Coordinated Voltage and Reactive Power Control of Offshore HVAC Meshed Grid and Wind Power

Wu, Qiuwei; Akhmatov, Vladislav; Takarics, Tibor

Published in:
IET Renewable Power Generation

Link to article, DOI:
10.1049/iet-rpg.2020.0425

Publication date:
2021

Document Version
Peer reviewed version

Coordinated Voltage and Reactive Power Control of Offshore HVAC Meshed Grid and Wind Power

Qiuwei Wu [1*], Vladislav Akhmatov [2], Tibor Takarics [1]

[1] Centre for Electric Power and Energy, Department of Electrical Engineering, Technical University of Denmark, Kg.Lyngby 2800, Denmark
[2] Energinet – Transmission System Operator of Denmark, Tonne Kjaersvej 65, 7000 Fredericia, Denmark
[*] qw@elektro.dtu.dk

Abstract: The Kriegers Flak Combined Grid Solution (KF CGS) is the first hybrid-asset project utilizing an offshore HVAC/HVDC interconnector for large offshore wind power plants between Eastern Denmark and Germany in the Baltic Sea. In total, the KF CGS utilizes above 520 km HVAC cables. On the Danish side, above 200 km 220 kV cables are arranged into a meshed offshore transmission grid (MOG). As the cables approach the critical length, the reactive power generation depends on the active power transfer. In order to maintain good voltages in the MOG and wind power plants, on the Danish side, the control is realized by an automatic voltage regulation and reactive power control (AVR/RPC) of several switchable and variable reactors and transformers with tap-position controllers, and the Wind Power Plant Controllers (WPPC); on the German side, the voltage control is achieved by the HVDC Back-to-Back converter, WPPC, and part of the Optimal Power Flow (OPF) by the Master Controller for Interconnector Operation (MIO). This paper presents the proposed coordinated voltage and reactive power control and assets of the HVAC MOG on the Danish side of the KF CGS interconnector. The efficiency and constraints of the proposed coordinated control scheme of the KF CGS at fluctuating voltage and reactive power in both ends of the MOG has been presented by simulations using the entire set up of the 220 kV AC MOG with the validated model of the AVR/RPC, the models of the 220/33 kV transformers and their control, and the models of the KFA and KFB WPPC.

1. Introduction

The Kriegers Flak Combined Grid Solution (KF CGS) is a hybrid-asset project of Energinet, the Transmission System Operator (TSO) of Denmark, and 50Hertz Transmission, the German TSO, in the Baltic Sea [1]. The KF CGS is an offshore interconnector between the two transmission systems, which utilizes the grid-connections of the large offshore wind power plants (OWPP) [1]. Fig. 1 shows an overview of the KF CGS including the wind power plants, offshore platforms, substations and cables. The KF CGS connects the wind power infeed and utilizes the remaining capacity by the market.

The existing 135 km long 150 kV AC submarine and underground cable connections of the Baltic 1 (48.3 MW) and Baltic 2 (288 MW) WPPs are extended by the two 24 km long 150 kV AC cables from the reconfigurable Baltic 2 platform to the new Kriegers Flak B extension platform (KFE). On the Danish side, the two platforms Kriegers Flak A (KFA) and Kriegers Flak B (KFB) are established to collect the planned 200 MW and 400 MW OWPP, respectively. The KFA and KFB platforms are linked through an approx. 9 km long 220 kV AC cable and connected to the onshore compensation substation Bjæverskov by two approx. 80 km long 220 kV submarine and underground cables. In Bjæverskov, there is a 400/220 kV step-up transformation with connection to the Eastern Danish 400 kV transmission grid. From Bjæverskov to Ishøj, there is another 35 km long 220 kV underground cable with another 400/220 kV step-up transformation to the 400 kV transmission grid.

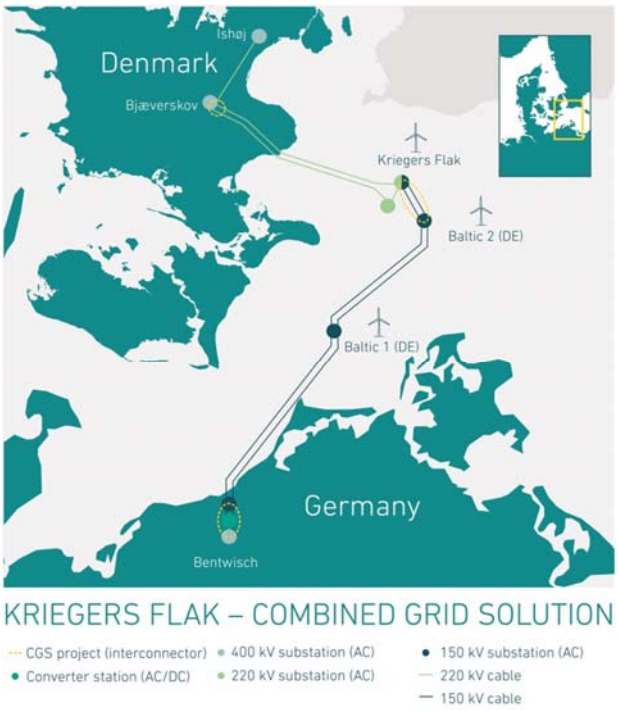


Fig. 1. *Overview of Kriegers Flak Combined Grid Solution.*

On the KFE platform, the 220/150 kV transformation is established and connects the 220 kV meshed offshore grid (MOG) with the 150 kV radial grid.

At present, the 150 kV terminal of the KFE platform serves as the point-of-settlement between Denmark and

Germany with the nominal active power transfer capacity of ±400 MW and the permitted reactive power range of ±40 MVar [1].

Since Eastern Denmark (the Nordic synchronous area) and Germany (the Continental European synchronous area) are not synchronised, there is an HVDC Back-to-Back (BtB) converter in the German Bentwisch substation. The active and reactive ratings of the BtB converter are 400 MW and 100 MVar, respectively [1].

The KF CGS interconnector includes approx. 520 km HVAC submarine and underground cables. The net reactive power generation of the cables is dependent on the active power transport, since the cable lengths of both 220 kV and 150 kV systems approach the critical cable lengths.

The 150 kV system utilizes the Optimal Power Flow (OPF) by the Master Controller for Interconnector Operation (MIO) enabling the continuous voltage and reactive power control of the commissioned OWPP and the BtB.

The 220 kV system is controlled by the AVR/RPC utilizing several switchable and variable reactors and transformers with tap-position controllers. The KFA and KFB OWPP shall be commissioned two years after the 220 kV system becomes part of the KF CGS interconnector.

When the KFA and KFB OWPP are commissioned, their WPPC will enable the continuous voltage and reactive power control in the 220 kV HVAC MOG of the KF CGS. This paper describes the present discrete control by the AVR/RPC, which is before connection of the KFA and KFB OWPP, and proposes a coordinated control scheme of the voltage and reactive power control including the KFA and KFB WPPC together with the existing AVR/RPC. Both efficiency and constraints of the coordinated voltage and reactive power control are presented `.

2. Control Principles

The control shall keep the voltages through the KF CGS interconnector and the reactive power exchange through the KFE platform and with the Danish 400 kV transmission grid within specified operation ranges [2]. On the one hand, increasing the operation voltages and minimizing the reactive power transfer shall reduce the transmission losses and increase the efficiency of the active power transport. On the other hand, introducing safety margins of the operation voltages shall mitigate a risk of overvoltage in case of tripping of the cable compensation or the voltage controlling assets [3].

The KF CGS interconnector utilizes the two types of control: (i) continuous control and (ii) discrete control. The WWPC and BtB deliver continuous voltage and reactive power control. The tap-position controllers of the transformers and reactors provide discrete stepwise voltage and reactive power control, and the AVR/RPC coordinates this discrete control type.

Since the assets and control systems are distributed in the KF CGS, and the KFA and KFB WPPC shall be commissioned about two years after the KF CGS interconnector is in operation, the overall control is divided at the middle of the interconnector between the two networks: (i) the 220 kV network with discrete controllers; and (ii) the 150 kV network with continuous controllers, as shown in Fig. 2. The 220 kV and 150 kV networks are treated as two separate areas with less possible control interaction between the areas. In the 150 kV network, the Master Controller for Interconnector Operation (MIO) conducts the Optimal Power Flow (OPF) by optimizing the voltages of the Baltic 1 and Baltic 2 WPPC and BtB [3]. In the 220 kV system, the AVR/RPC controls the tap-position controllers of the 400/220 kV transformers and the 220 kV reactors for minimizing the reactive power transfer at the maximum possible operation voltage.

Ref. [3] has shown a strong viability of the dynamic reactive power exchange through the KFE platform with varying operation conditions of the OWPP in the 150 kV network. The dynamic fluctuating reactive power exchange at the KFE platform may introduce dynamic fluctuations of the reactive power and voltages in the 220 kV system which may result in unnecessary, excessive activation of the tap-position controllers of the transformers and reactors by the AVR/RPC. Additionally, inherent dynamic variations of the Danish 400 kV transmission grid voltage, as illustrated in Fig. 3, may also cause variations of the 220 kV system voltages and initiate unnecessary activation of the tap-position controllers by the AVR/RPC.

By allowing only the small reactive power range of ±40 MVar through the 220/150 kV transformation in the KFE platform and letting the tap-position controller of the 220/150 kV transformer to control the 150 kV voltage of the KFE platform, such unwished control interaction and unnecessary activation of the discrete controllers will be reduced.

