Final report

1. Project details

Project title	Security Assessment of Renewable Power Systems
File no.	2016-1-12427
Name of the funding scheme	ForskEL
Project managing company / institution	DTU Elektro
CVR number (central business register)	30060946
Project partners	DTU WIND, DIKU, Copenhagen University
Submission date	30 June 2021

2. Summary

The SARP project aimed at pushing forward the development of the technology needed for ensuring secure operation of future electric power systems with a large share of power production based on fluctuating renewable energy sources (RES). Previous methods used to ensure secure operation are based on time consuming offline analysis and are foreseen to become inadequate for the future renewable power systems. The fluctuating nature of the production will make the planning of stable and secure operation a challenging task, as it can no longer be carried out offline several hours in advance.

To ensure stable and secure supply of power in the future renewable power system, methods are needed for real-time monitoring of system security and stability margins, together with approaches for determining the required coordinated control actions, to reestablish safe operating conditions when necessary. The SOSPO project, funded by the *Danish Council of Strategic Research*, initiated R&D on approaches for secure operation of future power systems. The SARP project aimed to continue the technology development by extending and pushing forward the breakthroughs initiated by the SOSPO project and addressing other critical areas that were not covered by previous R&D. A special focus was put on the algorithmic aspects related to real-time assessment of system security and how to cope with RES based generation and its control to achieve an accurate assessment of RES based systems.

The project delivered a range of results including high performance algorithms ensuring assessment of full scale systems in real-time, improved modelling of RES equipment with aim of easer assessment of their impact on system stability, new method for real-time assessment of voltage stability and further development of the WARTApp (Wide-Area Real-Time Application) platform where initial efforts were made to interface the platform to a real-power system.

Initatives have been taken by the Nordic TSOs to develop infrastructure and platforms where solutions inline with those delivered in the SARP project may be implemented and operated in real-time.

Dansk version:

Formålet med SARP-projektet var at fortsætte udviklingen af den nødvendige teknologi for at sikre stabil og sikker drift af fremtidens elforsyningssystemer der har en stor andel af produktionen baseret på ustyrbar vedvarende energikilder. Den traditionelle sikkerhedsanalyse baseres på tidskrævende offline metoder som forventes at blive utilstrækkelig til det fremtidige system. Produktionens svingende karakter gør planlægningen af stabil og sikker drift til en udfordrende opgave, da den ikke længere kan udføres offline flere timer i forvejen. For at sikre stabil og sikker elforsyning bliver der behov for metoder der i realtid kan overvåge systemets sikkerheds- og stabilitetsgrænser. Ligeledes er behov for metoder til bestemmelse af de nødvendige kontrolhandlinger der genopretter sikre driftsforhold, når det er nødvendigt.

Med det danske SOSPO-projekt, finansieret af det Stratetiske Forskningsråd, blev F&U initieret i metoder det kan sikre driften af det fremtidige VE baserede elforsyningssystem. SARP-projektet havde til formål at fortsætte teknologiudviklingen ved at udvide og skubbe de teknologigennembrud fra SOSPO-projektet, og adressere andre kritiske emner som ikke er dækket af tidligere F&U. Der blev lagt særlig vægt på de algoritmiske aspekter relateret til realtidsvurdering af systemsikkerhed og hvordan VE-baseret produktion inkluderes i stabilitetsmetoderne for opnå en nøjagtig vurdering af VE-baserede systemer.

SARP projektet leverede en række resultater, herunder højtydende algoritmer, der sikrer at vurdering af fuldskalasystemer kan foretages i realtid, forbedret modellering af VE-produktions enheder med henblik på lettere vurdering af deres påvirkning på systemstabilitet, ny metode til realtidsvurdering af spændingsstabilitet og videreudvikling af WARTApp-platformen (Wide-Area Real-Time Application), hvor de første skridt imod at anvende platformen på et virkeligt elforsyningssystem blev taget.

De nordiske system operatorer har taget initiativer til at udvikle infrastruktur og platforme, hvor løsninger som dem der leveres i SARP-projektet, kan implementeres og drives i realtid.

3. Project objectives

Stable and secure power systems are of fundamental importance to modern societies and will continue to be so in the future. The global challenges to electric power systems in the coming decades are great, where focus is on energy supply with a minimal dependency on fossil fuels. The challenges involve the development of future power systems that provide stable energy supply at competitive price and with minimal environmental impact. A power production that is a subject to prevailing weather conditions can introduce rapid changes in the system operating conditions, resulting in that planning for stable and secure operation can no longer be made a few hours ahead. The fluctuating power production introduces a need for short-horizon supervision, and fast planning and coordination of control actions that ensure system security. Present planning approaches based on offline analysis and set-point adjustments will not ensure stability and security.

The SARP project aimed at pushing forward the development of the technology needed for ensuring secure operation of future electric power systems with a large share of power production based on fluctuating renewable energy sources (RES). To assure stable and secure supply of power in the future renewable power system, methods are needed for real-time monitoring of system security and stability margins, together with approaches for determining the required coordinated control actions, to reestablish safe operating conditions when necessary. The SOSPO project, funded by the *Danish Council of Strategic Research*, initiated R&D on approaches for secure operation of future power systems. This project proposal aims to continue the technology development by extending and pushing forward the breakthroughs initiated by the SOSPO project and addressing other critical areas that were not covered by the previous R&D activities within the field.

Proposed technology for ensuring secure operation of future power systems

The approach envisioned for ensuring secure operation of renewable power systems is depicted in figure 1. The figure illustrates on the one hand, a future system characterized by a high share power production based on fluctuating RES and partly controllable consumption, and on the other hand, the central elements in an operational tool that is envisioned to ensure a secure and stable operation of fluctuating renewable power systems. The overall functionality of the operational tool is obtained from several individual modules and their interactions.

The operational tool is anticipated to function in the following way: PMU (Phasor Measurement Units) snapshots, that provide full observability of the system conditions, serve as input into modules that have the purpose of assessing system stability and security in real-time. Each individual assessment method focuses on a particular form of instability and assesses, for the observed operational condition, the distance to the stability or security boundary of concern. The results from the stability and security assessment modules are used as input to two different wide-area control modules. One of the control modules reacts when insecure operation has been identified; the other module identifies control actions that can be taken in emergency situations in order to avoid an impending stability problems and potential system blackout.

