Final report

1. Project details

Project title	***Voltage Control and Protection for a Grid towards 100% Power Electronics and Cable Network (COPE)***
File no.	**12561**
Name of the funding scheme	**Energy Technology Development and Demonstration Program (EUDP)**
Project managing company / institution	**Aalborg University**
CVR number (central business register)	**29102384**
Project partners	**SINTEF, Norway; DIgSILENT Germany**
Submission date	**28 February 2021**

2. Summary

English

The future Danish power system would become a power electronic converter (PEC) interfaced renewable energy generators and underground cables (UC) dominated grid (PE-UC-Grid), which will bring many challenges. The project aimed to investigate two aspects of these challenges: reactive power and voltage, and power system protection. The objectives are

PE-UC-Grid reactive power/voltage characteristics
Reactive power compensation and voltage control
Short circuit analysis of PE-UC-Grid.
New protection schemes for PE-UC-Grid
Validate the developed methods in hardware in the loop (HIL) platform

Main results

The following new methods and developments would find applications in practices

1. The analysis of future PE-UC-Grid
2. The method using renewable energy generators for reactive power control
3. The method for optimal wind power plant control
4. The method of assessing the stability of PEC based network
5. The parameter identification-based distance protection method
6. The model recognition-based line differential protection schemes
7. The protection compatible fault control scheme for PEC-based power plant
8. The HIL test platform and evaluation systems.

Result potential utilisations

The above results may be used as follows:

System planners may use *Result 1* for planning the future energy system
System operators may use *Results 1, 2, 4, 5, 6, 7, 8* for setting control, protection systems
Energy market regulator may use *Results 1, 2* for establishing reactive power market
Wind power plant operators may use *Result 3* for setting wind power plant control systems
Equipment manufacturers may use *Results 2, 3, 4, 5, 6, 7, 8* for designing control, protection systems, test systems
Research organizations may use *Result 8* for setting up test system

Danish

Det fremtidige danske elsystem vil blive forsynet via effektelektroniske omformere (PEC), der udgør grænsefladen mellem generatorer drevet af vedvarende energi og de nedgravede kabler (UC). Fremtidens net bliver derved et PEC-UC-Grid, hvilket vil medføre mange tekniske udfordringer. Projektet havde til formål at undersøge to aspekter af disse udfordringer: Reaktiv effekt og spænding samt beskyttelse af elsystemet. Hovedformål er:

- PE-UC-Grid reaktiv effekt og spændingsregulering
- Reaktiv effektkompensation og spændingsregulering
- Kortslutningsanalyse af PE-UC-Grid.
- Nye beskyttelsesprincipper for PE-UC-Grid
- Validering af de udviklede metoder i Hardware in the Loop (HIL) platformen

Hovedresultater

Følgende metoder og resultater kan anvendes i praksis

1. Analyser af fremtidens PE-UC-Grid
2. Metoder til brug af fornybare energikilder til reaktiv effektkompensering
3. Metoder til optimal regulering af vindkraftanlæg
4. Metoder til at vurdere stabiliteten i PEC baserede elnet
5. Parameter identifikation-baseret distance beskyttelsesmetoden
6. Modelgenkendelsesbaseret differential beskyttelse.
7. En beskyttelsesfilosofi, der er kompatibel med fejlscenarier i PEC baserede elnet.
8. HIL (Hardware in the Loop)-baseret test- og valideringsplatform.

Resultat ift. potentielle anvendelser

Ovenstående resultater kan anvendes som følger:

Systemplanlæggere kan bruge resultat 1 til planlægning af det fremtidige energisystem.
Systemoperatører kan bruge resultaterne 1, 2, 4, 5, 6, 7 og 8 til indstilling af kontrol-, beskyttelsessystemer.
Energimarkedsregulatorer kan bruge resultaterne 1 og 2 til etablering af et marked for reaktiv effekt.
Vindkraftværksoperatører kan bruge resultat 3 til at indstille kontrolsystemer til vindkraftværker.
Udstyrsproducenter (leverandører) kan bruge resultaterne 2, 3, 4, 5, 6, 7 og 8 til at designe kontrol-, beskyttelses- og testsystemer.
Forskningsorganisationer kan bruge resultat 8 til opsætning af testsystemer.

3. Project objectives

- ***The objectives of the project***

The main detailed technical objectives of this project are as follows:

- To understand the relevant characteristics of main PE-UC-Grid components, i.e. PECs and cables.
- To analyse and determine the optimal reactive compensation for PE-UC-Grid.
- To develop optimal reactive power /voltage control method for the renewable energy based PE-UC-Grid.

- To establish models for short circuit analysis of PE-UC-Grid.
- To conduct short circuit analysis and develop new methods to improve the performance of the existing protection system in PE-UC-Grid.
- To develop solutions for secure protection of the power systems in transition towards PE-UC-Grid.
- To validate the proposed methods via the hardware-in-the-loop platform.