When commissioned, the KFA and KFB WPPC shall together with the AVR/RPC establish a coordinated control to suppress dynamic reactive power fluctuation at the KFE platform, reduce activation of the discrete controllers without compromising the losses reduction and keeping high efficiency of the active power transport through the 220 kV system of the KF CGS interconnector.

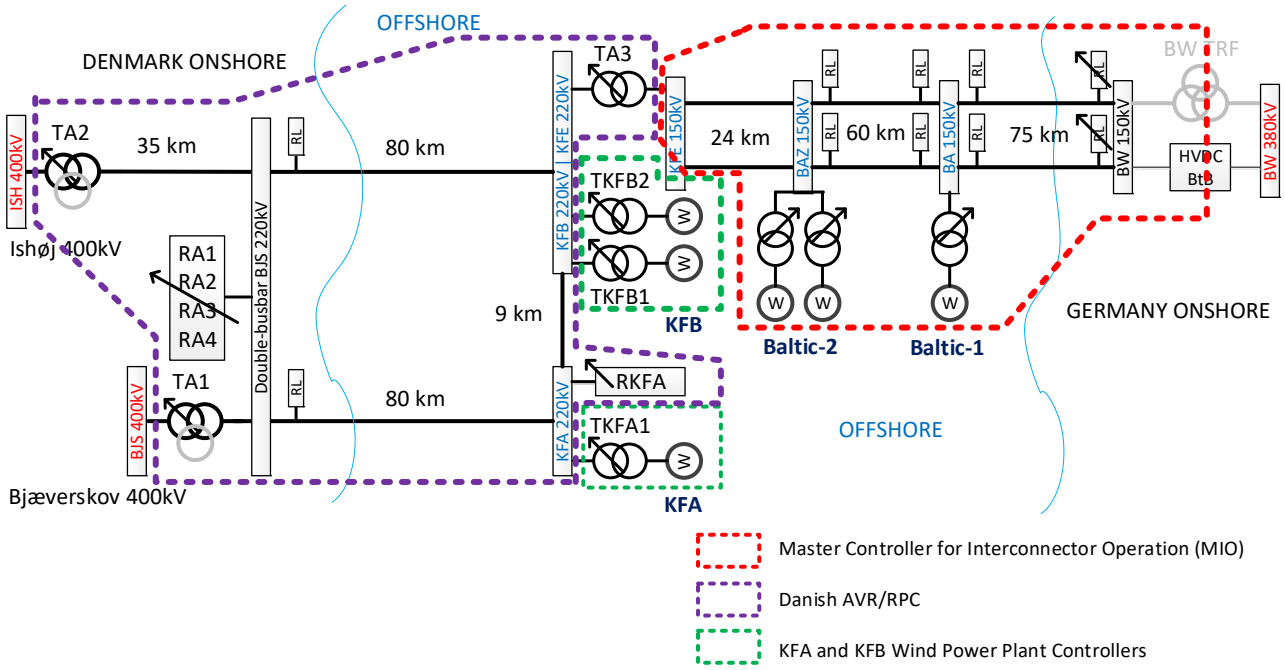


Fig. 2. *Voltage and reactive power control of Kriegers Flak Combined Grid Solution.*

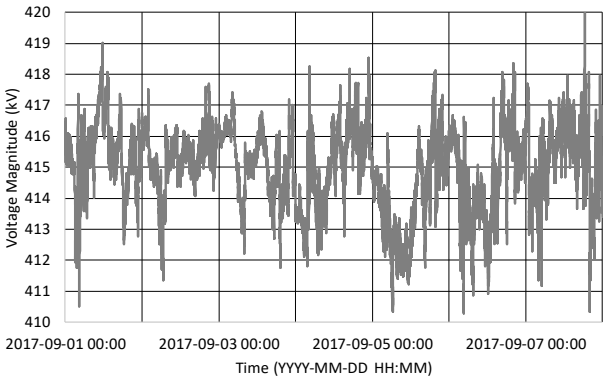


Fig. 3. *Measured 400 kV voltage magnitude in the Danish transmission grid with inherent dynamic variations over a week. The measurement is from the main 400 kV substation Hovegård.*

3. AVR/RPC Scheme

The 220 kV system includes a 220 kV cable MOG connecting the KFA and KFB platforms with the compensation substation BJS220 and the Danish 400 kV transmission grid. The nominal power transfer capacity of the submarine cables and the underground cables are 300 MW and 500 MW, respectively, plus their reactive power generation. The nominal capacities do not account for the dynamic line rating (DLR) of the cables [4].

The relevant assets are shown in Fig. 4, which include the tap-position controllers of the 500 MVA 400/220/10 kV TA1 and TA2 transformers in Bjæverskov and Ishøj, and the 450 MVA 220/150 kV TA3 offshore transformer in the KFE platform, and the 120 MVar switchable and 60-120 MVar variable reactors in the BJS220 substation and on the KFA platform. These devices are controlled by the Danish AVR/RPC. Appendix 1 presents the main electrical data of the transformers and reactors.

The tap-position controllers of TA1 and TA2 are to maintain the 220 kV platform voltage within a given voltage range, i.e., the AVR part shown in Fig. 4(a). The default voltage range is 235-240 kV on the platforms and 230-235 kV in the onshore substations, but adaptable from the National Control Centre (NCC) in Denmark. During normal (n-0) conditions of the 220 kV system, these transformers are in a master-follower mode. The master-follower mode means that the master transformer takes the action and steps the tap-position for keeping the specified voltage range in the controlled platform or substation. The follower transformer keeps the same tap-position as the master transformer with an inherent process delay of a few seconds. The master-follower regime is for preventing reactive-power circulation between the transformers through the 220 kV system and mitigating of hunting, i.e., stepping into opposite directions, between the tap-position controllers in discrepancy of the voltage measurements and/or operation ranges of the transformers.

The TA1 and TA2 transformers operate in the master-follower mode in both (n-0) and (n-1) interconnected operation conditions of the 220 kV network except of the fully separated condition. In the fully separated condition, the busbars of the BJS220 substation, i.e., the busbar coupling is open, and the KFA and KFB platforms, i.e., the KFA-KFB submarine cable is disconnected, are separated from each another.

In the fully separated condition, each transformer is in radial connection with a given platform. The AVR accounts for the cross-coupling variants between the transformers and platforms. Accounting for the cross-coupling ensures that each transformer controls the right platform voltage.

When one transformer is out of operation, the remaining transformer is in the single-master control mode.

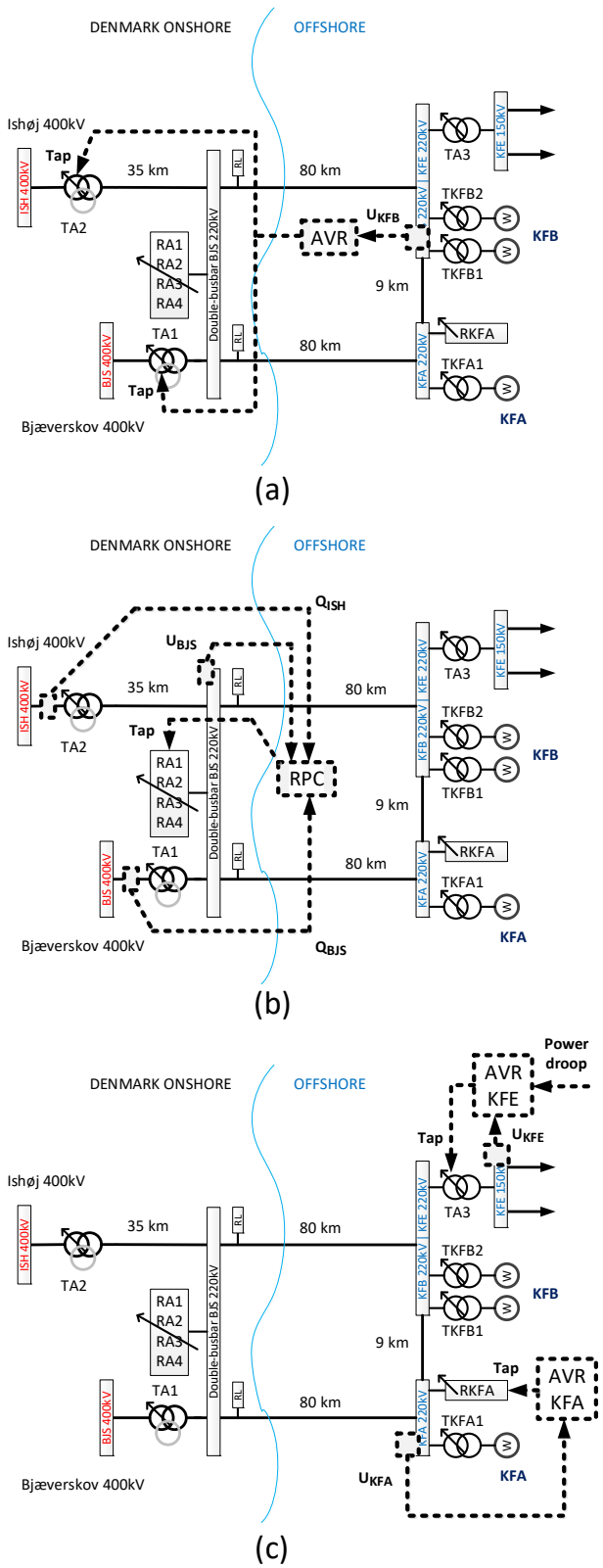


Fig. 4. *Schematic representation of the AVR/RPC in the 220 kV network of the Kriegers Flak Combined Grid Solution: (a) – the AVR controlling the tap-positions of the onshore transformers, (b) – the RPC controlling the switchable and variable onshore reactors, (c) – the two AVR controlling the offshore assets on the KFE and KFA platforms.*

If any busbar voltage in the 220 kV system is above the maximum permitted voltage, the TA1 and TA2 transformers immediately interfere and step the voltage down into the specified range. If any busbar voltage in the 220 kV system is below the minimum permitted voltage, the TA1 and TA2 tap-position controllers are blocked implying that stepping is discontinued. The blocking with discontinued stepping is a safety measure, i.e., against false voltage measurements or a transient voltage dip, preventing the transformers from stepping up the voltage and hazarding the assets when the voltage becomes high after the dip.

