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Influence of Protection Systems on the Vertical Grid Operation in Distribution Networks

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***Abstract*— The energy revolution, which has been forced by law, is leading to a change in the energy sector. Energy generation is moving from centralized large-scale power stations in the upper grid levels to decentralized small generators in distribution networks. The Renewable Energy Act prescribes that electricity from renewable sources can be fed into the grid ahead of conventional power. In addition, conventional power plants must reduce production in times of excess supply. Along with this reduction, there is a lack of sources for providing system services. Here, new potentials are searched for the distribution network level. For these potentials to be exploited, new concepts are needed to ensure safe network operation. The investigations in this work are focused on how the provision of system services from the distribution network level will be limited by network protection in the future. Because there are comprehensive protection concepts and a wide range of protection devices, an overview of the basics of protection systems is created. To identify the influence of the protection systems, a possible concept for detection of influences of protection systems has emerged. A simulation in a low-voltage grid has been implemented as part of this work and serves to test the proposed concept.**

***Index Terms*—distribution network, system service, protection system.**

I. INTRODUCTION

THE power supply is the foundation for prosperity and progressing of a highly developed country. Since the nuclear disaster in Fukushima, the energy revolution has been considered in recent years [1]. The conventional centralized power supply through the large-scale power plants is gradually being replaced by a decentralized energy supply through renewable energy generators [2]. Accordingly, this development has effects on all grid levels because the previously unidirectional load flow from the upper grid levels to the lower grid levels changes into a bidirectional exchange of energy between the grid levels [2]. This exchange between the levels, however, means that previous concepts of network operation management and monitoring of system parameters and equipment must be changed in order to meet the new requirements.

The change due to the increased feed-in from renewable energies, as can be seen in Fig. 1.1, leads to new grid conditions. The volatility of renewable energies leads to constantly fluctuating load flows, depending on weather conditions [2]. For example, to maintain a stable frequency despite these constant changes in the grid, the imbalance between production and consumption must be compensated [5]. This imbalance leads to a deviation of the basic frequency defined in the European network system. If the deviations from this frequency are too large, this can result in damage to equipment and dangerous conditions [6]. The network operators, therefore, make use of the possibility of system services to avoid such harmful consequences. One example of this is power-frequency control. This regulation consists of primary, secondary and tertiary management. The various types of power serve, on the one hand, the purpose of protecting the frequency in the event of a fault from excessive deviations and on the other hand, of returning it to its setpoint value. An imbalance in the power grid can be either positive or negative. On the one side, power plants can, therefore, be out of operation, on the other hand also large loads due to disturbances in the grid [5]. To ensure sufficient positive and negative compensate power in the future, it is considered to be retrieved from the distribution grid level [2]. For this project to succeed, new concepts are required, including vertical network operation [7]. However, the influence of the protective systems on this concept is so far uncertain. [2].

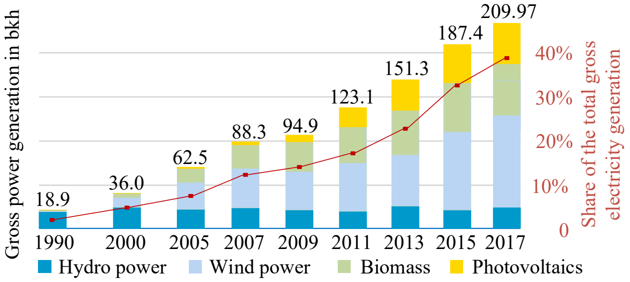

Fig. 1: Electricity generation from renewable energies in Germany from 1990 to 2017 according to [3], [4]

The previous research has usually been carried out in two directions. On the one hand, the issue about how decentralized power generation plants can contribute to system services was investigated. [2], [8]-[12]. On the other hand, it was researched how grid protection concepts can be adapted and optimized to changes in the feed-in situation in order to continue to enable secure grid operation [13]-[18]. In System Services 2030, it is repeatedly pointed out that there is a specific need for research to investigate the interactions between protection concepts and the planned potential realization of system services from the distribution grid level [2]. The present work is based on this point and intended to show a preliminary approach to the investigation of this influence. The aim of this thesis is to develop a concept to detect influences on the vertical network operation and minimize these influences by suitable methods.