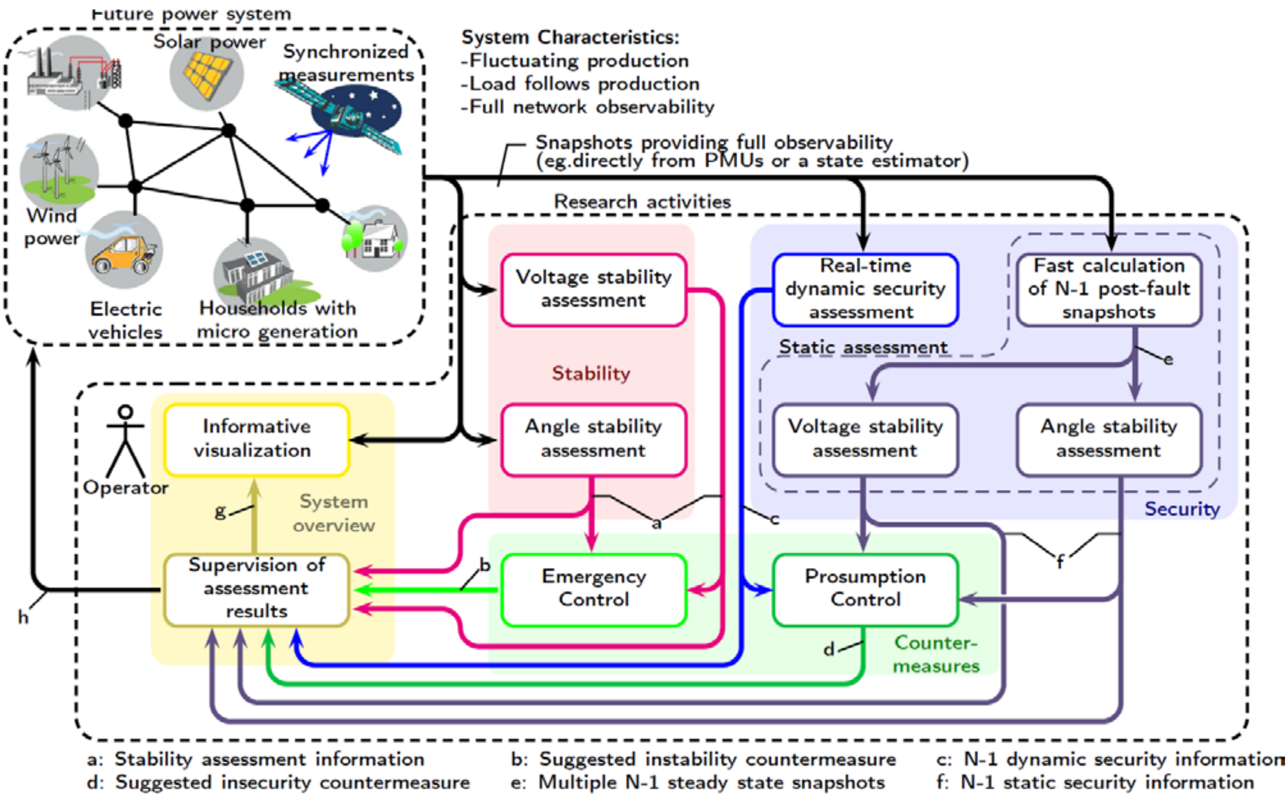

Figure 1: Functional overview of an operational tool intended to ensure secure operation of the future renewable power systems. A SW-platform handling the complexity of the flow of information was further developed in the SARP project.

The overall picture of the system security and stability is obtained in a supervisory module, which gathers the results from the various assessment modules and the wide-area control modules to determine the criticality of the system operation. The supervisory module determines which information should be presented to the operator through a man-machine interface for an effective decision support and the module can initiate counter-actions automatically during identified emergency conditions.

In order to facilitate and implement the various methods a SW-platform is needed, which has to be capable of handling the complexity associated with the various interactions and flow of information between the modules in figure 1.

<u>*Overall objective of the SARP project:*</u>

The overall objective of the SARP project is to push forward the envisioned technology (depicted in figures 1) needed for ensuring secure and stable system operation of future power systems with high share of fluctuating RES based production.

<u>The SARP project's main components:</u>

To address the project's objectives, the main R&D component of the project is divided into four parts as illustrated in figure 2 and described in the following.

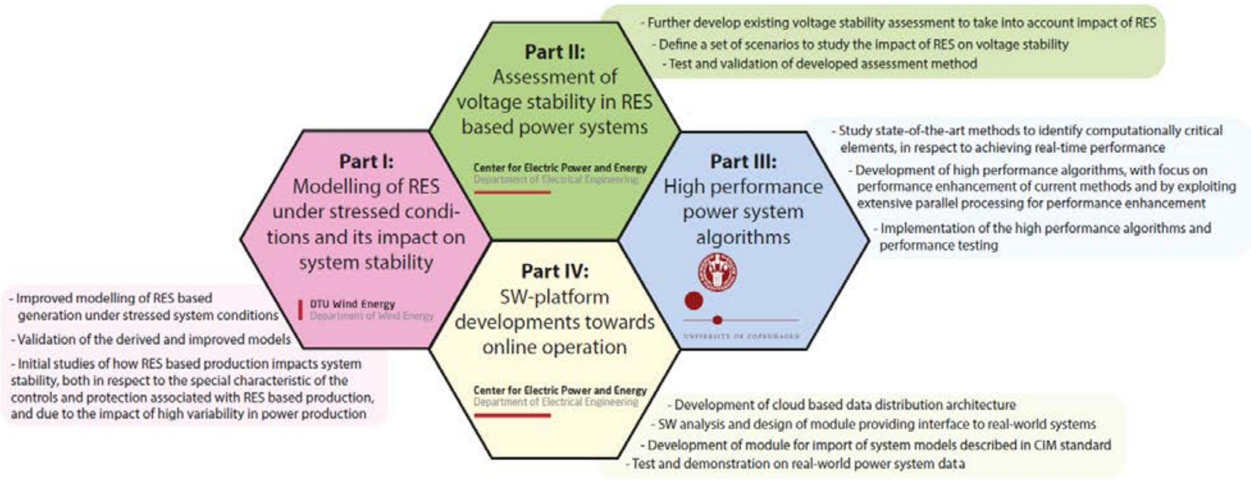

***Figure 2**: Overview of the four main components in the SARP project.*

<u>*Part I - Modelling of RES under stressed conditions and its impact on system stability:*</u>

The objective of this part of the project was to acquire improved models of RES based generation units, controls and protection for abnormal system conditions. System stability problems usually occur during very stressed system conditions. Therefore, it is crucial that the deployed simulation models provide a realistic representation of the RES based units and associated equipment during abnormal and stressed conditions when the impact of RES based production on system stability is to be investigated. The main contributors for this part were DTU Wind, that are recognized experts in modelling RES equipment, and CEE-DTU that have strong background in assessment of power system stability.

Part II – Assessment of voltage stability in RES based power systems:

This part of the project focused on how previously developed approaches for real-time stability assessment may be further developed, such that they become capable of coping with the impact that the RES based generation has on system stability. The objective is to derive updated expressions for critical boundaries or conditions, and exploit them for extending the previous methods. The main contributors in this part were CEE-DTU, with expertise in development of stability and security assessment methods, and DTU Wind, experts in advanced RES modelling.

Part III – High performance power system algorithms:

In order to pursue a real-time operation of the various methods, efficient algorithms ensuring fast execution will be developed in the project. Focus is on identifying computationally critical parts for the developed methods, develop effective algorithms that provide speedup in execution, i.e. allowing parallelization of the computationally heavy part of the algorithms. The contributors to this tasks were the *Department of Computer Science (DIKU)* at Copenhagen University, which provide expertise in numerical algorithms and CEE-DTU that provide the insight on the various developed methods intended for operation in real-time

Part IV – SW-platform improvements and developments towards online operation:

The final part focussed on further development of the SW-platform needed to cope with complexity of the suggested approach for ensuring secure operation of the future power system (as envisioned in figure 1). The aim was to extend and further develop the platform. Among others establish interface to real-world power systems datasets. The main contributor was CEE-DTU, with strong experience in development of SW-platforms for supporting implementation and performance tests of advanced real-time application of wide-area data.

4. Project implementation

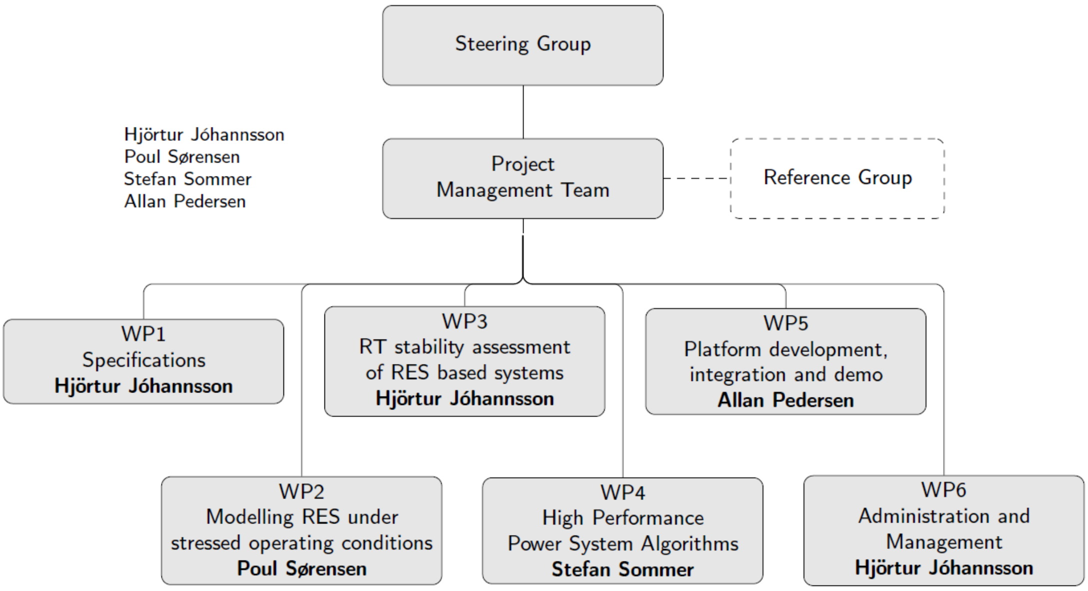

Figure 3: *Governance structure for the SARP project.*

The SARP project had an governance structure with clear distribution of responsibilities, effective communication procedures and appropriate backup mechanisms in the event of major deviations from the plan will be established. The management structure enabled efficient project management that ensured a successful completion of the project. To achieve this, the responsibilities and communication procedures need to be clearly defined. Figure 3 shows the management structure and organization for the SARP project. In the following, different management roles are listed and described:

- **Steering group:** The superior decision maker, consisting of one representative of each project partner.
- **Project manager:** Responsible for the overall management and progress. Manages the administrative and financial communication with the funding body.
- **Project management team:** Main operative body, responsible for everyday management tasks, scientific progress and deliverables.
- **Work package leaders:** Responsible for the progress, reporting and the deliverables from their work packages.
- **Reference group:** Provides feedback, opinions and support on individual activities and the project in general.