The control of the 220 kV reactors in the BJS220 compensation substation shall keep the reactive power transfer between the 220 kV network of the KF CGS and the Danish 400 kV transmission grid within a given range, i.e. the RPC part shown in Fig. 4(b). The default range is ±20 MVar in each 400 kV connection point Bjæverskov and Ishøj. The reference of the range is 0 MVar at each 400 kV connection point. However, the reference and range are adaptable from the NCC in Denmark.

The reactors can be connected to either busbar of the BJS220 double-busbar substation. However, the preferred connection is two reactors in each busbar.

In the coupled operation of the BJS220 substation, as shown in Fig. 4(b), the reactive power control works as a single RPC system. The RPC applies to all the reactors in-service and ensures that the absolute maximum reactive power transfer in either Bjæverskov or Ishøj stays within the range, e.g., ±20 MVar. Appendix 2 describes the switching procedure of the reactors in coupled operation and at the voltage in the range.

In the separated operation of the BJS220 substation, the reactive power control splits into two RPC systems. Each RPC keeps the reactive power transfer with its connected 400 kV terminal. When the connection to one of the 400 kV terminals is removed, the RPC works as a single RPC with the 400 kV terminal which remains connected to the BJS220 compensation substation.

Since the first steps of the reactors, i.e., 60 MVar, are larger than the ±20 MVar reactive power range, the RPC pre-calculates the reactive power after switching the reactor. Only if the switching gives a more favourable reactive power position with regard to the range, the RPC conducts the switching. Otherwise, the switching is not conducted and the reactive power transfer with the 400 kV grid may have a small deviation from the reactive power range.

Additionally, the RPC control of the 220 kV reactors monitors the voltage in the BJS220 compensation substation. If the voltage gets off the range, the RPC shifts the control mode from the reactive power control to the voltage control. When the RPC is in the voltage control mode, fast switching of the reactors may apply. However, excessive switching of the reactors in low voltage operations is prevented for avoiding unexpected overvoltage situations following an abrupt voltage recovery.

The switchable reactor on the KFA platform does not participate in the reactive power control. This reactor is normally in-service. The reactor disconnects by under-voltage and re-connects by overvoltage on the KFA platform. This part of the AVR control is illustrated in Fig. 4(c).

The tap-position control of the KFE transformer keeps a required operation voltage range in the 150 kV offshore terminal, which is shown in Fig. 4(c). The 150 kV voltage

reference and the band are adjusted by the active power flow through the 150 kV system using a power droop characteristic.

Since the characteristic time constants of the tap-position controllers are within several seconds and the time constants of the AVR/RPC are from several to tens of seconds, this discrete control is not designed for mitigating abrupt, transient voltage sags in the KF CGS grid. The tap-position steps are specified for not causing excessive voltage sags utilizing the lowest realistic short-circuit capacity levels in the Danish transmission grid. According to the specifications and short-circuit capacity levels in the Danish transmission grid from Energinet, stepping of the transformer tap-positions shall not cause unwished opposite actions of the tap-position stepping of the reactors and vice-versa. The 400 kV voltage fluctuations in the Danish transmission grid, as illustrated in Fig. 3, shall not initiate unwished action of the tap-position controllers. This is achieved by adjustment of the activation bands accounting for such natural voltage fluctuations.

The 400 kV substation Bjæverskov is also a connection point of a 280 MVA synchronous condenser and another RPC which controls the filters of the Kontek LCC HVDC connector with the rated power of 600 MW. The time constants and control functions of the AVR/RPC are carefully chosen and parametrized which helps avoid unwished disturbance of and interaction with the already existing equipment and control systems around Bjæverskov. The experience of Energinet is that the presented AVR/RPC of the KF CGS interconnector does not show interaction with the synchronous condenser or the Kontek RPC in Bjæverskov. Since the AVR/RPC is inhouse designed and built, Energinet has full access to the control functions and parameters, if unwished interaction with an existing or new equipment should be detected and mitigated.

4. Test and Model Validation

On May 2nd 2019, the AVR/RPC was tested for the first time and under supervision of the NCC. Fig. 5 shows the measured sequence of the AVR/RPC test operation.

The measured data resolution is 1 min. The 400 kV voltage measurement in Bjæverskov is within a range of 1.5 kV, which is below 0.5%, and accurate for operation and tests. The test operation provides the real-life data to validate the AVR/RPC simulation model.

Fig. 6 shows the simulated behaviour of the AVR/RPC model of Energinet. The model was implemented in the simulation program DigSilent® PowerFactory.

Since the AVR/RPC control shall comply with both voltage ranges in the offshore platforms and reactive power ranges in the onshore connection substations using tap-position controllers of numerous devices, the monitored key-parameters of the test include:

- the voltage responses in the platforms and in the onshore substation BJS220,
- the reactive power transport in the onshore connection substations, and
- the tap-positions of the transformers and reactors.

The response time of the AVR/RPC to the orders of the NCC has been qualitatively observed but not recorded. Therefore, the stationary values of the monitored voltage, reactive power, and tap-positions at the start and at the end of each test sequence are used for evaluation of the AVR/RPC responses and validation of the simulation model. The success criterion is that the monitored voltage and reactive power in the measurements are reached in the simulations within the given accuracy of 0.5% for each conducted sequence. The tap-positions in the measurements are fully reached in the simulations for each conducted sequence.

4.1 AVR/RPC Test Sequences

Prior to the test, the AVR/RPC had been inactive with locked tap-positions of the transformers and variable reactors.

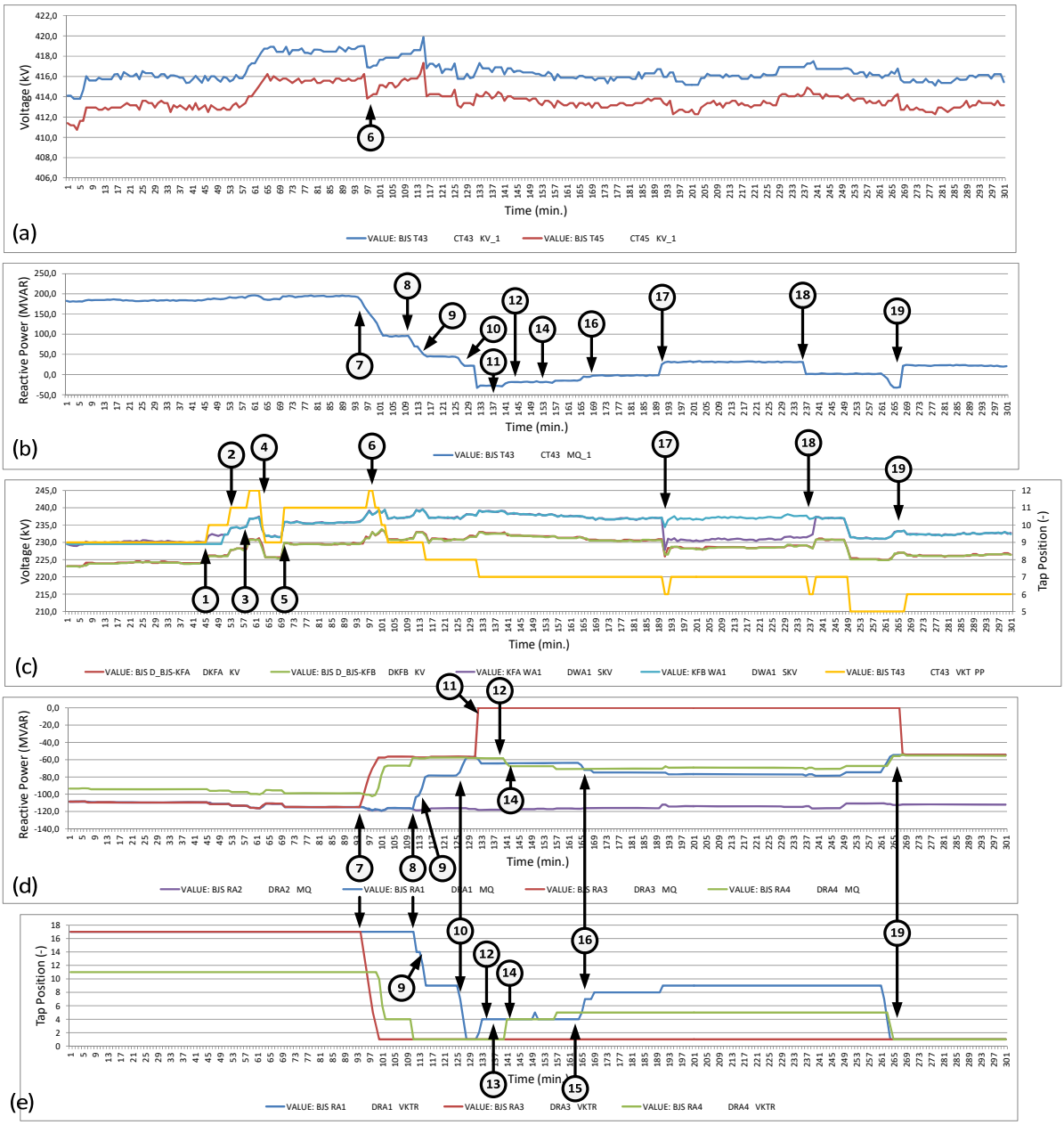


Fig. 5. *Test operation of AVR/RPC:* ***(a)*** *400 kV transmission grid voltage,* ***(b)*** *reactive power transfer with the transmission grid, positive is from the 400 kV grid to the KF CGS,* ***(c)*** *220 kV voltage and 400/220/10 kV transformer tap-position,* ***(d)*** *reactors reactive power,* ***(e)*** *reactors tap-positions.*