This paper is divided into five parts. The first chapter presents an overview of the current network operation in Germany and the novel approach of vertical network operation for the management of electrical networks. The second chapter is devoted to the concept of recognizing possible influences caused by network protection and incorporating this insight into operational management, particularly in power-frequency control using the secondary power control. After that, the influence of overcurrent protection devices on the low-voltage level when activate secondary control power is investigated by simulation in order to test the effectiveness of the concept recommended in the third chapter. A summary of the conclusions drawn from this work is given in the end chapter. The possibilities for improvement of the investigations are also dealt with as well.

II. VERTICAL OPERATION

In the following chapter, how current studies and publications investigate the changing significance of the distribution network in electrical energy supply with regard to network protection will be discussed. The influences of the increasing number of decentralized energy supply in the distribution network will be explained and then the current problems that occur during network expansion will be examined. This chapter will demonstrate that it is necessary to prepare the future distribution networks for vertical grid operation.

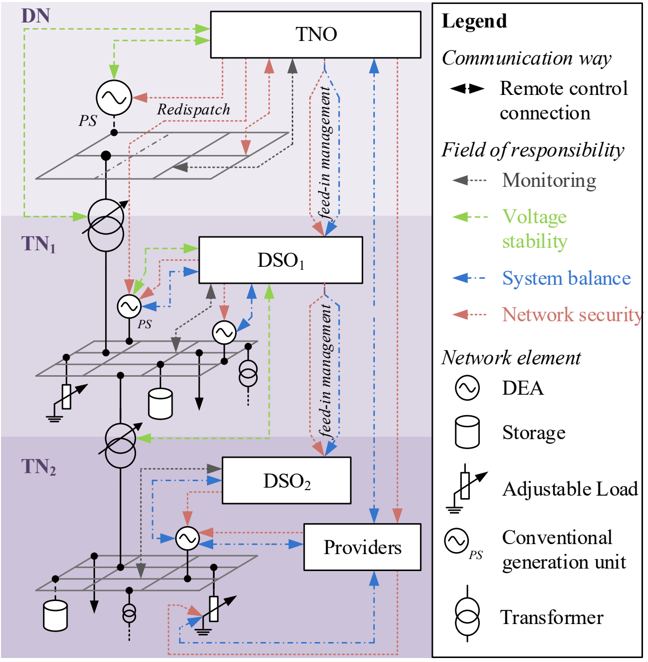

Fig. 2: Overview of existing responsibilities and interactions of participants [1]

The vertical operation is a concept for the coordination of grid operating services at different grid levels. It unites the advantages of two network operation approaches. First is the hierarchical method and the second is the centralized approach. The focus of vertical network operation is on the aggregation, utilization, and coordination of operational flexibility across the various grid levels. The responsibilities of the grid given by the regulations, as described in this section, are not involved. The approach is based on the fundamental principle that the relevant local grid operator can take part in the control. The requirement here is that the measures introduced by the transmission grid operator should not lead to a deterioration of the grid condition. The grid instance is established, which can realize the interaction between the participants of the grid operation as shown in Fig. 2. This grid instance is referred to as the aggregator. In order to fulfil the system services as described in Chapter 1, the aggregator and the transmission system operator have various options at their disposition [7].

It should be mentioned that in this approach the possibility of direct access by the transmission system operator to the technical units is facilitated. The advantage of vertical grid operation in contrast to other grid operation is the straightforward integration into the existing grid operation management system. The responsibilities and competencies with regard to the measures and tasks described in Fig. 3.3 remain untouched. The legal limits defined by the EnWG and EEG are also taken into account.