The project evolved in a smooth manner with well coordinated project management. The core project team consisting of three senior academics (at associate professor level and higher), senior SW developer and three PhD students. The small size of the core team made all coordination and management of activities easy and straight forward. The PhD projects were co-supervised by the senior academics which further supported good coordination between the various PhD project activities.

The project work was carried out in good accordance with the initial project plans. The only changes that had to be made during project period were related to shifting to certain tasks due to delays in recruitment of PhDs and a PhD student's maternity leave. The planned milestones and deliverables were met.

The COVID 19 pandemic resulted in that a final dissemination event could not be arranged as initially intended in march 2020 (as a physical event). Instead, a web-based dissemination workshop was arranged with participants from the Nordic TSOs where the major findings were demonstrated to the participants.

5. Project results

The SARP project resulted in solutions ranging from new ways of modelling renewable generation for stability assessment, HPC algorithms and new method for voltage stability assessment in real-time. The dissemination of the results is listed in appendix. The key journals and conferences where the SARP research was published are:

- *Journals:*
    - *IEEE Transactions on Power Systems*
    - *IET Generation, Transmission and Distribution*
    - *ELSEVIER Electric Power System Research*
    - *ELSEVIER International Journal of Electrical Power and Energy Systems*
    - *IEEE Access (open access journal)*
    - *Energies*

- Conferences:
  - IEEE PES General Meeting
  - IEEE PES PowerTech
  - Power System Computation Conference (PSCC)
  - IEEE PES ISGT
  - The international Cigre Symposium
  - IEEE PES Asia-Pacific Power and Energy Engineering Conference
  - International Conference on large scale Integration of Renewable Energy

The project covered four R&D areas as mentioned in a previous section, where in the following main findings within each section will be highlighted.

Results related to modelling of RES under stressed conditions and its impact on system stability:

This part of the SARP project investigated aspects of modelling of wind power for long-term voltage stability studies in power systems with large share of wind power. Focus was on exploring the technical capabilities of wind power plants comprising of modern full-rated converter based wind turbines. Using the maximum technical reactive power capability of wind power plants, control strategies where developed to provide voltage/reactive power support from wind power plants during stressed voltage conditions.

The overall results of this part are documented in PhD thesis [PhD_2] and were as follows:

- Model for accurate estimation of wind power plant reactive power capability was developed that can be used for long-term voltage stability studies. Current and voltage limitations of converter give rise to non-linearity in the reactive power capability. The results have shown that at any operating condition, the reactive power capability is minimum of either voltage limited or current limited reactive power. The developed reactive power capability model has shown that both the active power production and voltage at the point of connection play an important role in the reactive power capability of wind power plants. It has been shown that, at higher voltages, the reactive power capability is mainly dominated by the converter voltage limitation, while at lower voltages the converter current limitation is significant. The reactive power capability model is developed for Type 4 wind turbines based wind power plants; however, the methodology can easily be adapted to Type 3 wind turbines based wind power plants (with reduced converter capabilities).

  The reactive power capability model is developed for long-term voltage stability studies in power systems with large share of converter connected wind power generation. The length of collection cables affects the estimation of the reactive power capability when using simplified wind power plant models. Large wind power plants can have significant losses in the collection systems. The inclusion of the wind power collection system in the developed reactive power capability model results in fairly accurate estimation of reactive power capability. Furthermore, the proposed model, the number of parameters required for simulations is reduced, thereby substantially reducing the computational time. The simplified reactive power capability model may still be used for smaller wind power plants with small collection systems, owing to ease of usage and implementation.

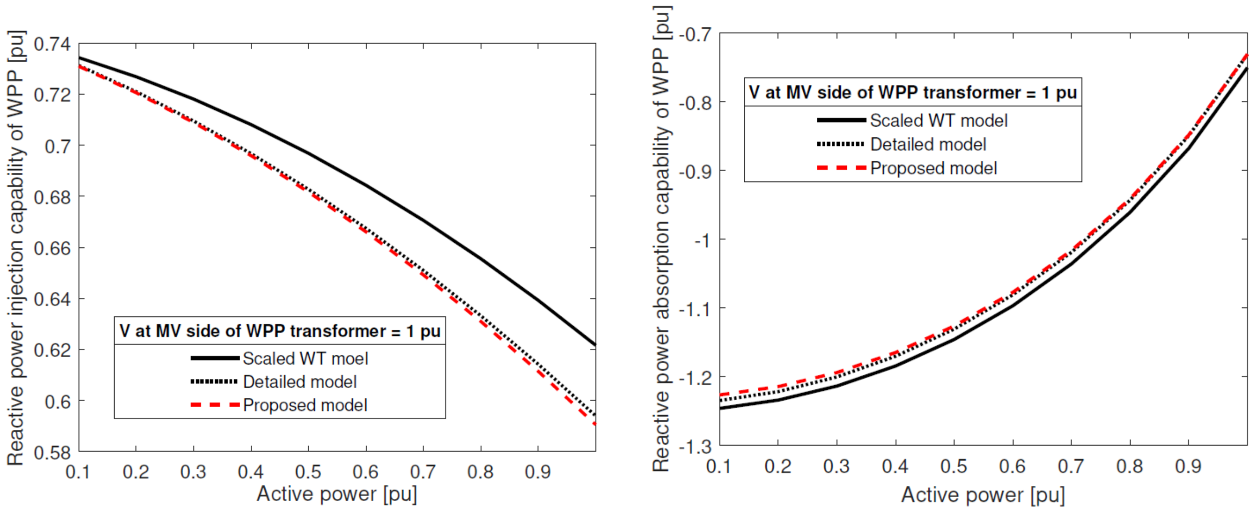

Figure 4: *Comparison of WPP reactive power injection and absorbtion capability respectively using Scaled WT model, detailed model and proposed model [PhD_2]. The proposed model enables an easy integration to the developed stability and security assessment methods, at the same time maintain accuracy in estimating the WPPs reactive power capabilities.*

- The reactive power support capabilities of wind power plants during stressed voltage conditions contribute to the alleviation of risk of voltage stability in power systems. A novel enhanced reactive power capability based voltage control strategy of wind power plant is proposed in the SARP PhD thesis [PhD_2], pertaining to the wind power plants' reactive power/voltage support during stressed voltage conditions. The conventional wind power plant control strategies, when applied during stressed voltage conditions, tend to reach the reactive power capability limit, hence the maximum power transfer of the power system remains the same no matter which control strategy is employed. In the view of this, the proposed control strategy enhances the wind power plant reactive power capability by controlling the wind power plant transformer control voltage, resulting in an increased maximum power transfer based voltage stability index of the power system. Results from case studies have shown that the maximum power transfer of the power system can be improved by 10% for reactive power, voltage and and droop control strategies; while, an additional improvement of 5% is achieved with the proposed enhanced reactive power capability based voltage control strategy. The control strategies can be applied with any type of voltage stability indices.

