2012 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe), Berlin

New Applications for Wide-Area Monitoring, Protection and Control

Sven C. Müller, *Student Member, IEEE,* Andreas Kubis, *Student Member, IEEE,* Sebastian Brato, *Student Member, IEEE,* Ulf Häger, Christian Rehtanz, *Senior Member, IEEE,* and Jürgen Götze, *Member, IEEE*

***Abstract*—As operation of electrical transmission systems faces new challenges due to liberalization and integration of renewable energies, novel solutions for power system management are needed. At the same time, the development of smart grids also pushes high performance communication and information technology that contribute decisively in enabling a dynamic monitoring, protection and control of large-scale and wide-spread power systems. The potential offered by smart grids and new fast controllable power systems equipment needs to be exploited by development of valuable applications for power system operation. Moreover, first experiences with selected dedicated applications call for the design of an integrated wide-area monitoring, protection and control (WAMPAC) system. This paper presents recent progress of research unit FOR1511 in the development of WAMPAC applications for stability monitoring, protection schemes based on wide-area information, and real-time congestion management. The research unit aims at developing a coherent WAMPAC system taking into account interdependencies and synergies of newly developed applications and conventional local systems in place.**

***Index Terms*—defense plan, power system operation, real-time congestion management, smart grids, stability assessment, system identificaton, WAMPAC.**

I. INTRODUCTION

INTEGRATION of renewable energy sources and the liberalization of electricity markets pose new challenges for the secure operation of the European power system. As grid expansion projects face obstacles in realization while network utilization increases and becomes more and more volatile, the electrical transmission system needs to be operated close to its operational limits and with increasing dynamic. An advanced dynamic system management will technically be enabled by new developments in power system equipment such as Flexible AC Transmission Systems (FACTS), High-Voltage Direct Current (HVDC) technology and synchronized Phasor Measurement Units (PMUs), as well as modern information and communication technology (ICT) that becomes wide-spread with the rise of smart grids. Research and engineering now need to develop efficient applications to make use of the new technical possibilities in order to meet current and future operational challenges. For this purpose, it is critical to design a coherent overall approach for system operation taking into account the strong interdependencies of various protection and control schemes.

A key concept of modern power system operation is the implementation of Wide-Area Monitoring, Protection and Control (WAMPAC) systems. Based on first practical experiences with dedicated wide-area monitoring, protection and control applications, it has been stressed that realization of the vision of an integrated WAMPAC system is highly desirable as it would provide significant benefits in sharing of data, network resources and ease of system expansion [1]. At TU Dortmund, DFG research unit FOR1511 "Protection and Control Systems for Reliable and Secure Operation of Electrical Transmission Systems" combines expertise from power and communication engineering, statistics and computer science in order to design coherent WAMPAC applications based on the latest progress of the disciplines involved. Furthermore, a comprehensive simulation environment is created for validation and testing of real-time capabilities of the newly developed algorithms in power system scenarios close to reality.

This paper is structured as follows: First, section II addresses state of the art applications and related work. In section III, recent developments and simulation results for three selected applications in FOR1511 are presented. These include stability assessment based on system identification and clustering (III-A), an agent-based control system for real-time congestion management (III-B) and a wide-area protection scheme for transmission corridors (III-C). Last, the paper is closed with a conclusion and outlook on future work.

II. STATE OF THE ART AND RELATED WORK

In this section, WAMPAC applications already state of the art or subject of current research are presented. As until today typically dedicated applications targeting either monitoring, protection or control are developed, the section is divided in these fields. Fig. 1 summarizes essential wide-area applications emphasizing the partial overlapping of the three domains that should be addressed in an integrated WAMPAC system.

A. Wide-Area Monitoring

A key enabler for modern wide-area monitoring systems (WAMS) is the introduction of multiple PMUs placed at several locations in the network as a complement to conventional measurements. The PMUs enable the availability of time-synchronized snapshots of the network including voltage and

This work was supported by the German Research Foundation DFG as part of research unit FOR1511 (http://www.for1511.tu-dortmund.de).

S. C. Müller, A. Kubis, U. Häger and C. Rehtanz are with the Institute of Energy Systems, Energy Efficiency and Energy Economics, TU Dortmund University, Dortmund, Germany (e-mail: see http://www.ie3.tu-dortmund.de).

S. Brato and J. Götze are with the Information Processing Lab, TU Dortmund University, Dortmund, Germany (e-mail: see http://www.dt.e-technik.uni-dortmund.de).