III. CONCEPT FOR AVODING OF PROTECTION INFLUENCES

The following chapter presents a concept for recognizing grid congestion caused by grid protection at an early time in the case of a demand for system services from the distribution grid using the example of secondary control power. The concept is based on vertical network operation.

In the future, transmission and distribution system operators and aggregators will, therefore, need an opportunity to verify whether the control power, as stated in the quantities offered, can also be freely supplied at the time of the retrieval. If restrictions occur due to limitations in the grid, e.g. on account of disturbances, utilization of operating resources at their limits or due to overloading of the grid and associated topology shifts due to protection trips, such restrictions must be recognized and then identified. In the following, an approach is presented how limitations by the protection systems in the grid to the provision of system services can be identified using the example of secondary control power. It is also discussed how the individual participants in the energy sector can deal with this acquired information.

If a fault occurs, for example, due to a power plant failure or the disconnection of a large load in the grid, an imbalance occurs in the system. This imbalance leads to a deviation of the mains frequency from its nominal value. The power-frequency control reacts to this deviation and, if possible, restores the balance between supply and consumption. Since this balancing must take place promptly, the operations are mostly automatic. In order to respond, for example, by adjusting the switchable loads or the feed-in of renewable energy systems in the distribution grid, the current grid status must be checked. This network status includes the current switching positions of disconnectors and circuit-breakers, the load of the grid and the current parameters of the protection technology. According to [19], each distribution system operator is responsible for its respective grid area by obtaining detailed information.

If control power, according to the proposals, is requested using the tenders defined on the market, possible restrictions in the grid may be identified on the basis of the forecasts made in step 7. In order to minimize the inaccuracies of the forecasts, this investigation is repeated in step 11 in order to identify possible problems with the current state of the grid when providing the compensation power.

Tab. 1: Information exchange between operators and distribution system operators according to DistributionCode [19].

Information on operational planning	Information on operational management
• feed-in schedules • reactive power capability • Start-ups and shutdowns	• Measured values for currents, voltages, powers • Limited values for active and reactive power • Switch positions and step controller positions • protection signals • Start-up and shutdown of the technical unit

In this case, the transmission system operator or its control equipment defines the setpoint of the control power for frequency. This set point is forwarded to the operators and the distribution system operators by the aggregator. The operator transmits the set point to the technical units. Based on the behavior of the technical units, the distribution system operator can carry out a load flow calculation of its network based on the current status. An exchange of information between the operators of the technical units and the distribution system operator is necessary in order to obtain information on the current state of the grid. According to [19], it is required to provide information as listed in Tab. 1 in the 110kV grid. Thus, it will be necessary in the future to exchange system services in the lower voltage levels between plant operators and distribution grid operators in order to retrieve system services from the distribution grid.

At the same time, the distribution grid operator also informs the plant operators if there is a fault in the grid. In addition, it informs which generation plants should not increase their feed-in during this period in order to avoid e.g. a tripping protection. The detection of such grid faults requires a further expansion of automation and information technology so that the operational management tasks required of the distribution grid operator can be fulfilled. According to the Distribution Code [19], these tasks include monitoring and adherence to the system variables current and voltage, controlling the switching state and operating the necessary measuring and counting devices. The distributor is thus obliged to collect the information required for the load flow calculation.

If the distribution network operator has carried out the load flow calculation (LFR) with current parameters of the grid, further system parameters can now be determined. These system parameters, for example, voltage and current, are used by the protection systems in the grid as protection criteria. In order to present this clearly, a state vector protection for the current state of the protective devices and a state vector for the current state of the grid can be determined. In order to present this clearly, a state vector $\boldsymbol{x}_{\text{protection}}$ for the current state of the protective devices and a state vector $\boldsymbol{x}_{\text{grid}}$ for the current state of the grid are generated for the respective connection. The status of the network refers to the system dimensions.