- The fluctuating nature of the wind speed causes fluctuations in wind power. The dependency of the reactive power capability on wind power necessitates the study of the impact of power fluctuations on the reactive power capability of wind power plants in the light of wind power plants being used as reactive power sources in power systems. A novel method developed for reactive power reserve estimation considering uncertainties such as active power fluctuation, technical availability of wind turbines and on-load tap changer position of the wind power plant transformer demonstrates, that the reactive power capability can reduce up to 25% and 40% for longer time horizon of study such as, 10-min and 30-min respectively. For shorter time horizon, like 1-min, reduction in the wind power plant reactive power capability due to fluctuations is much less, only up to 9%. Therefore, the study underlines the importance of selection of an appropriate time horizon in order to yield to higher confidence in wind power plants as reactive power sources. The proposed methodology enhances the potential in using the steady-state reactive power capabilities of wind power plants in future power systems with high share of wind power.

Results related to assessment of stability in RES based power systems

An approach for detecting voltage stability was proposed, which overcomes the limitations of the Thevenin impedance matching method. The new approach takes into account how load impedance magnitude changes are reflected in the angles of nodes of constant power injection. The modified coefficient matrix was utilized to determine, which nodes of constant power injection contribution to non-controlled loads. This information is useful for larger systems, because only contributing generators were considered in the computations.

An algorithm was proposed for the voltage stability assessment method that is applicable for an arbitrary sized power system. The algorithm uses PMU-snapshots as input, which provide full system observability. The method was tested and compared to another online approach (se figure 5) where the proposed method could detect the critical stability boundary with high accuracy. For the case shown in the figure, the reference methods was not capable of even detecting the occurrence of the instability before simulated blackout occurred.

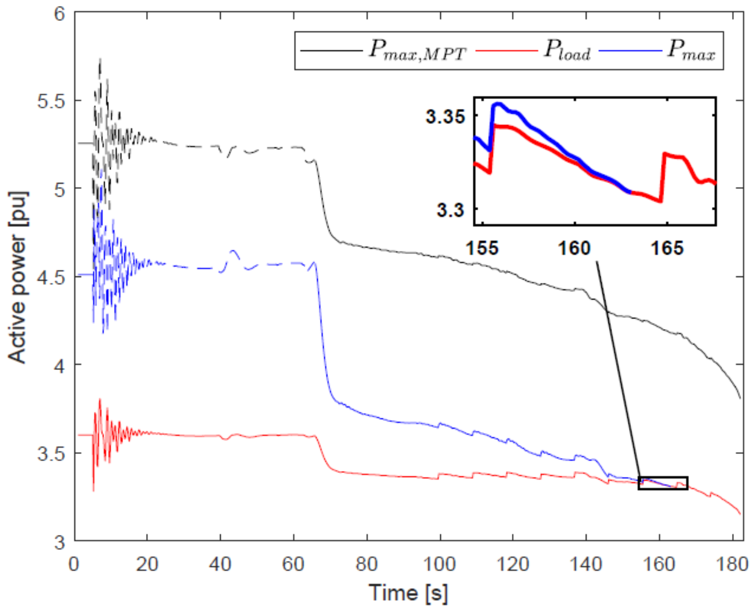

Figure 5*: Test of the voltage stability assessment method [PhD_1]. The methods determines the maximum deliverable power (Pmax, shown in blue) to a given node in the system. As the difference between the actual load (in red) and Pmax becomes smaller, the stability margin becomes smaller. A crossover is detected at 163s. The reference method (Pmax,MPT, shown in black) was not capable of detecting a crossover at all.*

Another important result related to the work on stability assessment was the derivation of a new stability boundary the copes with the impact the current-limited converters might have on stability. Grid related limitation for the transmission/injection of electrical power plays an essential role for many types of stability problems. For the development of an assessment method, it is of interest to derive expressions for critical limits for transmission/injection of electric power and to express the critical limits in terms of system variables that would make an eventual stability assessment easier. The new boundary for maximum injectable active power from current limited converters is shown in figures 6 and test results demonstrating boundary crossover are in figure 7.

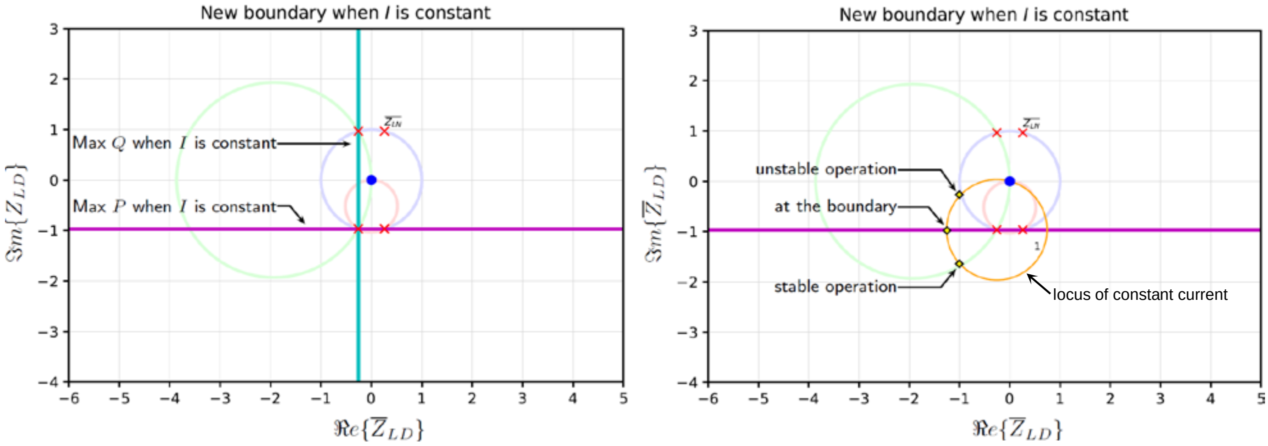

***Figure 6**: illustration of the new stability boundary for generation behind current limited converters [PhD_1]. As the Converter hits its limits for maximum current, the vertical purple line becomes the critical boundary, where an operation in the region below the line is stable while operation above the line is unstable.*

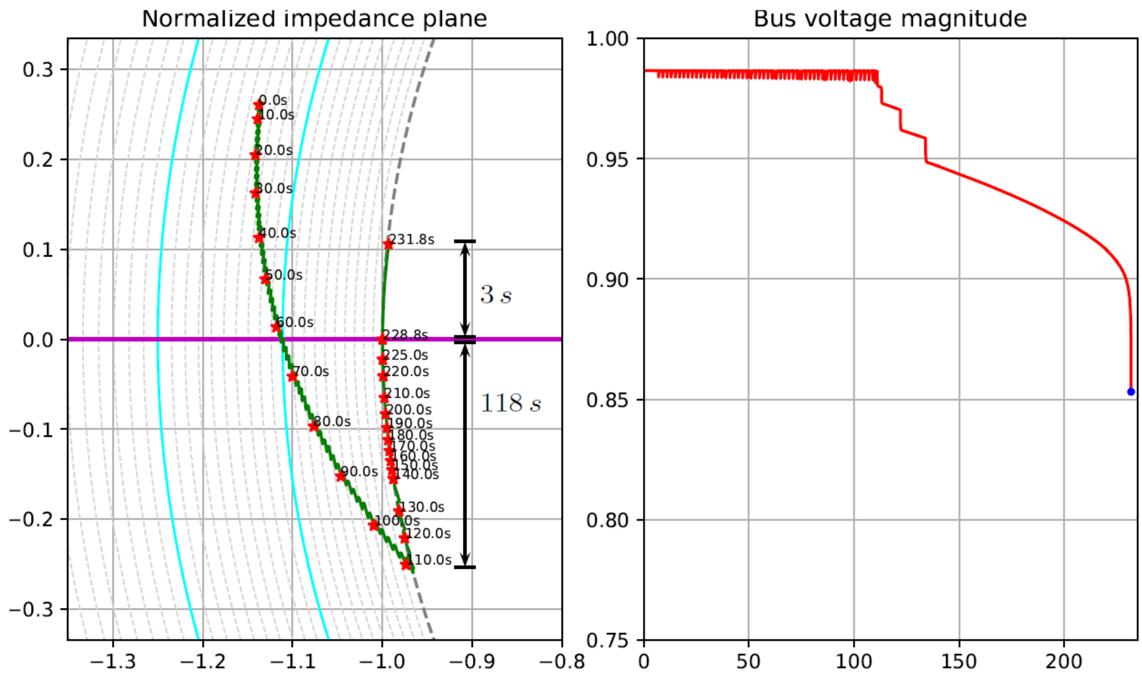

***Figure 7:** Test of the new stability boundary. The loading of a WPP is gradually increased until the converters current limit is reached at 110 s. The system is initially stable (operating below the critical boundary) but as the stress increases the operating point moves closer to the boundary. At last the boundary is crossed (at 228.8 s) and a rapid collapse in voltage is observed.*

To validate the discovered stability boundary for current-limited converters, three test cases were performed on a seven bus system. In the first test case the converter of the aggregated wind turbines reached its current limit, which lead to voltage instability of a non-controlled load. This further worsened the system conditions and the converter crossed the stability boundary and entered FRT-mode, which prioritized reactive power injection and reduced the active power injection. This operation moved the operating point into the stable region of the stability boundary, but the wind turbines had to be disconnected according to the grid codes.