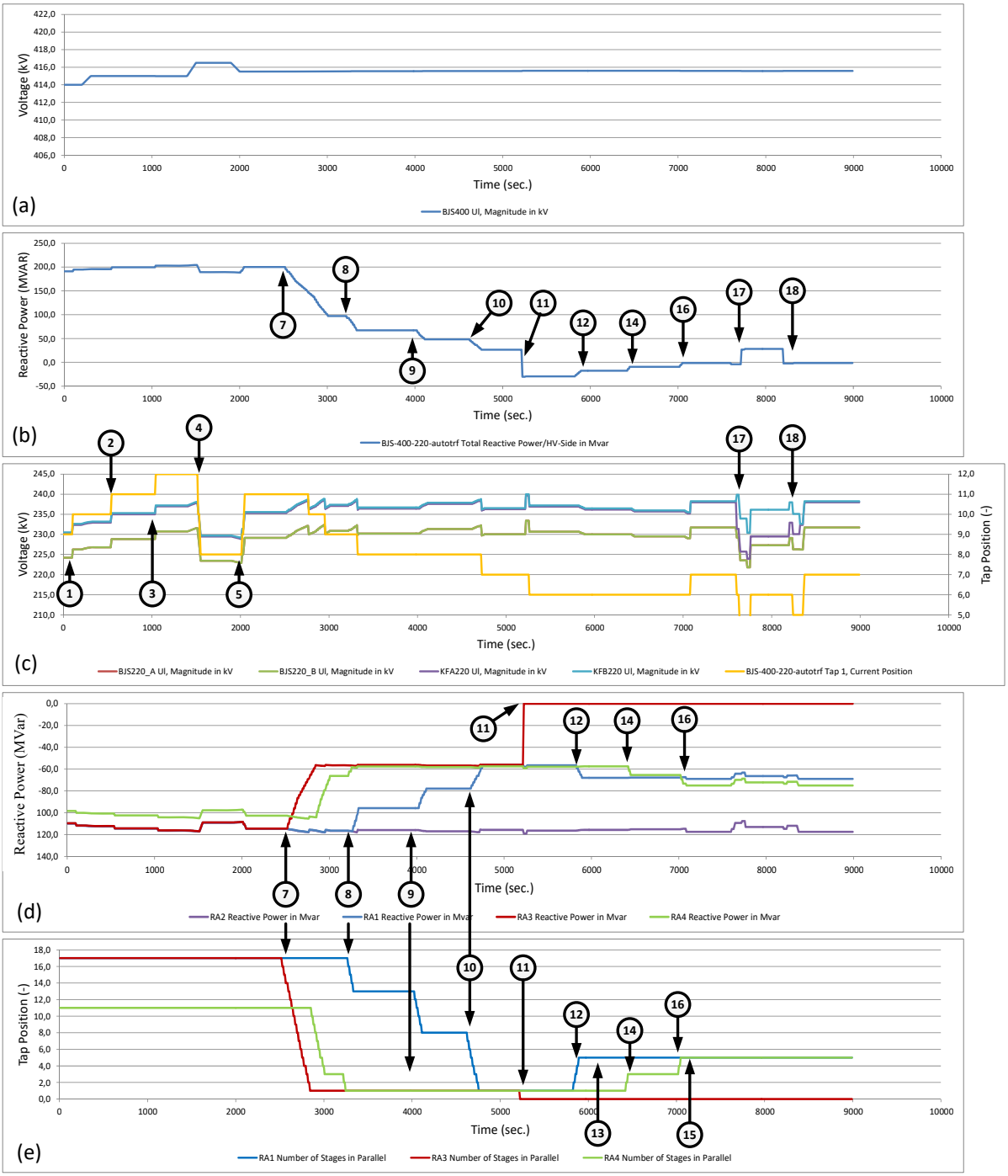


Fig. 6. *Simulation of AVR/RPC using the simulation model of Energinet:* ***(a)*** *400 kV transmission grid voltage,* ***(b)*** *reactive power transfer with the transmission grid, positive is from the 400 kV grid to the KF CGS,* ***(c)*** *220 kV voltage and 400/220/10 kV transformer tap-position,* ***(d)*** *reactors reactive power,* ***(e)*** *reactors tap-positions.*

The test began from the transformer tap-position at 9 giving 230 kV on the offshore platforms, and all reactors are connected causing about 200 MVar absorption from the onshore 400 kV transmission grid. The test duration was over 3 hours with the following events (the sequences):

1 Release automatic voltage control (AVR) of the transformer. The tap-position steps up to follow the given voltage reference 233 kV.
2 Set the voltage reference as 235 kV. The tap-position steps up to follow the reference.
3 Set the voltage reference as 237 kV. The tap-position steps up to follow the reference.
4 Set the voltage reference as 230 kV. The tap-position steps down to follow the reference.
5 Set the voltage reference as 237 kV. The tap-position steps up to follow the reference.
6 The grid voltage sags caused a single toggle of the tap-position. Not included in the simulations.
7 Release reactive power control (RPC) of the reactors, set the reference as 0 MVar and the range as

±100 MVar. The reactors step down in a specified order, as in Appendix 2, to comply with the operation range.

8 Reduce the range to ±70 MVar. The reactors step down in a specified order to comply with the operation range.

9 Reduce the range to ±50 MVar. The reactors step down in a specified order to comply with the operation range.

10 Reduce the range to ±20 MVar. The reactors step down in a specified order. The operation is with a small number of MVar off the range. All reactors are in the first steps and further stepping-down may cause unfavourable conditions. Therefore, the operation continues off the range.

11 Set the reference as 10 MVar (capacitive) to provoke the first reactor to switch off. A single reactor switches off as expected.

12 Set the reference as 0 MVar. The connected reactors step up in a specified order to comply with the operation range.

13 Lock the reactor with the first order, RA1, and set the reference as 10 MVar inductive. The reactor with the second order steps up to comply with the operation range.

14 Set the reference as 20 MVar inductive. The reactor with the second order steps up to comply with the operation range, as the first reactor, RA1, is still locked.

15 Unlock the first reactor.

16 The first reactor steps up due to varying conditions in the Danish transmission grid and manual actions of the NCC. Not included in the calculations.

17 Disconnect the 220 kV cable from the NCC between the KFA and KFB platforms.

18 Reconnect the 220 kV cable between the KFA and KFB platforms from the NCC. The cable discharging time before reconnection is not included in calculations.

19 Manually steps all reactors to their first tap-positions and manually steps the transformer from the NCC. Omitted in the calculations.

4.2 Comparison of Simulations to Test Results

In the test, the orders to the AVR/RPC were manually conducted by the NCC. The NCC decided when and whether the voltage and reactive power reached a new steady-state before conducting the next order to the AVR/RPC. The exact time of the NCC actions and orders to the AVR/RPC were not recorded. Therefore, the simulations are conducted by implementing the next order after 500-600 sec. of the previous order. Further, a duration of 15-20 min, when the KFA-KFB cable was disconnected, is shortened to 500 sec. in the simulations. The measured test sequence, which includes voltages, reactive power and tap-positions, is obtained from the SCADA of Energinet.

Table 1 compares the test results and the simulation results of the above listed sequences. The measured and simulated voltage and reactive power are rounded up to the closest integer values for easy and clear presentation of the test results and model validation. Rounding up to the closest integer complies with the given accuracy of the measurements, which is 0.5% of the nominal voltage (220kV) and nominal power transport (600 MW) within the KF CGS system.