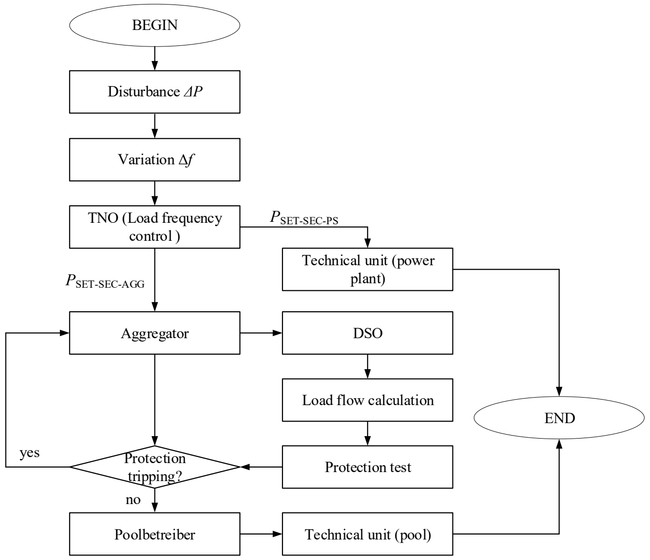

Fig. 3: Flowchart of the proposed concept

After the system parameters have been identified, a test is carried out using a function to verify whether protective devices are tripped. When a tripping occurs and at what time, and what maximum transfer power is possible at the network connection point without causing a change in the topology, it is returned to the aggregator as a reset value. The aggregator must decide, according to the result of the reset value, whether it is necessary to distribute the setpoint to other operators based on a set value in order to provide the secondary control power. This distribution may be necessary to avoid any tripping of the protective devices and therefore to provide the control power without changing the topology. It should be mentioned here that the distribution grid operator does not transmit the status and parameters of its own grid, only if there are problems with the protection systems in its grid area and the amount of secondary balancing power that can be provided from its grid area at the grid connection point. The network security and data protection of the own grid has a high priority here. The transmission network operator is not included, which is similar to the previous procedure described in Chapters 2. It issues an invitation to tender for the quantity of balancing power required on the market at a fixed price and the respective supplier must ensure that the available quantities are provided in accordance with its capabilities.

The advantage of the proposed concept is that it can be used in planning as well as in operational management. In the pre-qualification phase, the aggregator and the distribution grid operator can determine how much power can be retrieved, and it is also possible to test the current state of the grid when providing the secondary control power. In this way, possible faults with regard to the mentioned problems in chapter 2 can be detected by decentralized supply to the protection systems and hence, allow the smooth operation of the power-frequency control.

The disadvantage in the dynamic considerations include the inaccuracies of the model and the delay caused by the load flow calculation. These make the dynamic processes t<1s, which is impossible or even unrealistic. This means that, according to the present concept, no investigations can be carried out with regard to the provision of primary control power.

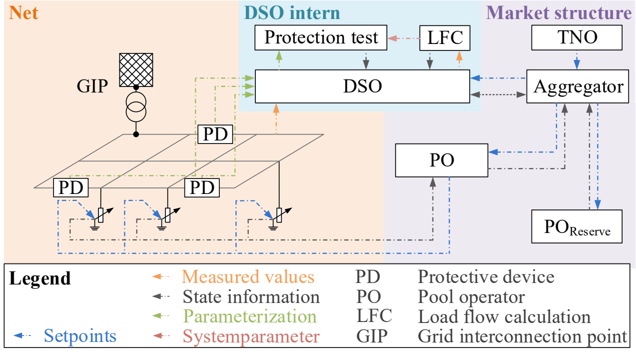

Fig. 4: Concept for effects of protection

IV. SIMULATION

The reference grid is needed to test the proposed approach and to monitor the impact of a protection tripping on the provision of system services. The medium voltage reference network according to Cigré Benchmark Systems for Network Integration of Renewable and Distributed Energy Resources European Configuration [45] is used. This represents, as shown in Fig. 4, an urban cable network (grey background) with a rural environment with overhead lines (green background). There are 15 nodes at which possible loads can be parameterized. The grid is operated as a closed ring (in Fig. 4 the red T stands for an open isolator and the green T for a closed isolator), as is usual in medium voltage with regard to (n-1) safety [7].