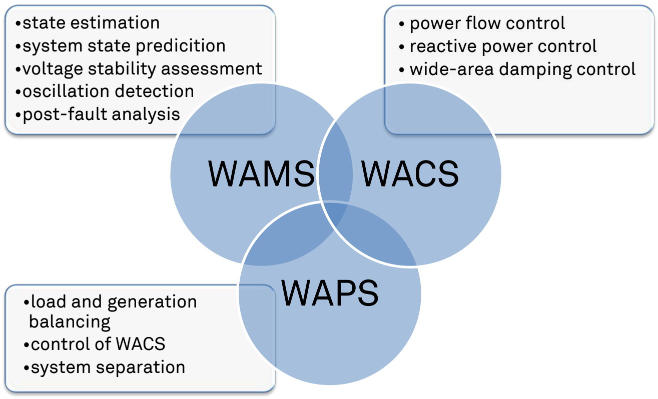


Fig. 1: Applications for wide-area monitoring, wide-area protection and wide-area control

current phase angles. A variety of WAMS applications has been proposed using these wide-area measurements.

Wide-area measurements enable enhanced stability assessments. With respect to small signal stability, eigenvalues of the system need to be analysed. With appropriate techniques, synchronized WAMS could enable online assessment of eigenvalues and identification of dominant modes. This analysis used to be undertaken offline whereas online assessment could provide significant insights in determining threats to system stability in online operation [2]. WAMS also offers new possibilities to improve voltage stability, detection of low frequency oscillations, and frequency instability [3].

In addition to stability analysis, several WAMS applications regarding state estimation, system parameter estimation and post-fault analysis have been presented [3], [4]. An overview on WAMS applications already implemented in wide-area transmission systems world-wide is given in [5].

B. Wide-Area Control

If by means of communication regional or system-wide data is available, wide-area control systems (WACS) can be deployed that exceed the functionalities of local control and respond faster than manual control from a control center [6]. Thereby, WACS can contribute as an effective additional layer to prevent blackouts and facilitate electrical commerce [7]. Besides the benefit of fast control in contingency cases, dynamic control is of growing importance along with the rise of fast controllable equipment such as HVDC and FACTS devices [8]. In this context, wide-area damping control with respect to oscillations in large-scale electrical transmission systems is subject of current research [9], [10]. Furthermore, wide-area congestion management by centralized [9] and decentralized [11], [12] power flow control concepts have been proposed, These make it possible to respond in real-time to contingencies, thus contributing to system stability, and to gain the economic benefits by dynamic power flow control for transmission corridors [13].

C. Wide-Area Protection

The fast evolution of WAMS enables real-time processing of wide-area measurement data for the use in system protection applications. Comprehensive studies on Wide-Area Protection Systems (WAPS) with focus on the development of versatile fully automatic protection systems, which are able to handle large disturbances and to prevent extensive blackouts in large power systems, have been carried out [14], [15]. Some systems have even proven their dependability on duty [14]. Such WAPS combine various Special Protection Schemes (SPS) and form a higher level of protection. They are also known as Defense Plans if they are able to act fully automatically in certain cases. The response time of Defense Plans is in the range of miliseconds up to minutes depending on the application and the communication infrastructure. The major application of Defense Plans applies to unforeseen contingencies where actions with very short response time are necessary in order to prevent wide spreading failures or even blackouts. Most common applications are central coordinated load or generation shedding, reactive power balancing and islanding, as last line of defense. In the case of out-of-step protection, today's interconnected systems are often equipped with out-of-step relays which operate locally at predetermined transmission corridors. The main disadvantage of local protected systems is the inability to execute controlled synchronous opening of transmission corridors. This causes excessive system stress due to vast transients at every interconnector opening procedure. This also applies to power plants where only local measurements are used in protection applications. Conventional power plant protection systems can be improved by making use of wide-area information. Several works have shown the possibility to prevent wide spreading blackouts due to loss-of-synchronism by initiating a controlled opening of transmission corridors based on PMU voltage angle measurements [16]. These approaches reduce the stress on the system and the occurrence of failed interconnector opening as it could occur in the local approach due to the mis-operation of one out-of-step relay.

All in all, WAMS applications are seen as enabler of fast, secure and well-functioning wide-are protection applications which will enhance power system capabilities and provide a huge step forward towards smart grids of the future.

III. New applications for WAMPAC systems

In the following, we describe selected WAMPAC applications currently under development in FOR1511. The results presented in sections III-A and III-B are based on simulations in the New England Test System (IEEE 39-bus 10-machine system) extended by four Phase Shifting Transformers (PSTs) and in the case of section III-B by an additional HVDC line (the network graph is shown later in Fig. 5).