Sequence (orders)	Comparison		
	Parameter	Measurement	Simulation
1. → 2.	Tap TA1	9 → 10	9 → 10
	U_{KFA} (kV)	230 → 233	230 → 233
	U_{KFB} (kV)	230 → 233	230 → 233
	U_{BJS} (kV)	224 → 227	224 → 227
2. → 3.	Tap TA1	10 → 11	10 → 11
	U_{KFA} (kV)	233 → 235	233 → 235
	U_{KFB} (kV)	233 → 235	233 → 235
	U_{BJS} (kV)	227 → 229	227 → 229
3. → 4.	Tap TA1	11 → 12	11 → 12
	U_{KFA} (kV)	235 → 237	235 → 237
	U_{KFB} (kV)	235 → 237	235 → 237
	U_{BJS} (kV)	229 → 231	229 → 231
4. → 5.	Tap TA1	12 → 9	12 → 8
	U_{KFA} (kV)	237 → 231	237 → 230
	U_{KFB} (kV)	237 → 231	237 → 230
	U_{BJS} (kV)	231 → 225	231 → 224
5. → 6.	Tap TA1	9 → 11	8 → 11
	U_{KFA} (kV)	231 → 235	230 → 235
	U_{KFB} (kV)	231 → 235	230 → 235
	U_{BJS} (kV)	225 → 230	224 → 229
7. → 8.	Tap RA1	17	17
	Tap RA2	1	1
	Tap RA3	17 → 1	17 → 1
	Tap RA4	11 → 4	11 → 3
	Q_{BJS} (MVar)	200 → 100	200 → 100
	Tap TA1	11 → 9	11 → 9
8. → 9.*	Tap RA1	17 → 14	17 → 13
	Tap RA2	1	1
	Tap RA3	17 → 1	17 → 1
	Tap RA4	4 → 1	3 → 1
	Q_{BJS} (MVar)	100 → 70	100 → 67
	Tap TA1	9 → 8	9 → 8
9. → 10.	Tap RA1	14 → 9	13 → 8
	Tap RA2	1	1
	Tap RA3	1	1
	Tap RA4	1	1
	Q_{BJS} (MVar)	70 → 48	67 → 48
	Tap TA1	8	8
10. → 11.	Tap RA1	9 → 1	8 → 1
	Tap RA2	1	1
	Tap RA3	1	1
	Tap RA4	1	1
	Q_{BJS} (MVar)	48 → 25	48 → 27
	Tap TA1	8	8 → 7
11. → 12.	Tap RA1	1	1
	Tap RA2	1	1
	Tap RA3	1 → 0 (off)	1 → 0 (off)
	Tap RA4	1	1
	Q_{BJS} (MVar)	25 → -30	27 → -30
	Tap TA1	8 → 7	7 → 6
12. → 13.	Tap RA1	1 → 4	1 → 5
	Tap RA2	1	1
	Tap RA3	0 (off)	0 (off)
	Tap RA4	1	1
	Q_{BJS} (MVar)	-30 → -18	-30 → -18
	Tap TA1	7	6
13. → 14.	Tap RA1	4	5
	Tap RA2	1	1
	Tap RA3	0 (off)	0 (off)
	Tap RA4	1	1
	Q_{BJS} (MVar)	-18	-18
	Tap TA1	7	6
14. → 15.	Tap RA1	4	5
	Tap RA2	1	1
	Tap RA3	0 (off)	0 (off)
	Tap RA4	1 → 4	1 → 3
	Q_{BJS} (MVar)	-18 → -10	-18 → -9
	Tap TA1	7	6

Table 1. *Comparison of measured in the test and simulated by the model key-parameters of the AVR/RPC. *A very short duration in the test. (Continues in the next page).*

Sequence (orders)	Comparison		
	Parameter	Measurement	Simulation
16. → 17.	Tap TA1**	7 → 6 → 7	7 → 6 → 5 → 6
	U_{KFA} (kV)**	237 → 231	238 →231 →226 →224 →230
	U_{KFB} (kV)**	237 →235 →237	238 →240 →234 → 230 →236
	U_{BJS} (kV)**	231 → 226 →228	231 → 229 →224 →222 →227
	RA1	8 → 9	5
	RA2	1	1
	RA3	0 (off)	0 (off)
	RA4	5	5
	Q_{BJS} (MVar)	0 → 37	0 → 28
17. → 18.	Tap TA1	7 → 6 → 7	6 → 5 → 7
	U_{KFA} (kV)**	232 → 237	230 →233 →230 →238
	U_{KFB} (kV)**	238 → 237	236 →238 →233 →238
	U_{BJS} (kV)**	229 → 231	227 →229 →226 →232
	RA1	9	5
	RA2	1	1
	RA3	0 (off)	0 (off)
	RA4	5	5
	Q_{BJS} (MVar)	37 → 0	28 → 0

Table 1. *Comparison of measured in the test and simulated by the model key parameters of the AVR/RPC. **Better time resolution in the simulation than 1 min. resolution in the measurement. (Continued from the previous page).*

The simulation model is in a good agreement with the test results, except of the omitted (not relevant for the model validation) sequences 6, 15, 16 and 19. The key-parameters of the model validation, which are the voltages in the offshore platforms and in the compensation substation BJS220, the reactive power of the connection substation, and the tap-positions of the AVR/RPC controlled devices, are in good agreement with the measurements.

The deviation between the test and the model within the tap-positions of the 220 kV reactors in the sequences 17 and 18 originates from some inherent dynamic behaviour of the 400 kV transmission grid during the sequences 15 and 16, which was present during the test but not included in the simulation.

5. Wind Power Plant Controller Model

The KFA and KFB wind power plants shall be commissioned about two years after the completion of the KF CGS interconnector. When conducting this work, the KFA and KFB wind power plants are not established yet and represented with generic-level models.

The modelling level reflects the subject of this work, which is dynamic voltage and reactive power control optimization in normal operation of the transmission grid excluding the fault-ride-through. Thus, fast control responses to abrupt voltage dips and post-fault voltage recovery of the fault-ride-through are omitted in the KFA and KFB wind power plant models.

The wind turbines will be connected along the medium voltage (MV) 33 kV cable radials, which gives different distances, impedances and charging capacitances of the MV cables from the wind turbines to the collection terminals of 220/33 kV transformers on the offshore platforms. Therefore, the wind turbines may exchange different amounts of the reactive power with the MV cable radials for fulfilling the WPPC control orders.

The specific conditions of voltage and reactive power at the MV terminals of the wind turbines and the reactive power generation and transfer through the MV cable radials become relevant for the control optimization on the WPP level. Therefore, the KFA and KFB WPP models include representations of the wind turbine models along with the MV cable radials.

The wind power plant model including the WPPC follows the description of [5] for the case of controlling several wind turbines with a single point of common coupling (PCC). The WPPC model structure is illustrated in Fig. 7. The WPPC model is implemented in the simulation program DigSilent® PowerFactory.

The WPPC model receives the voltage, active and reactive power signals from the wind turbine models, conducts comparison between the reactive power reference, Q_{REF}, and the measured reactive power, Q_{MEAS}, at the PCC and returns the control orders to the wind turbine models. The control orders shall adjust the voltages (and reactive power exchanges) of the wind turbines for mitigating discrepancies between the reactive power reference and the measured reactive power at the PCC. In the generic-level approach, the WPPC control is a proportional-integrator (PI) controller with non-windup limits. The aim of the PI controller is maintaining the measured reactive power, Q_{MEAS}, the same as the reactive power reference, Q_{REF}, by adjusting the control orders to the wind turbines in-service.

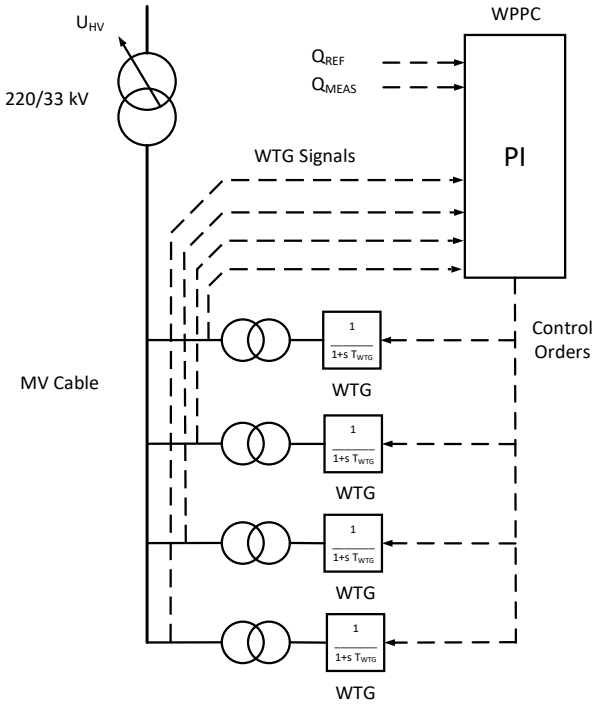


Fig. 7. *Wind power plant and WPPC model: Q_{REF} and Q_{MEAS} are the reference and measured reactive power on the wind power plant level, WTG signals, i.e., voltage, active and reactive power, and control orders, i.e., voltage, are exchanged between the WPPC and the wind turbines.*

The PI controller constants are: the proportional gain, K_P= 0.1 p.u., and the integrator gain, K_I= 0.2 p.u., where 1 p.u. equals to the nominal power of the WPP. The wind turbine models are the first order lag transfer functions. This representation implies that the wind turbines follow the WPPC control orders with a characteristic delay of T_{WTG}. The characteristic time is T_{WTG}= 50 ms.

Depending on the operational agreement between Energinet and the WPP operator, the PCC and the signals Q_{REF} and Q_{MEAS} may refer to either the HV or MV terminals of the offshore step-up transformers.

The operational agreement may also include utilization of the tap-position controllers of the step-up transformers to optimize the MV control for reducing the MV cable network losses. However, this may introduce a risk of excessive activation of the tap-position controllers and increase the operation cost due to the needs of more frequent inspections of the offshore transformers compared to operation with locked tap-position controllers.