In the second test case voltage instability of the non-controlled load was detected, while the grid-side converter was still able to maintain a constant voltage magnitude at its terminal. The converter reached its current limit, which moved the operating point into the stable region and the system stabilized.

In the third test case voltage instability for the non-controlled load was approaching. Before that instant, the converter reached its current limit in the unstable region defined by the aperiodic small-signal stability boundary. The moment the converter reached its current limit, the system experienced a blackout due to the fast acting converter.

The three test cases show that current-limited operation of the grid-side converter is possible, but in the first case the stability boundaries were pushed closer to the actual operating point and in the third test case the system voltages collapsed immediately.

Results from work on high performance power system algorithms

The main contributions for the task focused on the development of high performance algorithms for real-time stability and security assessment for future power systems is described in the PhD thesis [PhD_3]. Previous research delivered a range of stability and security assessment methods make use of Thévenin equivalents as it is efficient and gives a credible representation of the system. Therefore Thévenin equivalent computations were investigated to determine how these could be optimized. The computations are optimally done by utilizing a factorization to decompose the system.

Initially it was investigated what effect the chosen factorization method had on the computations. The factorization methods used was the standard LU factorization in MATLAB (UMFPACK), KLU and ILU. UMFPACK and KLU are direct methods computing the exact solution, whereas ILU computes an approximation and requires a tolerance level in computations.

Testing showed that the factorization step was in fact a negligible part of the computations and the computationally heavy part was to determine the impedance matrix for the current sources. For UMFPACK and KLU the accuracy of solutions was the same except for numerical cancellation, whereas the accuracy and runtime of ILU depended on the tolerance. To get runtimes competible with UMFPACK and KLU the error using ILU was dissatisfying making ILU have limited applicability for this kind of computations. It was shown how the density of the impedance matrix for the current sources and in consequence the coefficient matrix for determining Thévenin voltages could be determined using BTF for the admittance matrix for the current sources. Furthermore, one large block was seen to dominate the BTF and thereby being a dominating factor in computations.

The factor-solve method was developed on the basis of the conclusion from the investigation. It avoids computing the impedance matrix for the current sources to reduce both runtime and memory requirements. The method takes advantages of the block back substitution of KLU and uses the factorization directly instead of computing the coefficient matrix. The complexity of the algorithm for computing the factorization and the Thévenin impedance was shown to be the same as for the reference method, however the factor-solve method is more easily parallelized making it considerably faster for larger systems.

The greatest advantage was being able to compute Thévenin voltages in linear time compared to the close to quadratic complexity for the reference method. This made it possible to compute Thévenin voltages in 6 ms for a 30.000 bus system, which ensures that they can be recomputed for every measurement provides by PMUs, that normally arrive at system frequency (50 or 60 times per second).

Furthermore, the memory requirements for the factor-solve method was much lower. The factor-solve method only stores the factorization which takes up a few megabytes for the largest system compared to several gigabytes for the coefficient matrix in the reference method.

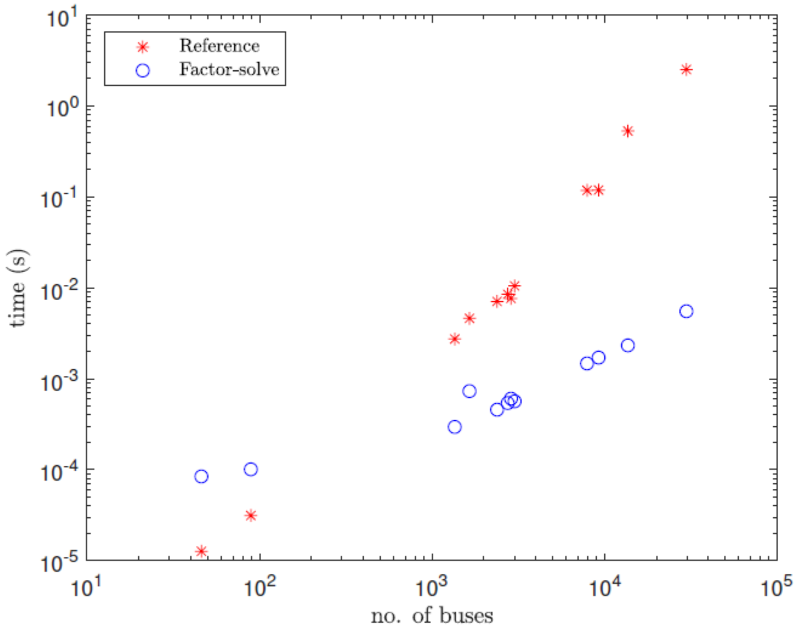

Figure 8: *Test results of the Factor-solve algoritm [PhD_3]. The plot shows the runtime for computing the Thévenin voltages with the reference and factor-solve method depending on the number of buses in the test system (note the logarithmic y-axis). The new algorithm is able to compute the needed results in the largest system in matter of few milliseconds resulting in a speed-up in the orders of 4-500 times.*

Another algorithm was developed to improve the computational performance of the voltage stability assessment method developed within the SARP project (see the results described above). The method determined the voltage stability boundary by accounting for non-linearity in the Thévenin voltage. This determines the maximum power transfer to a load by changing the load impedance multiple times and ideally this should be found accurately in as few steps as possible. A binary search is suggested to find this maximum, and it is furthermore improved by including a second order polynomial fitting as part of the search. This is done since nodes not limited by a generator starting to loose synchronism will have a shape similar to that of a second order polynomial. Therefore, it is possible to find the maximum of the second order polynomial to optimize the search for the maximum power transfer for the node.

Runtimes are lowered by using the binary search and the maximum determined compared to a naive algorithm is more accurate. The complexity is however still the same for all implementations and shows that each step computed should be optimized for better performances. Block-wise computations are therefore tested to achieve lower runtimes. Only nodes belonging to the same block in BTF has to be considered in the computations for that specific load. However, as determined earlier BTF is dominated by a big block, and this scales with system size, meaning that even though runtimes are lower it still has the same complexity as before.

To find the maximum power transfer the admittance matrix has to be refactorized multiple times. Therefore, the hierarchical structure is investigated to create a fast refactorization method to be used on the largest block in BTF. The hierarchical structure is a hierarchical tree, where the leaf nodes is a discretization of the matrix. The higher levels are used, when fill-in generated in the factorization by elimination of nodes is pushed to the parent level and approximated using SVD. The number of levels i.e. the level of discretization determines the runtime for both the initial factorization and the refactorization. Both the number of nodes and the resulting block size affect runtime. For the initial factorization the runtime is lowest somewhere in between the highest and lowest discretization. High discretization means many nodes computed, while low discretization means that block gets so large that the computation takes too long. For the refactorization the lower the discretization the faster, since fewer nodes are affected by the change in load impedance as the amount of nodes gets lower.

The implementation of the algorithms for the hierarchical factorization and refactorization had some different issues, which needs to be determined. The forward and backwards traversal of the solve step was not modified for recalculation.