A. Stability assessment by system identification and clustering

A matter of particular interest is the provision of supportive data for real-time system operation in order to maintain system stability. Applying system identification methods to wide-area measurements, it is possible to determine the system state of the network. Based on this information, a prediction of the stability margin can be undertaken making it possible to execute controlling and protective operations in the power

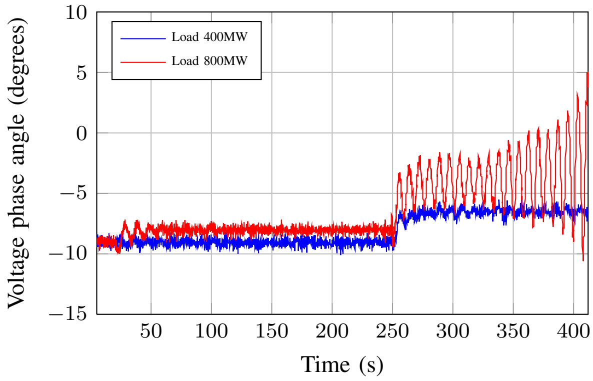


Fig. 2: Voltage phase angle at node 6 over time for different load situations in case of a line outage

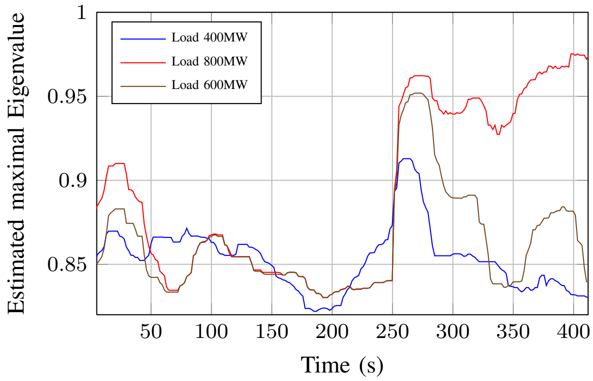


Fig. 3: ARMAX based stability estimation at node 6

system while preserving a stable system. As electrical transmission systems tend to be operated closer to its limits, this input becomes a viable part of real-time system operation. In this application, we apply subspace based identification techniques enabling the estimation of frequencies within the power system. For this purpose a frequency estimation algorithm based on the estimation of signal parameters via invariant techniques is used. This algorithm provides a fast, efficient and high-resolution estimation of the spectral components of the measured signals as shown in [17].

In FOR1511 a dynamic system identification application is developed. Due to sudden and volatile changes in the grid (such as load variations and faults) the system models needs to be updated frequently. In Fig. 2 an example for this behaviour is depicted. The plot shows the voltage phase angle at a single node over time for a line outage between nodes 1 and 2 under different loading situations (400MW and 800MW at node 4) of the network. At $t = 20s$ the load at node 4 is increased, and after the system has reached a steady state from the previous load change, the line outage takes place at $t = 250s$. For all cases the system is subject to noise caused by loadings. As it can be seen for a very high loading of 800MW, the power system tends to get unstable after the line outage.

The signals used are assumed to be gathered from PMUs and to contain information about the voltage magnitude and phase angle of each bus bar. With this data, different approaches were tested with respect to their usability as stability

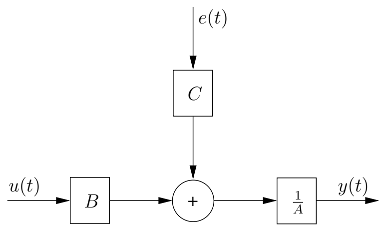


Fig. 4: Signal flow for ARMAX model

information criterion. The results for an ARMAX based estimation are shown in Fig. 3. For this approach an ARMAX model

$$A(q)y(t) = B(q)u(t - n_k) + C(q)e(t) \qquad (1)$$

is calculated for each node in the network. The model consists of the three system polynomials A, B and C which are computed from the output data $y(t)$, the input data $u(t)$, and an estimation of the system disturbance $e(t)$. The data used for the modelling process is gained from the node for which the model is currently computed. For this node, the voltage phase angle is treated as output. For the input data, each voltage phase angle of the neighbouring nodes is used. There is no further data of other nodes used in this process such that the network topology can be completely unknown. The signal flow for such an ARMAX model is depicted in Fig. 4.

After the modelling process, the Eigenvalues of the identified system are determined. The largest Eigenvalue which is closest to the stability border is then extracted and plotted. If this Eigenvalue tends to a value of one, the system can be interpreted as unstable. The whole process of modelling and the determination of Eigenvalues is done dynamically for each time-step and uses a data history of about 40s. The sampling of data is done every 10ms, this leads to a very time accurate view of the system and gives a quick response for changes within the network.

Till now, the modelling process was done for each node in the network separtly. After the system stability at each node has been computed, it is now possible to exchange this information and analyse the whole network by the stability condition at each node. It can be seen that the development of Eigenvalues is similar for some nodes within the network. Based on this data, it is possible to perform a clustering of the network. A simple correlation based method suffices to produce a clustering output as shown in Fig. 5.