6. Coordinated control scheme

The proposed coordinated control scheme applies to the 220 kV network of the KF CGS interconnector. The scheme utilizes the continuous voltage and reactive power control of the KFA and KFB WPPC for reducing switching and stepping of the discrete tap-position controllers of the offshore and onshore transformers, and the reactors in the following priority order:

- The first priority is to reduce activation of the tap-position controllers of the 220/33 kV offshore transformers. Located in the offshore platforms, these transformers are with the highest operation and maintenance cost and less redundant regarding the wind energy delivery from the KFA and KFB OWPP. In case of outage or during maintenance periods, the wind power shall be curtailed.
- The second priority is to reduce activation of the tap-position controllers of the 400/220/10 kV onshore transformers in Bjæverskov and Ishøj. The operation cost of these transformers is lower since located onshore. However, the active power transport and utilization of the DLR shall be restricted in case of outage or during maintenance periods of one transformer.
- The third priority is reducing switching and stepping of the 220 kV reactors when possible. Besides, the operation cost (due to maintenance and surveillance) is lower since these reactors are located onshore, the KF CGS interconnector can be operated (almost) without restrictions when a single reactor is either out-of-service or operated with a blocked tap-position controller. The negative impact is violation of the reactive power exchange range with the 400 kV transmission grid, which for a shorter period can be accepted and mitigated by other equipment within the 400 kV transmission grid.

In other words, the coordinated control scheme intends redistributing the activation between the devices, with reduction of the transformer tap-position stepping and acceptance of the onshore reactor stepping. Considering the energy losses reduction in the MV cable networks as the primary control objective, the tap-position controllers shall increase the operation voltage in the MV cable networks under precaution that sudden voltage jumps in the 220 kV network do not cause severe overvoltage in the MV cable networks. This implies that the voltage control of the wind turbine grid-interfaced converters shall not interfere with the voltage optimization by the tap-position controllers. The wind turbine grid-interfaced converters shall also be kept below the inductive current limits. Therefore, the wind turbine converters are subject to the continuous reactive power control of the KFA and KFB WPPC in a coordinated manner with the discrete-type controllers.

The 220 kV network is exposed to the two processes which may cause excessive activation of the discrete controllers by the AVR/RPC and the tap-position controllers of the 220/33 kV offshore transformers:

- Dynamic fluctuation of the reactive power transfer at the KFE platform with the 220 kV network.
- Inherent dynamic voltage fluctuation in the 400 kV transmission grid causing voltage and reactive power fluctuations in the 220 kV network.

Maintaining the reactive power transfer at the KFE platform within the static range of ±40 MVar allows dynamic fluctuation of the reactive power transfer within a total range of up to 80 MVar. This dynamic range is larger than the first 60 MVar step of the reactors RA1, RA3 and RA4. Dynamic fluctuation of the reactive power transfer at the KFE platform may propagate to the BJS220 substation and initiate unwished switching of these reactors. The tap-position controllers of the onshore and offshore transformers may be activated, as the reactor switching and stepping may start voltage fluctuations.

Fig. 8 shows the proposed coordinated control scheme. The proposed scheme applies the reactive power transfer at the KFE platform, Q_{KFE}, and the MV busbar voltages of the KFA and KFB platforms, U_{KFA1}, U_{KFB1}, and U_{KFB2}. The proposed coordinated control scheme calculates the reactive power references to the KFA and KFB WPPC, $Q_{KFA\text{-}REF}$ and $Q_{KFB\text{-}REF}$.

The proposed scheme in Fig. 8 is a proportional controller with the input Q_{KFE} having a characteristic control time, T_{CTRL}, and inherent delays, such as communication and signal processing delays. The proportional controller divides the processed output signals between the KFA and KFB WPPC according to their production capacities, i.e., 200 MW and 400 MW.

The proposed scheme includes also the MV voltage compensation of the inputs U_{KFA1}, U_{KFB1}, and U_{KFB2} with the selectors and integrators. The compensation is for preventing unwished tap-position changing of the 220/33 kV offshore transformers in dynamically varying (active power and) reactive power transfer through these transformers. Without this compensation, the MV cable network voltage may violate the optimized MV operation range when the current through the transformers fluctuates and causes the tap-position controllers to react on the fluctuating voltage. In other words, the MV voltage compensation mitigates an unwished positive feedback occurring between the WPPC and the tap-position controllers of the 220/33 kV offshore transformers.

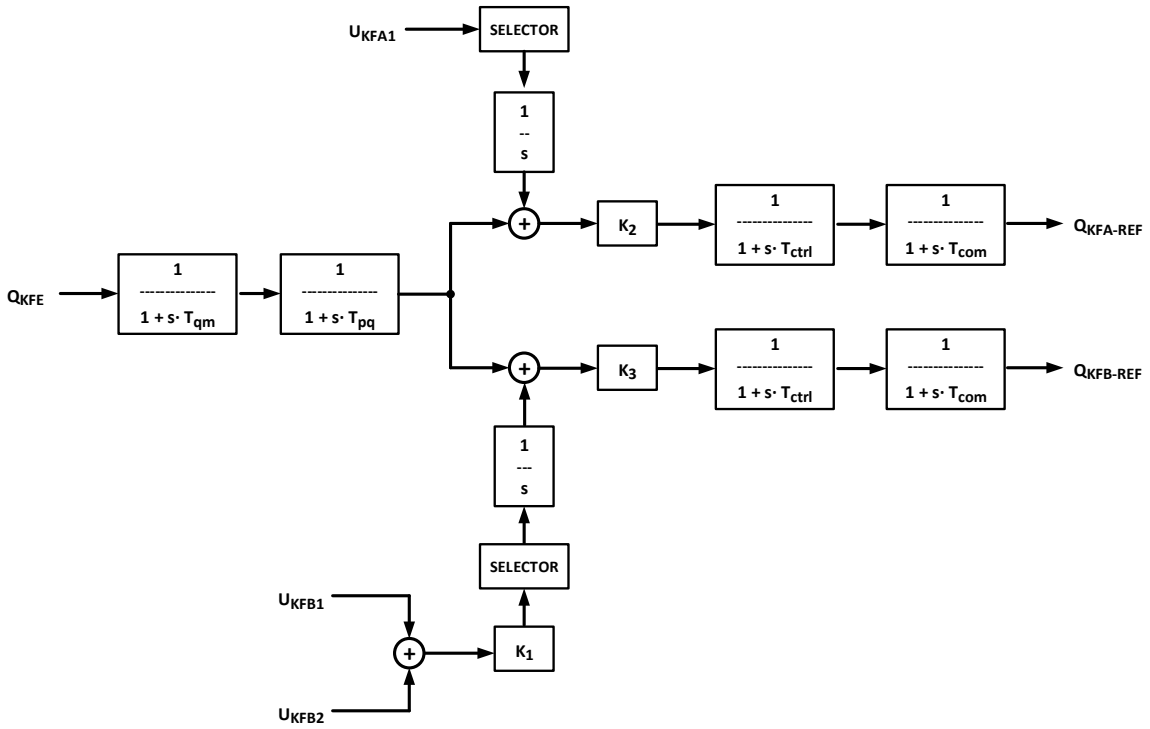


Fig. 8. *Proposed coordinated control scheme of the voltage and reactive power control in the 220 kV system of the Kriegers Flak Combined Grid Solution.*

The reactive power references are calculated and communicated independently to each WPPC and refer to the input signal Q_{REF} in Fig. 7. The KFA and KFB WPPC receive their reactive power references, $Q_{KFA\text{-}REF}$ and $Q_{KF\text{-}BREF}$, and adjust the reference orders to the wind turbine grid-interfaced converters in order to make the reactive power in the KFA and KFB PCC complying with the reactive power references, i.e., $Q_{KFA\text{-}REF} \rightarrow Q_{KFA}$ and $Q_{KFE\text{-}REF} \rightarrow Q_{KFB}$.

The gain K_1 is 0.50 because of the two available voltage measurements, U_{KFB1} and U_{KFB2} at the two 33 kV terminals of the 220/33 kV offshore transformers. The gains K_2 and K_3 are 0.333 and 0.667, respectively, representing unequally distributed power capacities of the KFA and KFB WPPs, 200 MW and 400 MW, in proportion to the total 600 MW power capacity of both WPPC control systems. The time constants are T_{QM} = 0.1 s, T_{PQ} = 0.1 s and T_{COM} = 0.1 s, and the control time is T_{CTRL} = 2.5 s.

7. Assessment results

This assessment demonstrates how the coordinated control scheme, which includes the continuous control of the KFA and KFB WPPC, reduces the tap-position activation of the transformers and reactors. The two cases of the voltage and reactive power control, which have been simulated with and without the proposed coordinated control scheme, are compared. The simulation period of each case is one calendar month (30 days).