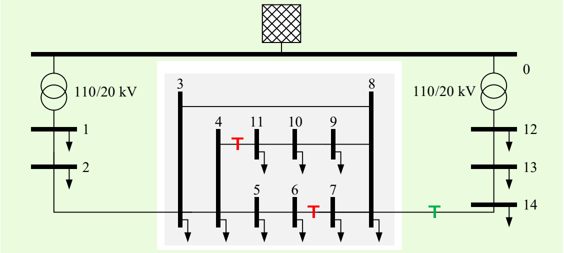

Fig. 5: Reference grid for medium voltage Cigré Benchmark System European Configuration according to [7], [45]

In the medium-voltage field, the protection systems are required to have a high degree of supply reliability and the requirements must be met by the plants and protection systems. In addition, research on the effects of decentralized feeders in accordance with [15] has been improved to such an extent that protection tripping due to overload will not occur, even when system services are provided from this voltage level. Therefore, the consideration of the low-voltage grid was extended, since here loads, for example, electric cars in private households, no permission is required, and neither is a load sharing between household and grid operator. In Europe, low-voltage networks are mainly designed as radial networks. Due to the geographical extent and the low density of loads in rural areas, low-voltage networks in Germany are designed as radial networks. The designs can vary between underground cables and overhead lines. A low-voltage network is normally fed by a local transformer. The above conditions are illustrated in the low-voltage network according to [45] [7]. The reference network, as shown in Fig. 5, contains 19 nodes, 12 of which are designed as cable distributors to which no loads are connected.

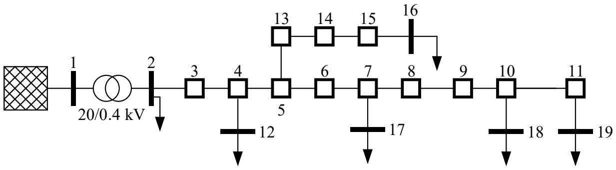

Fig. 6: Reference grid for low voltage Cigré Benchmark System European Configuration according to [7], [45]

Thus, five loads can be estimated in this network, which can also contain storage and electric vehicles as well as decentralized injection units. According to [2], these will in future be able to provide power supply and will be referred to as technical units as proposed by [7]. The parameterization of the networks and the loads they contain is based on the investigations, which is carried out in [7].

The threshold values are selected previously based on the maximum load according to [7] by a load flow calculation and the resulting current flows in the conductors since the protection in low-voltage networks is designed for the maximum load [6]. A distance of 1.6 between the threshold values is selected on the basis of selectivity. This ensures selective triggering [36]. The selected safety devices according to this principle are shown in Tab. 5.2. The NH protections are selected as full-range protections (label g). This means for lines on the basis of the nominal current rules described above and for the local network transformer (gTr) by selection from dimensioning tables.

To ensure the setpoint value as accurately as possible, it is transmitted to the technical units, which comes from a model in that a disturbance can be applied to a control area in Germany and from this, the frequency curve, as well as the primary control power and the secondary control power, can be calculated. The primary control power is provided here by a power plant model and the secondary control power by a pool of electric vehicles, which can be used for charging on the one hand and for feeding on the other hand. The setpoint for power change is taken from the value for the pool and scaled to a maximum change of ΔP_{max}=10kW per electric vehicle in order to obtain a feasible value for a vehicle in the low-voltage grid [47]. Depending on the scenario, these are distributed among the nodes in order to investigate the behaviour of the network shown in Fig. 5.2 and the protective elements contained in it. In the assessed scenarios, the electric vehicles are regarded as loads in the state of charge instead of as generators.