In addition to the ARMAX based approach, the data of each node is used within a subspace based identification technique enabling the estimation of frequencies within the power system. For this purpose the ESPRIT algorithm [18] is used. This algorithm provides a fast, efficient and high-resolution estimation of the spectral components of the measured signals as shown in [17]. This method is less complex than the previous presented ARMAX modelling, but its results are not suited for a clustering process afterwards.

The ESPRIT algorithm is based on the correlation matrix $\hat{R}_{yy}$ of the signal $y(t)$, which in this case is the voltage phase angle of the node, where the stability criterion shall be calculated. For this mxm matrix an Eigenvalue decomposition $\hat{R}_{yy} = \hat{U}\hat{\Lambda}\hat{U}^*$ is performed. The Eigenvalues are sorted in

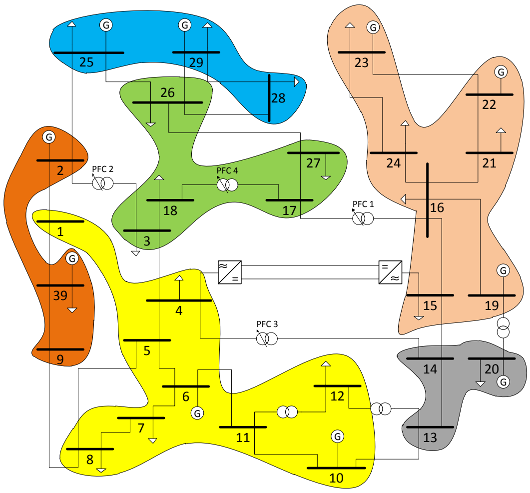


Fig. 5: Network clustering by ARMAX identification

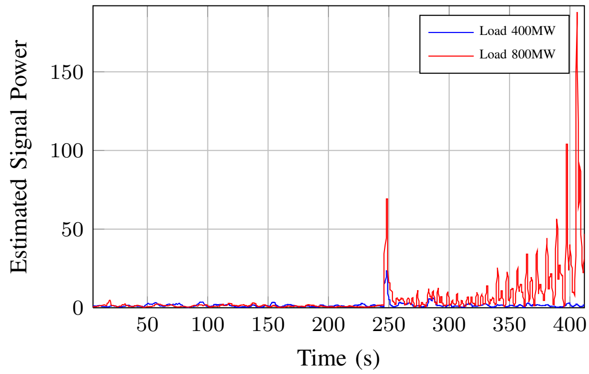


Fig. 6: ESPRIT based stability estimation at node 6

descending order and separated into noise and signal space $\hat{S}$. The signal space matrix is then decomposed to $\hat{S}_1 = [I_{m-1} 0]\hat{S}$ and $\hat{S}_2 = [0\ I_{m-1}]\hat{S}$ and the Matrix $\hat{\Phi}$ is estimated as $\hat{\Phi} = (\hat{S}_2^* \hat{S}_2)^{-1} \hat{S}_2^* \hat{S}_1$. The Eigenvalues $\hat{\chi}_i$ of $\hat{\Phi}$ give estimates of the frequencies $\hat{\omega}_i = arg(\hat{\chi}_i)$ of the original signal $y(t)$. From the frequencies the spectral power is determined by evaluating the following function:

$$f(\omega) = \left[\left| \prod_{k=1}^{n} e^{j\omega} - |\chi_k| e^{j\omega_k} \right|^2 \right]^{-1} \quad (2)$$

The main advantage of this identification by usage of ESPRIT algorithm is the fast estimation for high SNR values. As shown in Fig. 6, the stability criterion is the estimated power of the signal.

For an unstable network setting this estimated power tends to gain great values. Compared to Fig. 3, it can be seen that not only an unstable case can be identified but it is also possible to estimate the severity of the failure by accounting the information of the estimated power value. On the other hand, the ARMAX based approach allows a better stability estimation prior to the failure when the amplitudes of the oscillating signal are still very low.

As it can be seen, the combination of ARMAX and ESPRIT based system estimation leads to a comprehensive view on the system stability both in normal operation and in case of failures. When in the latter case power oscillations get significant, subspace based methods like ESPRIT tend to produce better and faster results. With this information and the clustering of the network in main areas, it is possible to get a detailed assistance information for controlling the network and for the protection of endangered lines.

B. Real-time coordinated power flow control

In several regions of the European grid Power Flow Controllers (PFCs) - such as PSTs, HVDC links, as well as serial or combined controlled FACTS devices - are installed. E.g., in the Benelux region several PSTs are installed and power flows between Spain and France will be controllable by existing PST close to the border and a new HVDC link. PFCs with areas of mutual impact require coordination of their control in order to avoid counter-productive or overcompensating control actions. Central coordination techniques (e.g. Optimal Power Flow (OPF)) for PFCs require a relatively long computation time, often in the range of several minutes [19], and depend on the availability of system-wide data. However, security constrained OPF calculations taking into account corrective actions could already provide a set of appropriate corrective PFC settings for a certain set of contingencies that could be initiated as new set points from a control center in case one of these contingencies occurs.