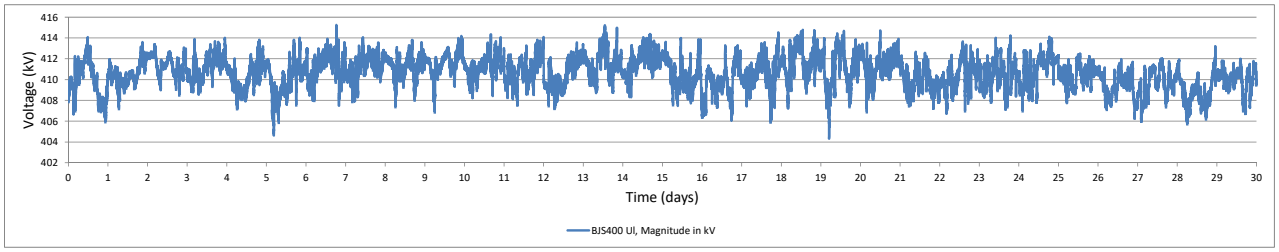
The effectiveness of the proposed coordinated control scheme has been demonstrated by simulations on the 220 kV area model of the KF CGS. The inputs to the simulation model are:

- The 400 kV system voltage with inherent fluctuations by historical measurements of the Eastern Danish transmission grid,
- The forecasted wind power production, and
- The forecasted active and reactive power transfer through the KFE platform.

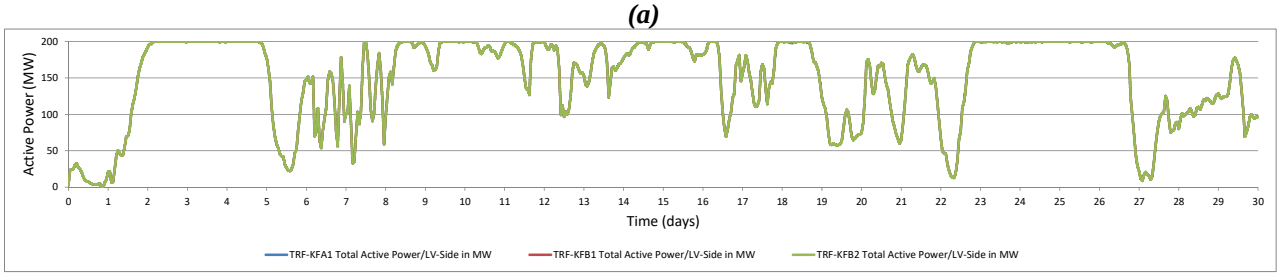
The forecasts and measurements are delivered by Energinet. Fig. 9 shows the inputs to the simulation model of the KF CGS. The simulation results are:

- The tap-position dynamics of the 220/33 kV transformers of the KFA and KFB OWPP,
- The tap-position dynamics of the 400/220/10 kV transformers in Bjæverskov and Ishøj, and
- The tap-positions of the 220 kV reactors in the compensation substation BJS220.

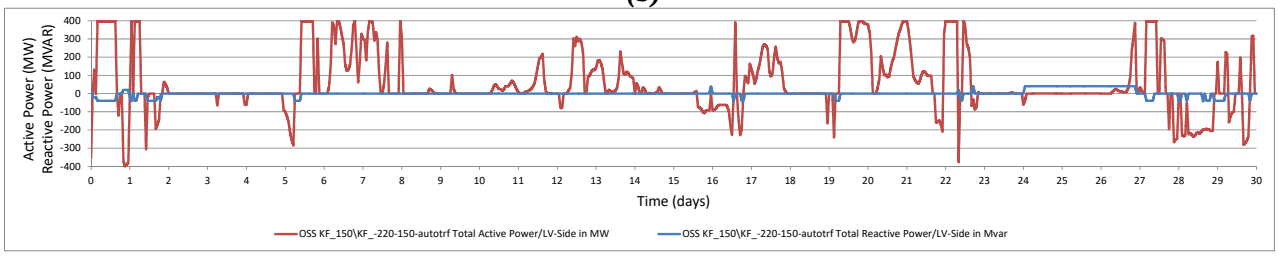
Figs. 10 and 11 show the plots of the simulation results with and without the proposed scheme. The plots give a qualitative impression of how the coordinated control scheme works on reduction of the tap-position utilization. Table 2 presents a quantitative comparison of the simulation results with a clear indication that the proposed coordinated control scheme achieves the main control objective, i.e., prioritised reduction of the tap-position activations of the offshore and onshore transformers. The penalty is increased activation of the tap-potion of a single reactor, RA3.



(a)

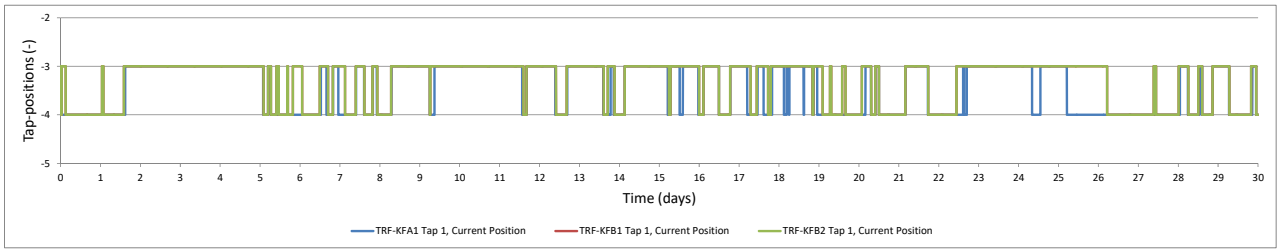


(b)

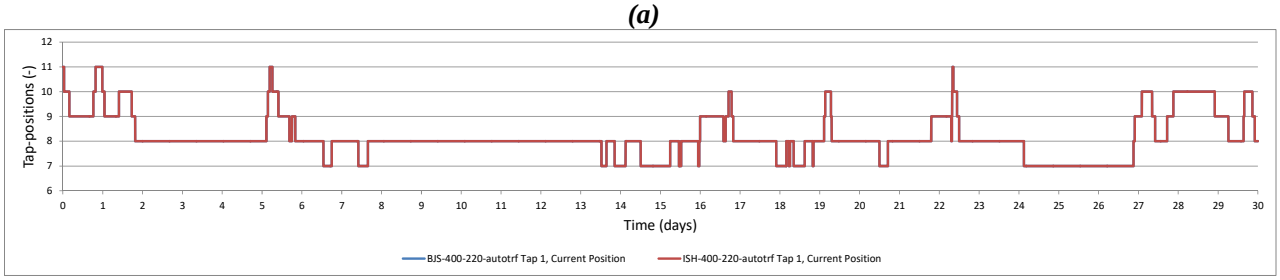


(c)

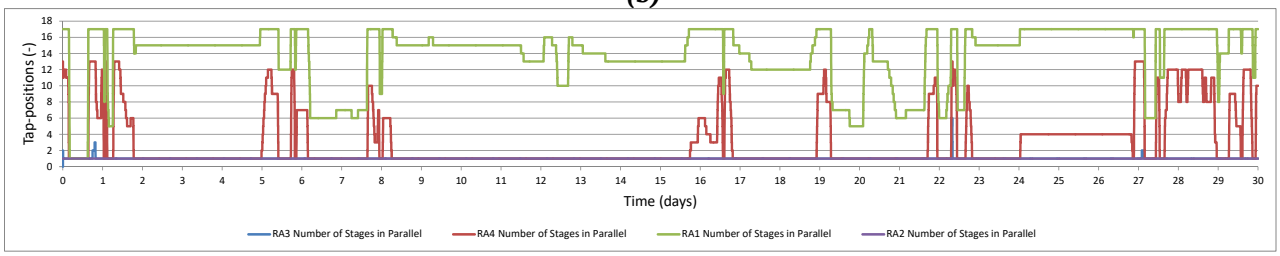
Fig. 9. *Inputs to the assessment:* ***(a)*** *400 kV transmission system voltage,* ***(b)*** *wind power production in each 200 MW section (KFA is with a single section and KFB is with two sections),* ***(c)*** *active and reactive power transfer via the KFE platform.*



(a)

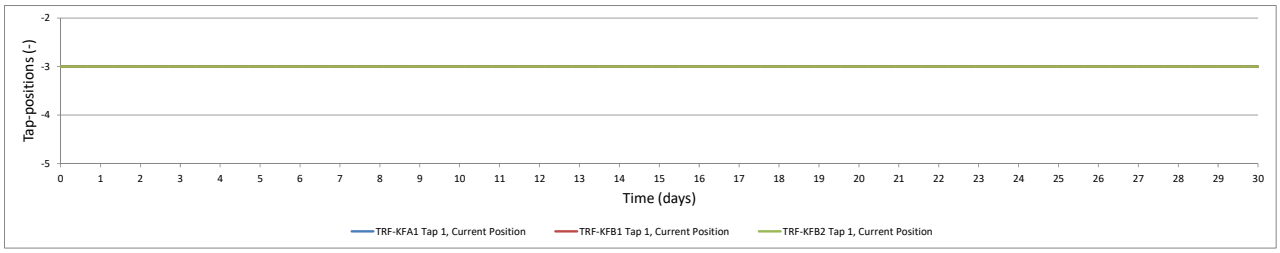


(b)

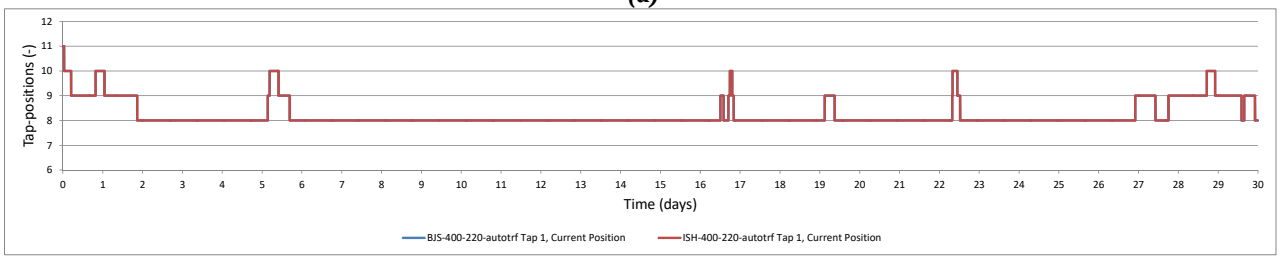


(c)