In the future, the power supply will be dominated by decentralized generation plants and new storage facilities [2]. These innovations are to be found mainly at the distribution grid. New challenges are brought with them, for example, new load conditions of the grid. In this chapter, various scenarios are used to test whether the concept presented can work. This test is carried out by the simulation explained in the previous chapter. The main task here is to analyze the transfer power at PCC including the triggering at the nodes of the low-voltage grid level.

Tab. 2: Selected and validated scenarios

Scenario	Load	Electric vehicles	Connection node for electric vehicles
A	low load	0	-
B	low load	1	12
C	low load	3	12, 16, 17
D	low load	5	12, 16, 17, 18, 19
E	heavy load	0	-
F	heavy load	1	12
G	heavy load	3	12, 16, 17
H	heavy load	5	12, 16, 17, 18, 19

The scenarios presented in Tab. 2 for a fault of P=3000MW at t=0 s are more closely examined. A positive P means that negative control energy is required. Negative regulation power can either be generated by reducing the feed-in or by increasing the load. Since in prospective scenarios, the power generated by renewable energies should not be reduced as far as possible, just as it is now decided by the EEG, an intelligent load management based on the example of electric vehicles is considered in this paper. This means that if generation is too large, it will be used to charge storage facilities in the grid [2]. In the simulation, 10 pools of electric vehicles with a total power of P_{EVges}=500 MW are simulated. This corresponds to 50,000 electric vehicles with a charging capacity of P_{EV}=10 kW.

When the load factor is 100%, it can be assumed as the heavy load. These loads were taken from [7]. Accordingly, the load factor of 20% will be assumed similar to [11]. In the condition of the heavy load and a technical unit at node 12, as the simulation in scenario F, the protective element F4-12 is stimulated and triggered, as shown in Fig. 6. The activation of the technical unit results in the rising of conductor current at t=25.3 s due to the load increase. The excitation occurs at t=48 s since the maximum current has arrived. The gradient of the phase current becomes smaller after the excitation and the phase current reaches a stationary terminal value. Since the maximum value is still overstepped, the protection system is triggered after the set delay time of 5 seconds. The triggering happens at time t=53.1 s.

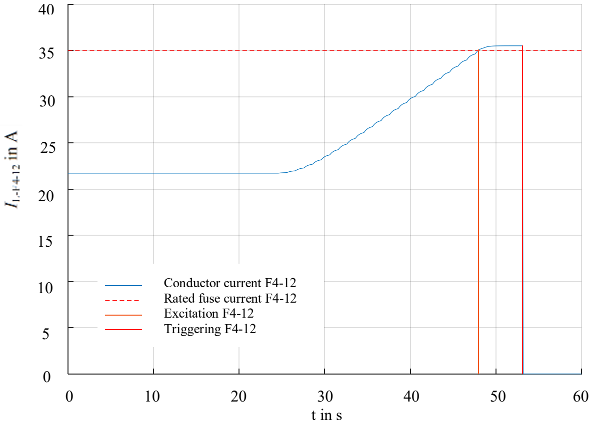

Fig. 7: Scenario F: Triggering of the protection system F4-12

In scenario H, in contrast to scenario F, two additional technical units are activated at nodes 18 and 19. As in scenarios F, the triggering by protective element F4 12 is expected. The protective elements F7 8, F4 12 and F10 18 were excited by an overcurrent during activation of the technical units. The protective element F4 12 is excited at time t=47.8 s, the difference of 0.2 s seconds is due to the sampling by the S function. Like the previous scenarios, this protective element is triggered in the case of a heavy load. The protective element F10 18 is also triggered at the time t=48.2 s. According to the selectivity, the protective element F7 8 is excited, but the other protective elements are triggered, causing the protective element to reset.