As a complement to such central control schemes, a decentralized coordination based on a Multi-Agent-System (MAS) could serve for enabling real-time congestion management. This enables the PFCs to contribute fast and robustly in counteracting overloads, being specifically of value for maintaining system stability in N-2 scenarios or higher. Based on first approaches in [11] and [**?**], a decentralized coordination system for PFCs, in particular extended to HVDC, is developed with the following design: software agents are installed at the substation level for all serial network devices in the respective area. The agents frequently forward state messages containing loading, impedance and predecessors of the message to their neighbouring agents. Thus, information about the topology and operating state becomes available at a decentralized level by direct communication between substations and independently of a central entity. From the state messages received, each agent at a PFC can derive a nodal admittance matrix $\underline{B}$ for DC load flow approximations with shunt elements being neglected. With the connected buses of a particular PFC c corresponding to the first two rows and column of B, the sensitivity $sens$ of a device d (located between nodes i and j) with respect to a control action c can be estimated by introducing a loop flow $\underline{P}$ between the two buses of c (see equations (3-5)) [19]:

$$\underline{P} = \begin{bmatrix} 1 & -1 & 0 & \ldots & 0 \end{bmatrix}^T \quad (3)$$

$$\underline{\delta}' = \underline{B}^+ \cdot \underline{P} \quad (4)$$

$$sens(c, d) = \frac{1}{x_{ij}} \cdot \delta'_i - \frac{1}{x_{ij}} \cdot \delta'_j \quad (5)$$

In the equations, $\underline{B}^+$ represents the pseudo-inverse of $\underline{B}$, x_{ij} represents the impedance between node i and j, and $\underline{\delta}'$ repre-

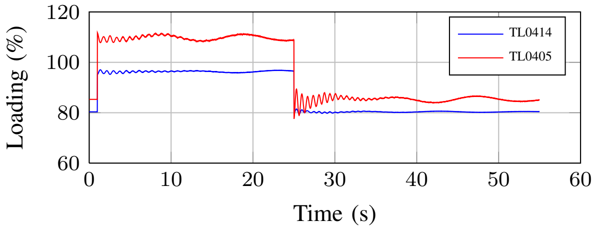


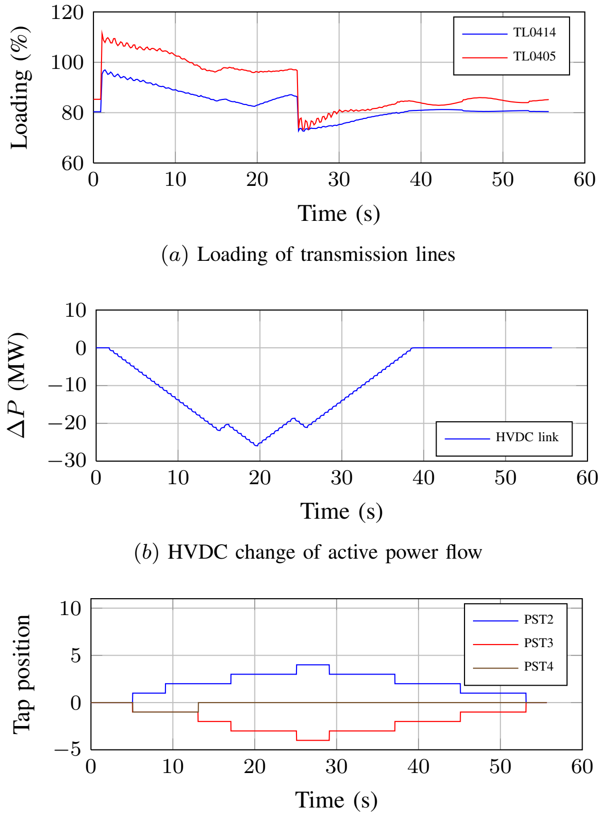
Fig. 7: Loading of transmission lines without power flow control

sents the change of voltage angles due to $\underline{P}$. Next, all agents at PFCs coordinate their actions in order to achieve a system-wide (respectively "area-of-significant-impact"-wide) relief of congestion thus avoiding cascading overloads. Different coordination concepts are considered: swarm-based intelligence, price-based negotiation, and criticality based prioritization. The last concept has shown good performance in the simulations: a PFC c calculates weights for all surrounding devices depending on the loading of the device and the sensitivity of the device with respect to control actions of c and the highest weight determines the next incremental control action of c (for more details see [11]).