- ***The energy technology has been developed and demonstrated***

The project has investigated and developed

The power flow analysis model of Danish PE-UC-Grid
The voltage profiles of PE-UC-Grid and effective compensation
The method using renewable energy generators to perform reactive power/voltage control
The method for optimal wind power plant control while delivering reactive power /voltage control services
The method of assessing the stability of PEC based network with respect to the PEC control loops
The parameter identification-based distance protection method
The model recognition-based line differential protection schemes
The protection compatible fault control scheme for PEC-based power plant
The HIL test platform to evaluate protection system and PEC-based network stability

The above contents have been investigated, the proposed methods have been developed, implemented in simulation environment and demonstrated the effectiveness. Some of them have been implemented in the HIL and prototypes in laboratories, such as protection schemes, PEC network stability assessments etc.

4. Project implementation

- *the project evolution*

The project has been progressed and completed well with all partners' efforts, all milestones have been achieved as planned.

- *the risks associated with conducting the project*

The real detailed system data is not easy to be obtained, such as control system parameters. This problem has been handled by using the open source public available data, including energinet.dk data hub, literatures, etc. The results are satisfactory. For practical and real implementations, real data would be required for the best effects.

- *the project implementation has been develop according to milestones agreed upon*

The project has been conducted as foreseen and meet all the milestones as agreed upon. Some additional work has also been done, such as the power electronic system stability, etc.

5. Project results

All original objectives of the project have been obtained.

- *The obtained technological results, including the proposed new methods and some work not originally planned are as follows*

- The reactive power /voltage characteristics of PE-UC-Grid.
- The effectiveness of reactive power compensation scheme at cable terminals in PE-UC-Grid.
- The effective reactive power/voltage control method using renewable generators in PE-UC-Grid.
- The method and procedure of assessing the stability of PEC based network with respect to the PEC control loops.
- Short circuit analysis models of PE-UC-Grid, in particular, PEC modelling for short circuit analysis.
- The parameter identification-based distance protection method.
- The model recognition-based differential protection method.
- The coordination of protection method and fault ride through grid code requirement for PEC-based wind power plant.
- The hardware-in-the-loop platform has been implemented in ET AAU lab, the developed new protection and control method has been tested to demonstrate the effectiveness
- PECs system prototypes have been established in lab, the stability assessments have been conducted to demonstrate the effectiveness of the proposed method of stability analyses.

The PEC control and stability issues and the relation to reactive power operation were not scheduled in the original work plan, but these issues are considered important, therefore, efforts have been made to get them conducted, useful results have been obtained for assessment of PEC system stability, operation of PEC systems, and PEC control system design.

- *Describe the obtained commercial results. Did the project produce results not expected?*

The project focuses on the technical aspects as reported above, there is no direct concrete commercial objective as planned. However, the technical results would be practically useful and important for future Danish renewable energy based power systems, the technical results can improve the grid economic performance, stability and security, therefore, would have good practical and commercial value.

Some technical results, such as wind power plant (WPP) control method, PEC network stability assessment, the protection methods, etc. have good potential to be commercialised by the designers, operators and manufacturers of WPP control system, PEC, grid protection system.

- *The technologies and the related target group.*

As indicated in the Section 1, some new methods would find applications in practices, including

1. The analysis of future PE-UC-Grid
2. The method using renewable energy generators for reactive power control
3. The method for optimal wind power plant control
4. The method of assessing the stability of PEC based network
5. The parameter identification-based distance protection method
6. The model recognition-based line differential protection schemes
7. The protection compatible fault control scheme for PEC-based power plant
8. The HIL test platform and evaluation systems.

The above results may have the added value to the following target user groups:

System planners may use Result 1 for planning the future energy system
System operators may use Results 1, 2, 4, 5, 6, 7, 8 for setting control, protection systems
Energy market regulator may use Results 1, 2 for establishing reactive power market
Wind power plant operators may use Result 3 for setting wind power plant control systems
Equipment manufacturers may use Results 2, 3, 4, 5, 6, 7, 8 for designing control, protection systems, test systems
Research organizations may use Result 8 for setting up test system

- *The dissemination of the project results been disseminated.*

The related work and research results have been presented at the project meetings and discussed with the advisory committee members, the grid operator, Energinet.dk and the wind turbine manufacturer, Vestas. The project results have also been disseminated through publications at conferences and journals, including top international conferences and top journals, e.g. IEEE PES Innovative Smart Grid Technologies – Asia, IEEE Transactions on Industrial Electronics, IEEE Industrial Electronics Magazine, IEEE Transactions on Power Delivery, etc.

A list of publications with the detailed associated conferences and journals have been attached with this report as one of the appendixes.

The project leader has been invited to deliver a number of keynote /plenary speeches at the following international conferences with some project results being disseminated.