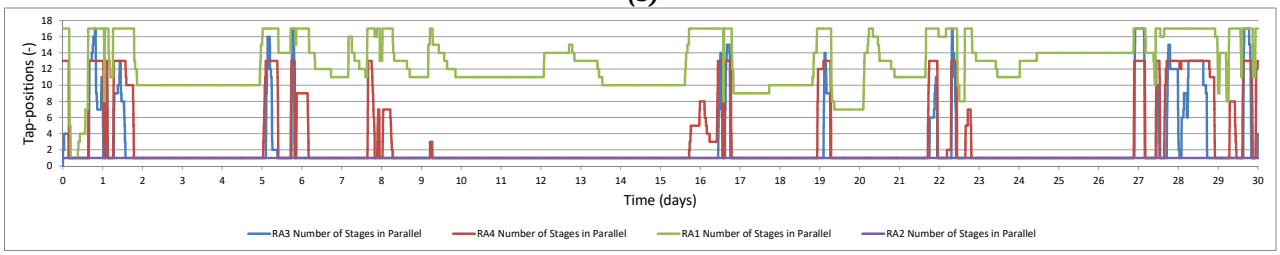
Fig. 10. *Outputs of the assessment without coordinated control:* ***(a)*** *220/33 kV offshore transformer tap-positions,* ***(b)*** *400/220/10 kV transformer tap-positions,* ***(c)*** *tap-positions of 220 kV reactors in substation Bjæverskov*



(a)



(b)



(c)

Fig. 11. *Outputs of the assessment with coordinated control:* ***(a)*** *220/33 kV offshore transformer tap-positions,* ***(b)*** *400/220/10 kV transformer tap-positions,* ***(c)*** *tap-positions of 220 kV reactors in substation Bjæverskov.*

Device	Tap-position activation		
	Coordinated Control		Reduction
	Disabled	Enabled	
TKFA1	65	0	65
TKFB1	69	0	69
TKFB2	69	0	69
Offshore Transformers (Sum)	203	0	203 100%
TA1	73	29	44
TA2	73	29	44
Onshore Transformers (Sum)	146	58	88 60%
RA1	358	318	40
RA2	0	0	0
RA3	18	427	-409
RA4	475	466	9
Onshore Reactors (Sum)	833	1211	-378 -45%

Table 2. *Application of the coordinated control scheme on reduction of the tap-position activations of the transformers and onshore reactors.*

The result is interesting because it, on the one hand, demonstrates that reduction of the tap-position activation of the transformers is possible due to coordinated reactive-power control of the AVR/RPC and WPPCs without compromising with the voltage range of the control and operation optimization. On the other hand, it shows that utilization of the tap-positions of the 220 kV reactors will increase. Thus, a wider range of the reactive-power exchange from the KF CGS network to the 400 kV transmission grid shall be accepted if activation of the tap-positions of the 220 kV reactors is to be reduced.

Resulting utilization of the 220 kV reactor stepping relates to the two simultaneously occurring processes in the opposite ends of the 220 kV network of the KF CGS interconnector. The processes are: (i) the inherent voltage fluctuations in the 400 kV grid, and (ii) the WPPC control inputting the reactive power transfer at the KFE platform and reducing activation of the tap-position controllers of the transformers due to the dynamic adjustment of the reactive power of the KFA and KFB OWPP.

The dynamic reactive power fluctuations in the BJS220 (onshore) substation causes the 220 kV reactor tap-position stepping. The reactive power fluctuations in the BJS220 substation cannot be attenuated within the same coordinated control scheme imposed onto the KFA and KFB WPPC, unless some increase of the tap-position changes of the transformers is to be accepted or the reactive power range of the AVR/RPC for transfer in Bjæverskov and Ishøj with the 400 kV transmission grid is increased.

The simulated case illustrates a possible constraint with regard to efficiency and optimization of the voltage and reactive power control of the KF CGS system.

8. Conclusion

The automatic voltage regulation and reactive power control (AVR/RPC) of the Krieges Flak CGS has been discussed. The main focus of this presentation is the control design, validation and coordination within the 220 kV AC network connected to the Danish 400 kV transmission grid.

The control principles of the AVE/RPC have been described and the simulation model has been successfully validated against the test operation results conducted by the Danish NCC of Energinet on May 2nd 2019.

The models of the wind power plants and WPPC have been presented and included in the simulation model. The coordinated control scheme utilizing the discrete tap-position controllers by the AVR/RPC, the tap-position controllers of the 220/33 kV offshore transformers, and the continuous voltage and reactive power control of the WPPC has been described. The main objective of the coordinated control scheme is reducing activation of the discrete-type controllers, which are vital for operation and security of energy supply, including the continuous control of the WPPC in the operation conditions with fluctuating voltages in the onshore transmission grid and fluctuating reactive power transfer at the remote offshore end of the 220 kV network.

The simulations results demonstrate both efficiency and constraints of the coordinated control scheme. For the efficiency, it is shown that the proposed coordinated control scheme achieves prioritised reduction of the tap-position activations, i.e., in the offshore and onshore transformers which are vital for security of energy supply. The proposed coordinated control scheme has fully stopped the tap-position stepping of the 220/33 kV offshore transformers and significantly reduced the tap-position stepping of the onshore transformers in Bjæverskov and Ishøj. For the constraints, it is shown that stepping of a single 220 kV reactor increases and stepping of the other three reactors is almost unchanged. In order to attenuate the reactive power fluctuations at the BJS220 substation, increased activation of the tap-positions of the reactors should be accepted. A trade-off approach with reduced activation of the tap-positions of the 220 kV reactors will be accepting a wider range of the reactive fluctuations between the KF CGS and the Danish 400 kV transmission grid.

9. References

[1] Marten, A.-K., et al., 'Kriegers Flak – Combined Grid Solution: Coordinated cross-border control of a meshed HVAC/HVDC offshore wind power grid', IET Renewable Power Generation DOI: 10.1049/iet-rpg.2017.0792, Online ISSN 1752-1424 Available online: 19 February 2018.

[2] Akhmatov, V., 'Automatic voltage and reactive power control of Kriegers Flak offshore wind power plant grid-connection system', Offshore Wind Conference 2017, PO-0255, London, UK, June 6-8 2017. 10 p.

[3] Akhmatov, V., Wu, Q., Takarics, T., 'Reactive power and voltage control interaction and optimization in the Danish largest wind power plant at Kriegers Flak', Journal of Physics: Conference Series, Volume 1102, WindEurope conference 2018 within the Global Wind Summit 25–28 September 2018, Hamburg, Germany, 11 p. Available online: https://doi.org/10.1088/1742-6596/1102/1/012031.

[4] Olsen, R.S., 'Dynamic Loadability of Cable Based Transmission Grids', PhD Thesis, Technical University of Denmark, 2013, 284 p.

[5] Ackermann, T., (Editor), 'Wind Power in Power Systems', Second Edition, 2012, John Wiley and Sons Ltd., West Sussex, U.K., in Chapter 40 'Modelling of Large Wind Power Plants', p. 913-936.

[6] 'Multi-DC - Innovative Methods for Optimal Operation of Multiple HVDC Connections and Grid', https://www.cee.elektro.dtu.dk/news/nyhed?id=670ca9b7-06d3-4f25-992d-fde8c379531f, accessed 08 April 2020.

10. Appendix 1 – Electrical data of assets

The electrical data of the transformers TA1, TA2, and TA3, are listed in Table 3. The electrical data of the 220 kV reactors RA1, RA2, RA3, RA4, and RKFA are listed in Table 4. The electrical data of the WPP transformers TKFA1, TKFB1, and TKFB2 are given in Table 5.

Table 3 – Electrical data of 400/220/10 kV and 220/150 kV transformers.

Transformer	MVA	U_{HV}	U_{MV}	e_X	Tap-positions	du%/tap
TA1	500 MVA	410 kV	238 kV	13,8%	1-21, 11	1,0143%
TA2	500 MVA	410 kV	238 kV	13,8%	1-21, 11	1,0143%
TA3	450 MVA	235 kV	155 kV	10%	1-13, 9	1,032%

Table 4 – Electrical data of 220 kV reactors.

Reactor	U_N	Tap positions	First tap	Maximum tap
RA1	235 kV	17	60 MVAR	120 MVAR
RA2	235 kV	1	120 MVAR	120 MVAR
RA3	235 kV	17	60 MVAR	120 MVAR
RA4	235 kV	13	60 MVAR	120 MVAR
RKFA	235 kV	1	120 MVAR	120 MVAR

Table 5 – Electrical data of 220/33 kV offshore transformers of WPPs.

Transformer	MVA	U_{HV}	U_{MV}	e_X	Tap-positions	du%/tap
TKFA1						
TKFB1	220 MVA	225kV	32 kV	18,1%	-10-10, 0	1,667%
TKFB2						