A particular focus in further developing this approach is set on testing the real-time capability of the coordination system by simulating agent communication based on IEC 61850 as well as considering execution times and potential failure of components. In addition, interdependencies with conventional local and new wide-area protection schemes (e.g., opening of transmission corridors as discussed in subsection III-C) as well as response to power oscillations are investigated. As exemplary results, Fig. 7 and 8-(a) depict the loading of two highly loaded lines without a reaction and with a coordinated real-time control of HVDC and PSTs, respectively. In the investigated scenario, the transmission line TL0304 between nodes 3 and 4 trips at $t = 1s$ and is reconnected at $t = 25s$. It can be seen that the load of the lines is reduced successfully by the control system and the overload of TL0405 is reduced below 100% in about $11s$. The HVDC line (assuming a moderate control speed of max. $0.8MW$ steps every $0.5s$) reacts quickly and flexibly, shown in 8-(b). The PSTs (Fig. 8-(c)) also contribute to the overload mitigation but due to the internal mechanics (a delay of $4s$ for a tap change is assumed) they adjust their tap position less flexibly and with delay. All controllable devices readjust their setpoint stepwise to neutral after the line is reconnected and former system operation point is regained.

C. Wide-Area Transmission Corridor Protection

The use of wide-area protection applications implies a strong crosslink between information and communication technology, measuring technology and power system operation. It is important to detect critical system states accurately so as to react with suitable defense actions. A wide-area protection scheme using voltage angle measurements based on the research of [11] is used in this approach. It is proposed to separate transmission corridors in case of emergency



(a) Loading of transmission lines

(b) HVDC change of active power flow

(c) PST tap positions (PST1 not shown because it did not change tap)

Fig. 8: Simulation results for test case: line loadings, change of active power flow on HVDC link and PST tap positions

caused by wide-spreading disturbances in order to prevent total blackouts. The separation of an interconnected system into sub-systems will prevent the penetration of well working systems with vast disturbances from neighbouring systems. After the disturbance has been cleared, the sub-systems will be resynchronized.

Voltage angle measurements will be performed at the beginnings and ends of interconnecting transmission lines and at important substations. The differences and changes between voltage angles are monitored and can be used for the estimation of load flows as well as for drawing conclusions regarding static and transient angle stability of different regions in the interconnected system. The observation of voltage angles with PMUs enables the application of an innovative system protection scheme focussing on the protection against loss of synchronism. Such a protection system based on voltage angles is able to determine maximum power transfer capabilities dynamically and is able to react in case of disturbances with system separation to prevent sub-systems to collapse due to loss of synchronism issues or spreading disturbances.

In contrast to conventional Out-of-Step (OOS) relays placed at important transmission corridors, the synchronized opening of transmission corridors to separate systems reduces the number of stressing actions towards the affected systems to one single action. OOS relays detect Out-of-Step conditions locally. Thus, the asynchronous opening procedure causes massive stress towards the system at each relay trigger operation. Nevertheless, load and generation need to be balanced immediately in each sub-system after separation not matter what kind of separation technique is used.

This wide-area protection scheme uses an approach based on a characterisation of the system operation state due to voltage angle measures. The system classifications are based on the absolute voltage differences δ_{AB} between beginning ϑ_A and end ϑ_B of a transmission corridor line or different areas, as well as the rate of change in dependency of time δ'_{AB}.

$$\delta_{AB}(t) = \vartheta_A(t) - \vartheta_B(t) \tag{6}$$

According to this approach, power systems could operate in following system states as a function of voltage angle differences and changes over time:

- secure operation state
- endangered operation state
- disturbed operation state
- separated operation state
- blackout

Fig. 9 shows a generic interconnection between two grids consisting of a double tie line. We assume a high active power flow P over the two lines. Both lines are electrical equal, thus, the same power flows on the lines. A 3-phase short circuit (3-ph sc) is simulated on line 2 at $t = 60s$. The impact on the voltage angle difference between bus BB-A and bus BB-B δ_{AB} is shown in Fig. 10. Due to the disturbance, line 2 needs to be kept out of operation and the power flowing on line 2 will shift to the remaining line 1. This is indicated by an increase of the voltage angle difference. The voltage angle difference is further increasing due this large disturbance. The increase of δ_{AB} indicates a rotor angle instability problem. Loss of synchronism may happen. In order to detect loss of synchronism conditions and to take adequate actions for avoiding loss of synchronism, the progress of the voltage angle difference δ_{AB} is monitored. It can be seen that the rise of δ_{AB} develops with different rates of change. Due to this, it is necessary to observe the absolute voltage angle difference δ_{AB} as well as the rate of change δ'_{AB}.

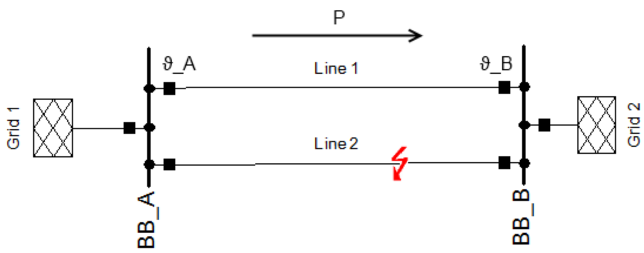


Fig. 9: A short circuit on an exemplary double line interconnector between Grid 1 and Grid 2.