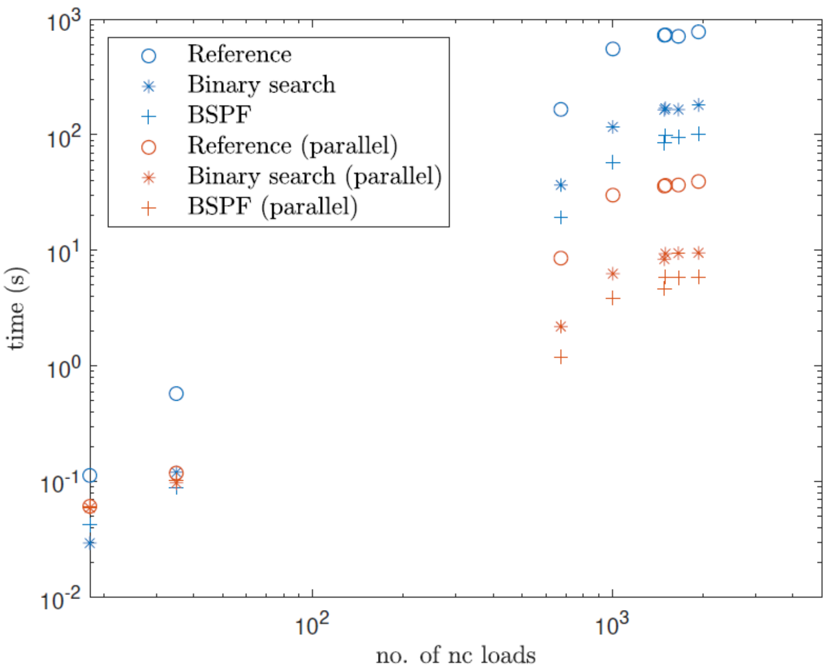

Figure 9: *Runtime for the proposed algorithms for voltage stability assessment compared to a reference implementation [PhD_3]. The results are shown for different test systems (up to 30.000 busses) where 24 core parallelization is exploited. A full voltage stability assessment is carried out in matter of couple of seconds and can be decreased further by increasing the number of cores (results achievable in the milliseconds range).*

Results on SW-platform improvements and development

During the project, the Wide-Area Real-Time Application (WARTApp) platform was further developed and matured. The work consisted of

- Developing input interface to allow the platform to read in text files provided from Energinet's SCADA system that contain snapshots of a given condition. Establishing this interface is the first step towards online operation, as real-world system data and measurements can be processed in real-time on the platform.
- Increasing the number of system components that can automatically be treated by the platform
- For more versatile usage of the platform, TCP communication capability was added to the platform

- Development of Python libraries that make it easier to develop/implement new applications of wide-area data. The Python libraries facilitate: (i) automatic creation of snapshot receiver and publisher objects that is executed in a thread on its own; (ii) automatic creation and update of the network model/matrices from a snapshot. The creation of the Python module significantly simplify the usage of the platform and sup-port the ongoing research and demonstration activities in the SARP project.
- Developing Real-Time Digital Simulator (RTDS) interface to enable closed loop demonstration of the early-warning and early-prevention functionalities of the SARP technology.
- Implementation of a range of method for demonstration of real-time assessment of system stability and security, automated countermeasure determination and informative visualization.

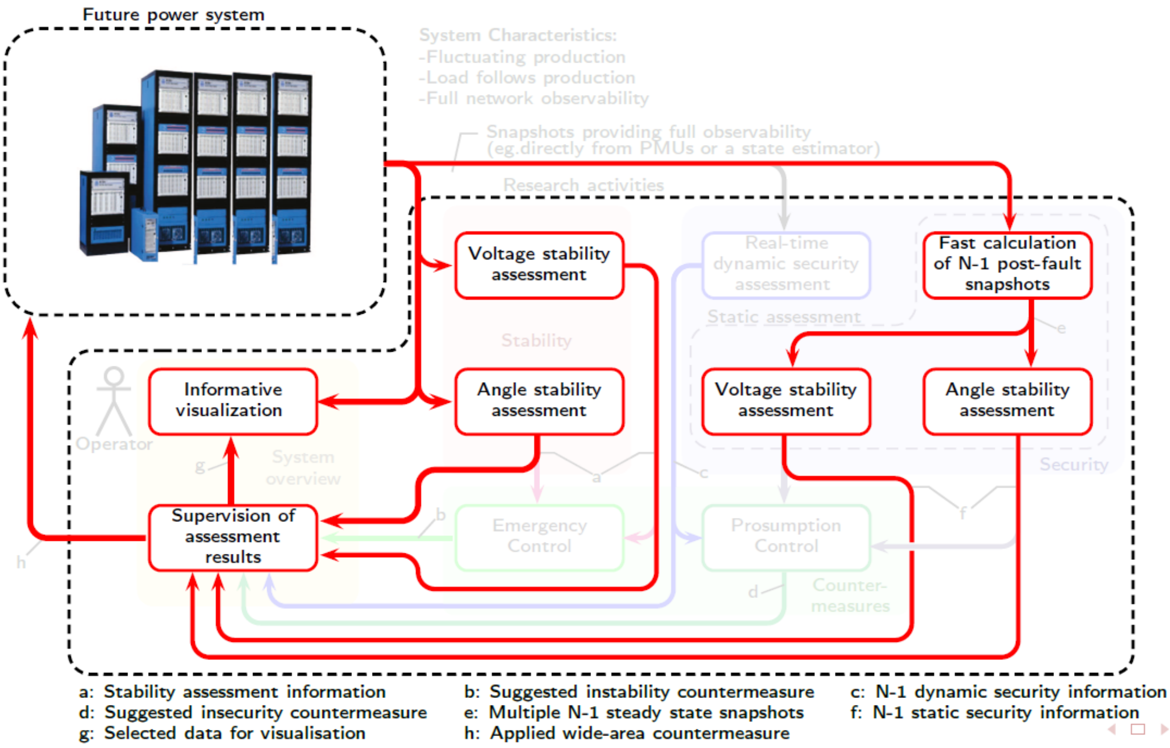

Figure 10*: One of the setups used to demonstrate SARP results where range of assessment methods were operating in parallel providing in real-time detailed assessment of the distance to instability.*

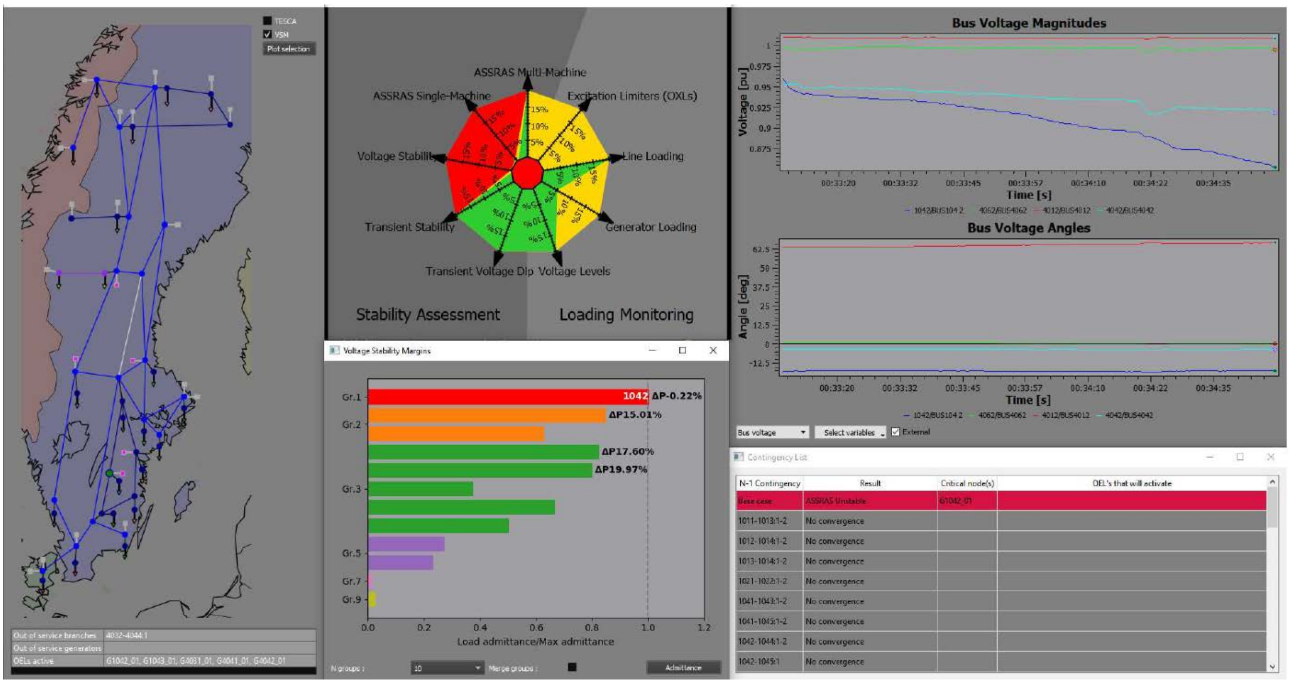

Figure 11: *Snapshot from the demonstration (figure 10) at an instance of time where system instability had been identified by the real-time applications.*

6. Utilisation of project results

The end-user of the technology will be the transmission system operators (TSOs). The technology addressed in the project will support the TSOs in fulfilling the important societal responsibility of ensuring a secure and stable operation of the future RES based power system. The addressed solution provides greatly enhanced insight into the stability conditions in the grid, improves security of grid operation and facilitates a transition to a renewable and cost-efficient grid.