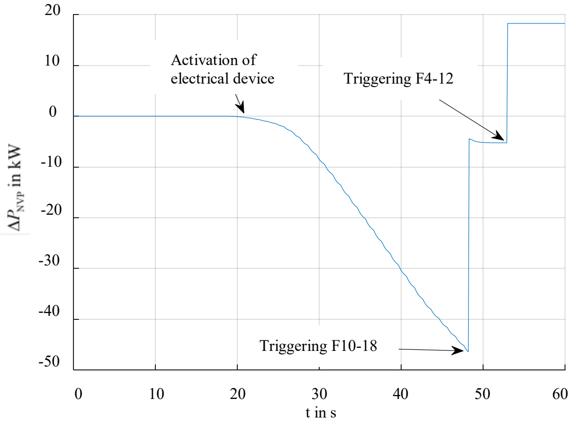

Fig. 8: Scenario H: Power Change at PCC

Due to the two triggering operations, the change in power results in a stepped curve from the time of the first triggering. As shown in Fig. 7, the power at the PCC drops here on the basis of the setpoint up to the triggering of the protective element F10 18. Here the power change at the PCC climbs from 46.25 kW to 4.42 kW, which corresponds to the connected load and the power change of the technical unit.

This is followed by a further reduction of the load since at node 12, the load continues to follow the setpoint. Then, similar to the other heavy load cases with load increase, the load at node 12 is reduced by triggering the protective element F4-12.

The triggering of the protective devices of individual branches can affect the frequency stability. According to the current selectivity setting by using the nominal current, the protective device on the power supply unit is excited, but not triggered. The results of the simulation are clearly presented in Tab. 3. The heavy load scenarios can be assumed to be the worst case. Thus, the probability of impact is fairly low. The charging of more than two electric vehicles simultaneously in a low-voltage grid with only one jet is currently still regarded as improbable, but trends towards more electric vehicles can be recognized and such a load should be expected in the future [49].

Tab. 3: Evaluation matrix der Simulation

🟧	Trigger	Scenario							
🟩	Excitation	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
▨	Normal operation	**low-load**				**heavy-load**			
Protective device	**F1-2**	▨	▨	▨	▨	▨	▨	▨	▨
	F2-3	▨	▨	▨	▨	▨	▨	▨	▨
	F4-5	▨	▨	▨	▨	▨	▨	▨	▨
	F4-12	▨	▨	▨	▨	▨	🟧	🟧	🟧
	F5-6	▨	▨	▨	▨	▨	▨	▨	▨
	F5-13	▨	▨	▨	▨	▨	▨	▨	▨
	F7-8	▨	▨	▨	▨	▨	▨	▨	🟩
	F7-17	▨	▨	▨	▨	▨	▨	▨	▨
	F10-11	▨	▨	▨	▨	▨	▨	▨	▨
	F10-18	▨	▨	▨	▨	▨	▨	▨	🟧

V.CONCLUSION

The simulated scenarios led to the conclusion that the protective devices in the low-voltage grid are primarily designed for the event of a fault. In order to observe a triggering of these protection elements, the grid must be heavily overloaded. The proposed concept can help the distribution system operator to detect such overloads and the effects of the protective devices before providing the secondary control power from his own system. In the scenarios at the nodes to which a controllable load can be connected, it was used to increase the load in the network until a triggering occurs. The influence of this triggering can be observed based on the power at the PCC point and thus, it can be connected between the distribution system operator and the aggregator. The aggregator now has the option of correcting the setpoint for this distribution network for the power change at which there is no influence by the protection systems. So that the available secondary control power can be used completely for power-frequency control. According to the principle, the secondary control power would be operated from a reserve pool. This would ensure that the setpoint requested by the transmission system operator can be fulfilled. In the low-load scenarios, there was, as expected, no effect from the protection systems. Here, the system dimensions were shown in the prescribed ranges. The voltage moves within a tolerance band of ±10 % around the nominal voltage and the conductor currents did not excite or trigger the protective devices.

