industrial level, this Young Investigator Group will collaborate with the digital real time simulator company OPAL-RT, to develop real time models of the Hybrid Networks (WP 1), and flexible stability and accuracy tools for power hardware in loop evaluations (WP 5). The collaboration with OPAL-RT will offer technical knowledge developed for more than 20 years, and it will add industrial experience to the project, with the goal to bring the developed solutions on the market (e.g., start-ups). Another strong industrial collaboration has been established with Maschinenfabrik Reinhausen in WP 3, with the goal to tackle the design of the non-synchronized network protection systems, both from system and control point-of-view. This collaboration will strengthen the group, providing industrial-insights from a well-known power electronics converter manufacturer, otherwise not available to public.

7.3. Communication plan

To communicate with other researchers, we will regularly publish the research results in international journals (IEEE Transactions, IEEE Magazines, Electric Power Systems Research Journal) and specialized conference (IEEE PES, IEEE ECCE, PSCC, PowerTech). The scientific results will be presented under tutorial forms in the aforementioned conferences, in order to introduce the project achievements in more organic and complete way. Part of the project budget will be assigned for open access journals, that will be strongly advised during the project duration, to ensure the widest dissemination of our scientific results outside the academic community. The achievement in real time modelling and hardware in loop interface algorithms will be made available in the project webpage (developed in within KIT), fully accessible to the public, with the purpose to disseminate the results obtained in this project to other researchers and students. The communication plan targets the scientific community, publishing in international journal and conferences, and the industry, holding seminars and tutorials in national (Hannover Messe), international (CIRED, CIGRE) fairs, and participating in CIGRE and IEEE working groups. The national-level power hardware in the loop workshop (50 attendees), held in KIT ITEP/IEH every year in November, will be used as the main reference point for advertising the project results to German companies in the field. As an outcome of the project, an industrial PhD course (2/3 days) will be organized at ITEP on multi-modal modelling and hardware in loop evaluation, in order to disseminate the gained experience in the project to the industrial sector.