Utilization and further deployment of results must be carried out in close collaboration with TSOs, as the solutions need to be integrated into their system. The Nordic TSOs have initiated efforts to establish a common project aiming at creating the infrastructure and platform for implementation of such real-time solutions focussued on in the SARP project.

The technology treated in the SARP project contributes to the solution of one of the major challenges in the realization of the future power systems with a very high proportion of CO2-free production, which is to ensure stable and secure system operation. Without a solution to this problem, these future visions cannot be realized. The energy political importance of the fundamental challenge is therefore very high.

7. Project conclusion and perspective

The SARP project pushed forward the development of the technology needed to ensure a secure operation of power system that have a high share of the power production based on renewable energy sources. The project provided necessary results for incorporating the effects of inverters control and protection into the real-time assessment and identified new stability boundary that needs to be monitored closely as the share of inverter isolated production increases in the grid.

The developed method for assessment of voltage stability provides a solution for monitoring this critical stability phenomena in real-time and providing crucial awareness and confidence in operating the system as the operation conditions become more dynamic and volatile. The work on the algorithmic implementation ensures an real-time performance of other Thevenin based assessment methods, and hence eliminate the computational obstacles associated with the overall vision for secure system operation as depicted in figure 1.

The implementation of the methods and algorithms on to the WARTApp platform and closed demonstration in PowerLabDK showed the potential of the proposed technology. The next steps in the technology development require implementation of a demonstrator in the TSO's control room. The Nordic TSOs have initiated internal efforts to develop the needed infrastructure and platform on which the real-time solutions can be implemented on. The results from the SARP project will fit directly into such efforts, contributing to safe and secure operation of systems with very high share of fluctuating renewable energy sources.

8. Appendices

The homepage for the SARP research project is at www.sarp-research.dk

Journal Publications

[J1] S.Sommer, A. Aabrandt and H. Jóhannsson, "Reduce-Factor-Solve for Fast Thevenin Impedance Computation and Network". IET Generation, Transmission and Distribution, 2018.

[J2] C.H.L. Jørgensen, J.G. Møller, S. Sommer and H. Jóhannsson. "A Memory-Efficient Parallelizable Method for Computation of Thévenin Equivalents used in Real-Time Stability Assessment". IEEE Transactions on Power Systems, 2019.

[J3] M. Sarkar, M. Altin, A.D. Hansen and P. Sørensen. "Reactive Power Capability Model of Wind Power Plant Using Aggregated Wind Power Collection System". Energies, vol. 12, issue 9, 2019.

[J4] M. Sarkar, A.D. Hansen and P. Sørensen. "Probabilistic Voltage Stability Assessment Considering Variability of Wind Power." Electric Power System Research, 2019.

[J5] B.C. Karatas, H. Jóhannsson and A.H. Nielsen. "Voltage Stability Assessment Accounting for Non-linearity of Thévenin Voltages". IET Generation, Transmission and Distribution, 2020.

[J6] M. Sarkar, A.D. Hansen and P. Sørensen. "Quantifying Robustness of Type 4 Wind Power Plant as Reactive Power Source". International Journal of Electrical Power & Energy Systems, 2020.

[J7] M. Sarkar, T. Souxes, A.D. Hansen, P. Sørensen and C.D. Vournas. "Enhanced Wind Power Plant Control Strategy during Stressed Voltage Conditions". IEEE Access. 8, p. 120025-120035, 2020.

[J8] B.C. Karatas, M. Sarkar, H. Jóhannsson and A.H. Nielsen "Voltage stability assessment accounting for current-limited converters". Electric Power System Research, 2020.

Conference Publications

[C1] B.C. Karatas, H. Jóhannsson, and A.H. Nielsen, “Real-Time Countermeasures Preventing Power System Instability by using PMU data from RTDS simulation”, IEEE PES Asia-Pacific Power and Energy Engineering Conference, 2016

[C2] A. Perez, B.C. Karatas, H. Jóhannsson and J. Østergaard, “Considering wind speed variability in real-time voltage stability assessment using Thévenin equivalent methods”. In proceedings of 12th IEEE Power and Energy Society PowerTech Conference, 2017, Manchester

[C3] M. Sarkar, M. Altin, A.D. Hansen and P. Sørensen. “Impact of Wind Power Plants on Voltage Control of Power System”. Paper presented at 1st International Conference on Large-Scale Grid Integration of Renewable Energy in India, New Delhi, India.

[C4] M. Sarkar, J. Jia and G.Y. Yang. “Distance relay performance in future converter dominated power systems”. In Proceedings of 12th IEEE PES PowerTech Conference IEEE. DOI: 10.1109/PTC.2017.7981144

[C5] C. Hildebrandt, B.C. Karatas, J.G, Møller and H. Jóhannsson, “Choice of Factorization Method for Thévenin Equivalent Computations”. Power System Computation Conference PSCC 2018, Dublin, Ireland.

[C6] H. Jóhannsson. “Real-Time Early Warning and Early Prevention System to Avoid System Blackouts”. IEEE PES General Meeting 2018 in Portland, US.

[C7] B.C. Karatas, H. Jóhannsson, and A.H. Nielsen, “Improved Voltage Stability Boundary Monitoring by Accounting for Variations in Thevenin Voltage Magnitude”. The 8th IEEE PES ISGT Conference - Sarajevo, Bosnia and Herzegovina.

[C8] P.F. Petersen, C. Oxholm, J.G. Møller and H. Jóhannsson, “Cascading Outage Assessment using Thévenin Equivalent Static Contingency Assessment”. The 2019 PowerTech Conference, Milano, 2019.

[C9] C.H.L. Jørgensen, B.C. Karatas, S. Sommer and H. Jóhannsson. “Binary Search and Fit Algorithm for Improved Voltage Stability Boundary Monitoring”. The 9th IEEE PES ISGT Conference, Bucharest, Romania, 2019.

[C10] M. Sarkar, M. Altin, A.D. Hansen and P. Sørensen. “Impact of power fluctuations in reactive power capability of wind power plants”, The 2019 International CIGRE Symposium, Aalborg, 2019.

[C11] M. Sarkar, P. Sørensen and A.D. Hansen. “Impact of Different Load Types on Voltage Stability of Power System Considering Wind Power Support”. In 18th Wind Integration Workshop, Dublin, 2019.

[C12] B.C. Karatas, M. Sarkar, H. Jóhannsson, A.H. Nielsen and P. Sørensen. “Voltage Stability Assessment Accounting for Current-Limited Converters”. Presented at the 2020 Power System Computation Conference (PSCC).

[C13] D.Müller, H. Jóhannsson and K. Uhel. “Impact of Reduced Synchronous Machine Capacity on Inter-Area Oscillations”. Proceedings of 2020 IEEE PES Innovative Smart Grid Technologies Europe.

[C14] H.Haugdal, K. Uheln and H. Jóhannsson, “Estimation of Oscillatory Mode Activity from PMU Measurements”. Proceedings of 2020 IEEE PES Innovative Smart Grid Technologies Europe.

[C15] D.Müller, H. Jóhannsson, K. Uhel and A. H. Nielsen. “*A Method to Determine the Distance to the Critical Oscillatory Stability Limit in Terms of Active Power Injections*”. The 2021 IEEE PowerTech conferene, Madrid, 2021.

[C16] H.Haugdal, K. Uheln and H. Jóhannsson, “An Open Source Power System Simulator in Python for Efficient Prototyping of WAMPAC Applications”. The 2021 IEEE PowerTech conferene, Madrid, 2021.