The applicability of the approach can be verified by the simulation. In order to provide sufficient secondary control power in the future, it is necessary to resort to the capacities in the distribution grid. The processing of current measurement data in the grid and their use for operational planning is a meaningful method to react to changes in the distribution grid. In this way, it is possible to identify tendencies towards endangered states at an early time and to implement suitable preventive measures to ensure system stability. To achieve this with the increasing volatility of the feeding components and changing loads, it is necessary to take the protection measures within the grid in considerations. With the help of the approach, the influences of the protective devices can be identified and eliminated. Thus, it is possible to react preventively to current restrictions caused by the grid conditions. Furthermore, it is also possible to carry out simulations in the intra-day area by integration into a dynamic model in order to identify tendencies to endangered states in plant management.

REFERENCES

[1] R. Schwerdfeger: “Vertikaler Netzbetrieb,” Ph.D. dissertation, Dept..Power System. Ger., Univ. TU Ilmenau, 2016.

[2] Cao, Wenchao; Zhang, Xuan; Ma, Yiwei; Wang, Fred: Stability criterion and controller parameter design of radial-line renewable systems with multiple inverters. In: 2016 IEEE Applied Power Electronics Conference and Exposition (APEC). Long Beach, CA, USA, pp. 2229–2236.

[3] Chen, Jikai; Ma, Xiuwei; Li, Yang: Dynamic interaction analysis of two-parallel active power filter. In: 2016 China International Conference on Electricity Distribution (CICED). Xi'an, China, pp. 1–5.

[4] He, Jinwei; Li, Yun Wei; Bosnjak, Dubravko; Harris, Brent (2013): Investigation and Active Damping of Multiple Resonances in a Parallel-Inverter-Based Microgrid. In: *IEEE Trans. Power Electron.* 28 (1), pp. 234–246.

[5] Wang, Xiongfei; Blaabjerg, Frede; Wu, Weimin (2014b): Modeling and Analysis of Harmonic Stability in an AC Power-Electronics-Based Power System. In: *IEEE Trans. Power Electron.* 29 (12), pp. 6421–6432.

[6] Wan, Cheng; Huang, Meng; Tse, Chi K.; Ruan, Xinbo (2015): Effects of Interaction of Power Converters Coupled via Power Grid. A Design-Oriented Study. In: *IEEE Trans. Power Electron.* 30 (7), pp. 3589–3600.

[7] Yu, Yanxue; Li, Haoyu; Li, Zhenwei: Impedance modeling and stability analysis of LCL-type grid-connected inverters with different current sampling schemes. In: 2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC 2016 - ECCE Asia). Hefei, China, pp. 974–981.

[8] Parker, Stewart Geoffrey; McGrath, Brendan P.; Holmes, Donald Grahame (2014): Regions of Active Damping Control for LCL Filters. In: *IEEE Trans. on Ind. Applicat.* 50 (1), pp. 424–432.

[9] M. Schärfenberg, *Untersuchung der Wechselwirkungen zwischen leistungselektronisch integrierten Netzelementen im Verteilernetz*, Masterarbeit, Ilmenau, 2017.

[10] M. Schärfenberg, T. Jiang, S. Schlegel, D. Westermann, „Development of a Voltage-dependent Stabilizer for a converter dominated distribution grid“, ISGT Europa, Turin, 2017.

[11] S. Yang, F. Schaller, B. Schönfeld, S. Schlegel, B. Fischer, T. Jiang, S. Nicolai, S. Prinz, M. Malsch, D. Westermann, P. Bretschneider, „A cross voltage-levels simulation approach for interaction analysis in converter-dominated distribution networks “, Bonn, 2017.

[12] Y. Liu, *Untersuchung der Wechselwirkungen in Verteilnetzen mit hohem Anteil umrichtertechnologiebasierter Erzeuger und Lasten*, Ilmenau, 2016.

[13] Cigré Working Group B4.57, “Guide for the Development of Models for HVDC Converters in a HVDC Grid,” Cigré, 2014

[14] CIGRE, "Benchmark Systems for Network Integration of Renewable and Distributed Energy Resources", Task Force C6.04.02, 2010