The time frame of such an disturbance is in a typical time range of $3 - 20s$ [20]. In this short time-frame it is impossible for system operators to react adequately with manual actions. Therefore, this time frame requires fully automatic defense actions. As soon as a limit is exceeded, the protection scheme will be excited. The first limit $\delta_{excitation}$ is set close to the operational stability limit. If $\delta_{excitation}$ is exceeded, the protection scheme is excitated and switches from secure operation state to endangered operation state. In the endangered operation state coordinated actions in order to lower the voltage angle differences are performed. These actions are corrective and could include load and generation shedding or interventions in the load flow like it is referred in section III-B.

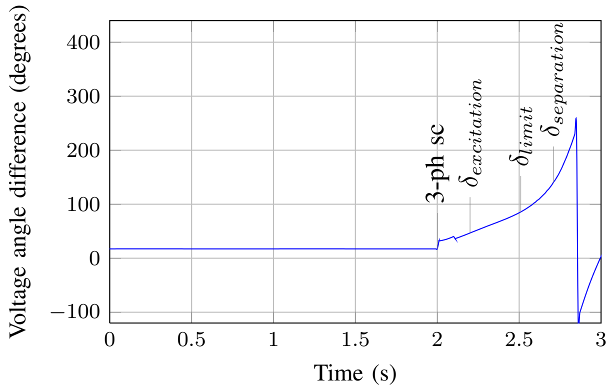


Fig. 10: Voltage angle difference between BB-A and BB-B

If the voltage angle difference even exceeds δ_{limit} and if the rate of change δ'_{AB} accelerates as well, the system is in disturbed state. This means that previous actions were not successful or not completely finished. Load and generation balancing actions which were already initiated in endangered operation state will not be cancelled. Furthermore, the system separation will be prepared. With reference to the multi-agent based wide-area power flow control, new parameters for power flow controllers in all sub-systems can be calculated assuming a separated unsynchronized power system. This procedure has the advantage that corrective power flow and load balancing actions could be applied just in the moment when the voltage angle difference excesses $\delta_{separation}$ and the protection system forces the separation command. After separation, the maintenance of operation has the highest priority in the separated systems and could be achieved by significant load and generation shedding, if necessary. Fig. 11 shows the system operation states and the possible control capabilities of the proposed protection schemes.

This kind of wide-area protection has the potential to be used in addition to conventional relays in form of an additional backup protection scheme, as last line of defense. Protection decisions based on voltage angle differences do not need to take into account specific topology characteristics. Nevertheless, a lot of research needs to be done. It is necessary to determine the limiting values more precisely and to evaluate extensive simulations about the behaviour of this protection scheme including its excitation and triggering behaviour as well as an evaluation about the risk of mal-operation. Moreover, the ability of the system to react in real time needs to be evaluated.

D. Coherent WAMPAC system design

A particular focus in FOR1511 is set on the design of a coherent and integrated overall WAMPAC system. The

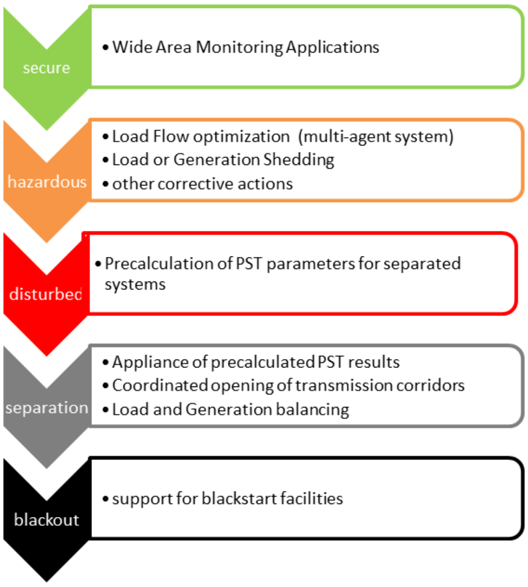


Fig. 11: Possible WAPS actions due to its system operation state

development of the applications presented in subsections III-A - III-C also aims at accounting for interdependencies and synergies among the modules involved. In this context, we currently investigate performance of monitoring algorithms, e.g., also spectral clustering, in order to determine whether the information gained by these can be used as beneficial input for the protection and control applications. Furthermore, the contributive coordination of power flow controllers in case of the execution of a defense plan is under investigation.