[C17] B. Sævarsson, J.G. Møller and H. Jóhannsson. “Enhanced early-warning for multiple aspects of stability and security in real-time”. Submitted to the IEEE ISGT EUROPE Conference 2021.

PhD dissertations:

[PhD_1] Bahtiyar Can Karatas, “Voltage Stability in RES Based Power Systems”, June 2019.

[PhD_2] Moumita Sarkar, “Modelling of Wind Power under Stressed Voltage Conditions”, February 2020.

[PhD_3] Christina Hildebrandt Lüthje Jørgensen, “High Performance Algorithms Enabling Real-Time Security Assessment of Sustainable Electric Power Systems”, March 2021.

Presentation of SARP activities in panel sessions, workshops etc.

09/2016 CEE Power Event: High-Dimensional Data Analysis in Power System Monitoring using Low-Rank Matrices. Presenters Prof. Joe H: Chow, Rensselaer Polytechnic Institute, NY US and Dr. Hjörtur Jóhannsson, CEE - DTU.

12/2016 Workshop for participants in the SARP project’s reference group at GE Grid Solution domicile in Edinburgh. The content of the SARP project and planned activities were presented and discussed with participants from GE Grid solutions and Energinet.dk.

03/2017 CEE Power Event: Monitoring, control and optimization of power systems with emphasis on real-time applica-tions and high performance computing. Presenters Dr. Zhenyu Huang, Pacific Northwest National Laboratories, WA US, Prof. Gabriela Hug, ETH Zurich, Switzerland and Dr. Hjörtur Jóhannsson, CEE – DTU.

06/2017 CEE Power Event for external audience: Demand response to improve power system stability. Presenters As-soc. Prof. Johanna Mathau, University of Michigan, PhD stud. Mengqi Yao, University of Michigan and Dr. Hjörtur Jóhannsson, CEE - DTU.

06/2017 R&D Collaboration Workshop: “Hands-on implementation on CEE’s Wide Area Data SW-platform”. Four day workshop presenting the state-of-the-art SW-platform to the researchers in the SARP project and at CEE.

03/2018 SARP Workshop where cross-collaboration research topics (interdisciplinary) within the project were identified and corresponding cross collaboration activities planned.

06/2018 SARP Workshop to define a range of supporting R&D activities (M.Sc. student project proposals), with the aim of having several students working on topics supporting the SARP R&D during the spring semester 2019.

08/2018 Seminar on R&D in application of Wide-Area data held at the Pacific Northwest National Laboratory, WA, US in conjunction with the 2018 IEEE PES GM conference. On the seminar PNNL and SARP researcher presented R&D results related to the topic.

01/2019 SARP workshop to support R&D: “Using CEE's WARTApp Platform for R&D”, Four day workshop presenting the latest development of the WARTApp platform to the researchers in the SARP project and at CEE.

06/2019 Talk in a panel session at the PowerTech 2019 conference in Milano, Italy. Talk: “Pushing forward the develop-ment of real-time methods for early-warning and early-prevention of system blackouts”.

08/2019 Panel session at the 2019 IEEE PES General Meeting, Atlanta, Georgia, US. Talk: “Secure operation of future electric power systems by real-time assessment based on wide-area data”.

09/2019 Invited talk at the 2019 DynPower Workshop, Zurich, Switzerland: “Real-time assessment for secure operation of sustainable power systems”.

11/2019 Symposium at Tianjin University: Applications of data-driven approaches for power system situational Aware-ness, Tianjin, China. Talk: “Secure operation of sustainable power systems by real-time wide-area assessment and control”.

11/2019 Panel session at the IEEE iSPEC Conference: Data-driven application for modeling and security assessment of energy systems, Bejing, China. Talk: “Avoiding blackouts by real-time early-warning and early-prevention system based on wide-area data”.

05/2020 Webinar – demonstration of SARP results to Nordic TSOs. The intention was to organize a final demonstration event in April 2020, but due to the COVID19 pandemic, the plans had to be changed, Instead of carrying out an onsite demonstration event at PLDK, alternative online demonstration event was arranged for a group experts from the Nordic TSOs (Energinet, Svenska Krafnätt, Stattnet and Findgrid). During the event, overview of the project was presented and the dveloped solutions demonstrated on the WARTApp platform.

05/2021 Panel session at the IEEE SGSMA Conference: Panel 1 - Role and Use Cases of Real Time Simulators (RTS) Towards Advancing and Deploying Synchrophasor Based Wide Area Monitoring Protection and Control (WAMPAC) Systems. Talk: *“Use of RTDS in R&D of Wide Area Early-Warning and Early-Prevention Systems”*

Student projects supporting the SARP R&D activities

M.Sc. Project: *"Real-time Assessment of Transient Voltage Sags for Electric Power Systems"*, Jacob Bollerslev, (01/2021-07/2021)

M.Sc. Project: *"Small-signal stability analysis of weak-grid large offshore wind farms considering active mitigation methods"*, Claus Skov Heissel, (08/2020-01/2021)

M.Sc. Project: *"Hybrid power system unit commitment: extension of active power model to include voltage and reactive power constraints"*, Piera De Matteis, (01/2020-07/2020)

M.Sc. Project: *"Stability assessment of impact of wind integration in weak isolated system with a large share of renewable energy sources"*, Sólveig Helga Gudjónsdóttir, (01/2020-06/2020)

M.Sc. Project: *"Geographical visualization of emerging power system stability problems"*, Páll Viðar Árnason, (01/2020-06/2020)

B.Sc. Project: *"Modelling and simulation of power systems with high penetration of renewable energy sources"*, Daniel Brøndsted Vesterlund Nielsen, (09/2020-12/2020)

Special Project: *"Dynamics and Stability in Electric Power Systems"*, Jacob Bollerslev, (09/2020-12/2020)

Special Project: *"Implementation of generic time-domain models of active components for stability analysis, in large offshore wind farms"*, Claus Skov Heissel, (02/2017-06/2020)

Special Project: *"Introduction to Voltage Stability Analysis"*, Jacob Bollerslev, (02/2020-06/2020)

M.Sc. Project: *"The 2035 Nordic Power System: Modeling, Simulation and Stability Studies"*, Nilakantha Roy, (01/2019-07/2019)

M.Sc. Project: *"Dynamic stability of the east Danish transmission grid imposed by connection of the Kriegers Flak offshore wind power plant"*, Rasmus Bærholm Glasdam (01/2019-07/2019)

M.Sc. Project: *"Implementation of an online contingency screening method into real-time test platform"*, Yihao Sun, (01/2019-07/2019)

M.Sc. Project: *"Implementation and demonstration of early-warning and early-prevention system to avoid power system blackouts"*, Brynjar Sævarsson (01/2019-06/2019)

M.Sc. Project: *"Implementation of large power system model for real-time performance testing of assessment methods"*, Seyyid Ibrahim Hadi Öztoprak, (01/2019-06/2019)

Special Project: *"Study and Analysis of Synthetic Inertia Control in Offshore wind farms and its impact on system damping"*, Nilakantha Roy and Abhishek Chaudhary, (08/2019-10/2019)

M.Sc. Project: *"Real-Time Voltage Stability Assessment based on Voltage Stability Indices"*, Seyyid Ibrahim Hadi Öztoprak, (08/2017-01/2018)

M.Sc. Project: *"Real-Time Identification of Vulnerabilities in an Electric Power system towards Cascading Outages"*, Christian Oxholm (02/2017-07/2017)

Special Project: *"Software Implementation of Voltage Stability Assessment Method"*, Seyyid Ibrahim Hadi Öztoprak, (01/2017-06/2017)

Special Project: *"Simulation and Modelling of Cascading Outages in Electric Power Systems"*, Christian Oxholm (09/2016-01/2017)

Courses with SARP related learning activities

- A new 3 week special course was designed and carried out for first time in January 2019. The course focussed on real-time stability assessment and hands-on implementation of such methods using CEE's SW-Platform for applications of wide-area data. The course was established to enable M.Sc. students to work with the platform in their M.Sc. projects. In total 6 M.Sc. project students and 2 PhD students followed the special course in January 2019.
- The above 3 week special course was carried out for the second time in January 2020. The course was established to enable M.Sc. students to work with the platform in their M.Sc. and special projects. In total 6 M.Sc. project students followed the course in January 2020.