- IEEE PES Conference, Innovative Smart Grid Technologies Asia (ISGT Asia), Chengdu, China, 2019 (keynote)
- The 18th Annual Power Symposium, Energy Redefined in the Era of the Internet and the Renewables, Hong Kong, 2019 (keynote)
- The 3rd Asia Energy and Electrical Engineering Symposium (AEEES), Chengdu, China, 2020 (keynote)
- IEEE/PES General Conference, Montreal, Canada, 2020 (plenary)
- Symposium on Energy and Sustainable Development, India, 2020 (keynote)
- The 6th International Conference on Electric Power and Energy Conversion Systems (EPECS'20), Istanbul, Turkey, 2020 (keynote)
- International Conference on Renewable Energy, (ICREN 2020), Rome, Italy, 2020 (keynote)

There are also a number of keynote speeches in 2021 and new publications, the project results will be further disseminated.

6. Utilisation of project results

- *Describe how the obtained technological results will be utilised in the future and by whom.*

As described in above Sections, the obtained technological results listed in Section 5, have good potential for real applications, by the energy system planners, system operators, energy market regulators, wind power plant operators and owners, equipment manufacturers (manufacturers of WPP control system, PECs, protective relay, HIL test system), etc.
For examples, the full renewable energy powered grid analysis and associated power flow/ voltage profiles results would provide system planner with the information on how to appropriately plan the system development to meet the technical limits, provide information for energy market regulator to appropriately design reactive power market. The new protection methods can be implemented into the protection relays by relay manufacturers to provide effective protection for future power electronic dominated power grid, etc.

It is intended to approach the aforementioned target groups, for example, inviting the target group for seminars and meeting, meeting the potential users at the exhibitions associated with conferences etc. to promote the project obtained technology results for commercial applications.

If the results would be implemented, they could help to

Provide the new methods to contribute to the development of economic, secured, sustainable clean energy system
Hele the relevant manufacturers to produce new products suitable for future energy systems

The project partners are a simulation package provider and a research organisation, the simulation software provide may not see direct increase in their turnover, employment etc. however, the developed algorithms can further enhance their software function and ability, the project, in particularly the disseminations of the project, provide excellent opportunity to promote their product, the simulation package. While the research organisation partner would enhance their reputation and gain more knowledge, which effectively promote their consultation opportunities.

As mentioned above, the project directly address the challenges of reactive power/voltage control and protection for full renewable energy supplied power systems, provide solutions to these two key technical challenges, therefore to contribute to the realization of the country's energy policy objectives.

A number of PhD projects have been partially or fully associated with the project, the PhDs have actively participated and contributed to the result disseminations, such as produce conference and journal publications, PhD thesis etc. as presented in the publication list as one of the appendices.

Some of the project results have already be integrated into the PhD and master courses, such as wind power plant control, PEC stability etc., and more results will be included in the future courses.

7. Project conclusion and perspective

Project conclusions

The project has been conducted by following the milestones, the project tasks of the two work packages have been successfully completed, the most important technology results are

- The frequency dependent cable model
- The analysis of impact of replacing overhead lines with underground cables on distribution grid voltage profile
- Modelling and power flow analyses of Danish power grid dominated with power cables
- Analyses of future Danish power systems dominated with renewable energy generators
- A new reactive power and voltage control method using renewable energy generators
- Optimal coordinative active power and reactive power dispatch within a wind power plant
- Small-signal stability analysis procedure and method for PEC dominated power systems
- Modelling of PEC-interfaced power plant for short-circuit analysis
- The novel parameter identification-based distance protection method
- The model recognition-based line differential protection schemes, including
    - the single phase fault model-based differential method,
    - the relevant modified differential methods for PE-UC-Grids.
- The protection compatible fault control scheme for PEC-based wind power plant during unbalanced grid faults.
- Testing and validating the new protection algorithm based on novel HIL test platform and evaluation systems.

The next steps for the developed technology

Further test the developed methods under various scenarios, to improve the robust performance
Further disseminate the results and contact the potential user group
Based on the conducted study, new research would be conducted to address other technical challenges, such as system dynamics under large disturbances and voltage dynamic control etc.

The potential influence of the project developed results on future development

The project has investigated some key technological challenges of future Danish power systems, provide useful information for planning and development of future power systems.
The developed technologies would be further extended for more technological development.
The developed relevant technologies, such as controller setting, protection algorithms etc. can be promoted to industrial manufacturers to be potentially used in the commercial products.
The developed network related technologies, such as system modelling, analysis, control methods can be promoted to system operators to be potentially used in the system planning, operation and control practice.

8. Appendices

Appendices

1. the project technical project.
2. the publication list.

The project website page, where the project publications may be found, is as follows

https://www.et.aau.dk/research-programmes/wind-power-systems/activities/cope/