As a special analysis, the integrated execution of all aforesaid applications in a smart grid environment will be investigated in a novel hybrid simulator featuring a co-simulation of power systems and communications networks as well as the accounting for execution times of algorithms (details see [21]). With this simulation environment, the applications will be tested with respect to their real-time performance taking into account delays and dynamic behaviour in the power system as well as in the ICT domain. Details on the hybrid simulator and analyses of the real-time performance of applications will be published in the near future.

IV. Conclusion and Outlook

Smart grids and fast power system equipment technically enable an increasingly dynamic power system operation. Based on latest innovations in power systems technology, communication technology, statistics and computer science, new WAMPAC applications are designed in DFG research unit FOR1511 with a focus on developing a coherent integrated WAMPAC system. In this paper, recent advancements for three applications and simulation results have been presented. Research on stability monitoring applications proposes a combination of ARMAX and ESPRIT based state identification and clustering for dynamic stability assessment. Moreover, real-time congestion management based on decentralized coordination of PSTs and HVDC could adaptively mitigate overloads being of particular importance in an N-2 scenario in order to avoid tripping of additional lines. As an extension, the inclusion of power plants in the multi-agent system could enable real-time redispatch in disturbed system state and will be examined in the future. Furthermore, a wide-area protection concept including the synchronous opening of transmission corridors based on the observance of voltage phase angle differences is proposed as a last line of defense.

As future work, the applications will be tested in a new simulation environment for smart grids with respect to their real-time performance and with respect to their behaviour when applied jointly. Based on these results, interdependencies and potential synergies between the aforesaid and additional applications of FOR1511 (including spectral clustering and power plant protection based on wide-area information) will be analysed and accounted for in the application design in order to ensure a well suited and coherent system performance.

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BIOGRAPHIES

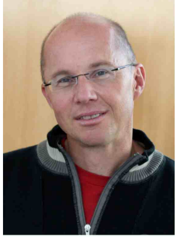
Sven Christian Müller was born in Germany in 1986. He received the Diploma degree in Industrial Engineering and Management at TU Dortmund, Germany, and a Master of Science in Industrial Engineering at the Georgia Institute of Technology, USA. Since 2011, he is working on his Ph.D. degree at the Institute of Energy Systems, Energy Efficiency and Energy Economics at TU Dortmund. His research is focused on modelling and simulation of power systems and electricity markets, power system operation and network integration of renewable energies.

Andreas Kubis (S'10) was born in Dortmund (Germany) in 1985. He graduated from the University of Applied Sciences in Dortmund with Bachelor degree in 2009. Afterwards, he studied at the University of Kassel and received his Masters degree in 2011. Since 2011, he is employed as research associate at the Institute of Energy Systems, Energy Efficiency and Energy Economics (ie^3), TU Dortmund University, Dortmund, Germany. His research is focused on power system stability and system separation studies.

Sebastian Brato was born in Germany in 1984. He received his Diploma degree in electrical engineering in 2011 from TU Dortmund University. Afterwards he began as research associate at the Information Processing Lab at TU Dortmund University. His research is focused on system modelling and machine based learning algorithms.

Ulf Häger (M'08) received his diploma degree in electrical engineering in 2006 from the TU Dortmund University, Germany. Currently he is working as research associate at the Institute of Energy Systems, Energy Efficiency and Energy Economics (ie^3) at the TU Dortmund University. His fields of interest are wide area power flow control and wide area protection systems as well as the application and development of FACTS devices for power flow control. Furthermore he is involved in national and international network expansion studies.

Christian Rehtanz (M'96–SM'05) received his diploma degree in electrical engineering in 1994 and his Ph.D. in 1997 from the TU Dortmund University, Germany. From 2000 he was with ABB Corporate Research, Switzerland and from 2003 Head of Technology for the global ABB business area Power Systems. From 2005 he was Director of ABB Corporate Research in China. From 2007 he is professor and head of the Institute of Energy Systems, Energy Efficiency and Energy Economics (ie^3) at the TU Dortmund University. His research activities include technologies for network enhancement and congestion relief like stability assessment, wide-area monitoring, protection, and coordinated FACTS- and HVDC-control.



Jürgen Götze (M'1987) received his Dipl.–Ing. and Dr.–Ing. degrees in Electrical Engineering from Munich University of Technology in 1987 and 1990, respectively.

From 1991 to 1992 he held a research position at the Computer Science Department of Yale University. From 1992 to 1995 he was with the Department of Electrical Engineering and Information Technology of Munich University of Technology. From 1995 to 1996 he was with the DSP group of the Electrical and Computer Engineering Department of Rice University. Since 1997 he is Professor (Information Processing Lab) at the Department of Electrical Engineering and Information Technology of TU Dortmund University.

He served as Associate Editor of *IEEE Transactions on Circuits and Systems, Part I: Fundamental Theory and Applications* from 1997 to 1999. His research interests include: signal and array processing, wireless communications, parallel algorithms and architectures, system-on-chip.