Mixed Grid-Forming and Grid-Following Wind Power Plants for Black Start Operation

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***Abstract*—Grid forming wind turbines allow for additional services to be provided by wind power plants. These additional services include self-start operation, islanding operation of off-shore ac-grids and contribution to system restoration after a black-out. As the complete electric system will consist of both grid-following and grid-forming wind power plants, the aim of this paper is to study possible interactions between grid forming and grid following wind turbines during black-start operation. The presented case study includes a 400 MW off-shore wind power plant connected by means of a 75km HVac cable to the on-shore transmission grid. The results show adequate islanded and black-start operation with less than 25% grid forming power.**

I. Introduction

Currently installed grid scale wind power plants are almost uniquely based on grid following control strategies, both for type-3 and type-4 wind turbines.

However, wind turbine grid side converters can also be controlled to be grid forming, i.e. capable of controlling their ac-side frequency and voltage, with adequate active and reactive power sharing and adequate load rejection. These converters are hence capable of performing some of the power system control tasks normally assigned to synchronous generators. Islanding operation and load sharing control of both type-3 and type-4 wind turbines has been reported in the past [1], [2], [3], [4].

The use of grid forming wind turbines is the key component of transmission technologies such as the use of HVDC Diode Rectifier stations in off-shore wind power plants (OWPPs) [5], [6], [7], [8], [9], [10], [11].

Recently, a large interest has been placed into the ability of off-shore wind power plants to be able of islanding and black-start operation, so more inefficient traditional back-up generation becomes redundant.

OWPPs consisting of grid forming converters can perform some or all of the aforementioned services. Nevertheless, many existing OWPPs consist of grid following converters.

Therefore, this work aims at studying the joint operation of grid forming and grid following wind turbines during black-start operation. Particular stress will be paid to issues that affect the minimum number of grid-forming wind turbines required for a particular scenario.

II. System Description

Figure 1 shows the system under consideration. The considered off-shore wind farm consists of 50 wind turbines of 8 MW each, totalling 400MW. The wind turbines are arranged in six strings, connected to a 66 kV collector bus, which, in turn is connected to a 66/220kV substation. The 220kV HVac export cable is 75km long and is shunt compensated at both ends. For the purposes of this study, off-shore grid shunt compensation is not considered.

To achieve reasonable simulation times, the 9 wind turbines of the first string are considered in detail, whereas the rest of the wind power plant is simulated by considering aggregated wind turbines for each one of the remaining strings.

Of the first string, wind turbines WT_{1-1}, WT_{1-2} and WT_{1-3} are grid forming, as well as all the wind turbines of string 2 (WT_2), totalling 12 grid forming wind turbines (96 MW).

The remaining wind turbines of the first string WT_{1-4}, to WT_{1-9} are all grid following, as well as all those in strings 3 to 6. Therefore, the considered system includes 38 grid following wind turbines with a combined power of 304MW.

III. Grid following and grid forming wind turbines

A. Grid Following Wind Turbines

A grid following wind turbine is defined as one that requires an already powered ac-grid to operate. Specifically, it is assumed that the grid side converter is used for control of the dc-link voltage and to follow a reactive current or reactive power set-point. This definition includes most of the type-4 large scale grid connected wind turbines currently in the market.

Figure 2 shows the control scheme of the considered grid following wind turbines. A PLL is used for orientation angle detection and also in order to provide a clean angle estimate during low voltage fault-ride-through events. The dc-link voltage E_{Bi} control loop includes a PI controller that provides the I_{Wd} current reference to the inner current loop. The dc-link voltage controller includes standard feedforward terms (not shown in the figure).

On the other hand, the reactive current reference (I^*_{Wq}) is obtained from the reactive power control loop. The active and reactive reference currents are then transformed to the $\alpha\beta$ stationary frame and then fed to a proportional+resonant controller. Obviously, standard dq synchronous frame current controllers can be used, noting that the PR controller is equivalent to positive and negative sequence PI synchronous frame controllers.

The reactive power reference and active power limit is set by the wind power plant controller.

B. Grid Forming Wind Turbine

In the context of this paper, a grid forming wind turbine is the one that has the following capabilities:

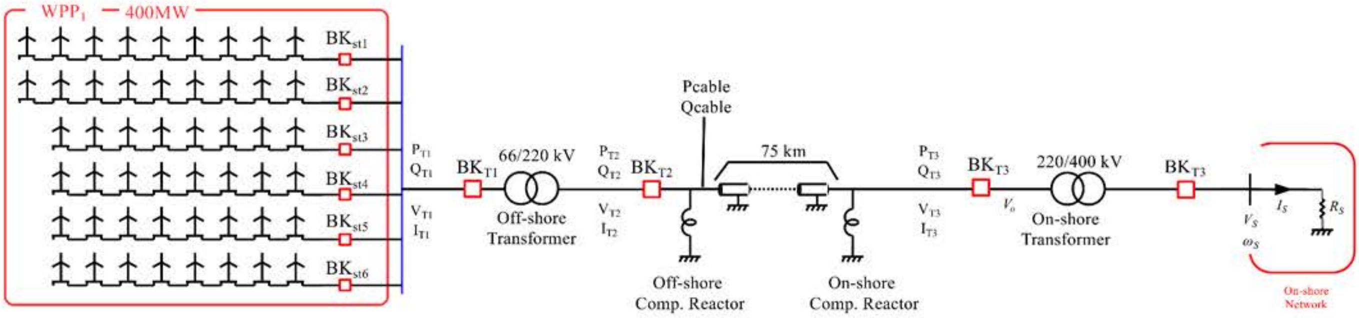

Fig. 1. Considered HVAC Connected Off-shore Wind Power Plant

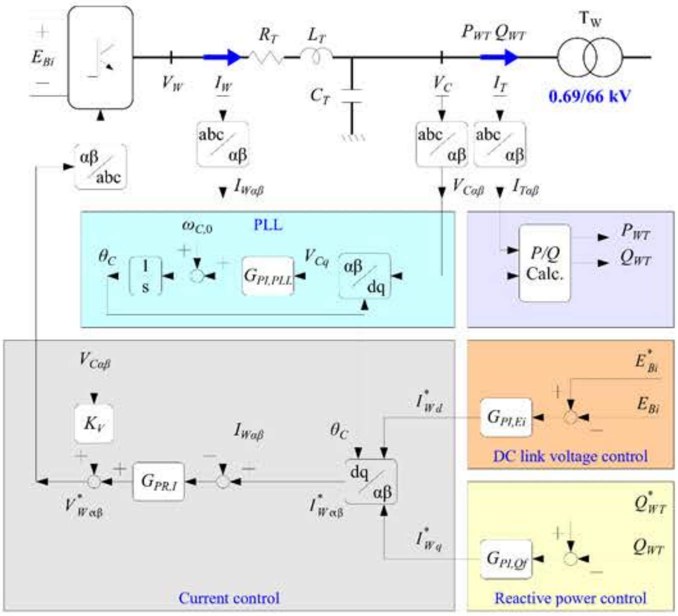

Fig. 2. Basic Control Structure of a Grid Following Grid Side Converter

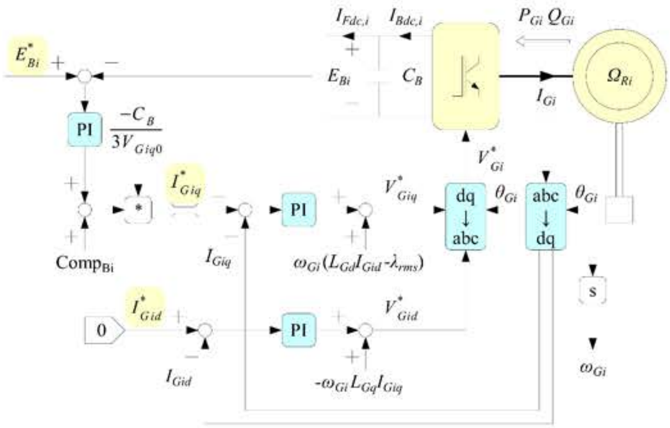

Fig. 3. Machine side and dc-link voltage control

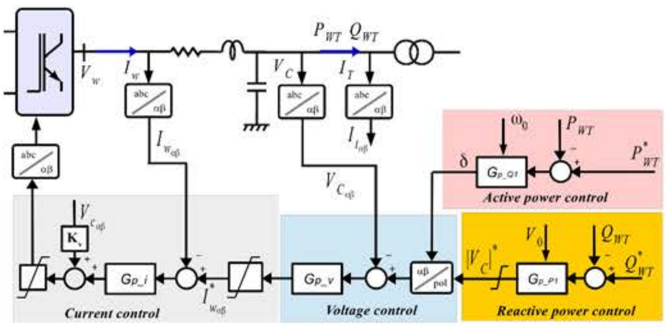

Fig. 4. Basic Control Structure of a Grid Forming Converter

- is able to fully control voltage and frequency of the ac-grid to which it is connected (within its operational limits) even if the ac-grid is not initially energised by other equipment.
- it is capable to share the control effort (e.g. in terms of active and reactive power) with other grid-forming converters or generators connected to the same ac-grid.

Clearly, most advanced wind turbines can contribute to control ac-grid frequency and/or voltage, through different mechanisms, albeit they cannot operate if the ac-grid has not been energised by other converter or generator. Therefore, a large extent of already installed grid-following wind turbines are capable to perform grid support roles (voltage control, frequency support, etc).

As the two degrees of freedom of the grid forming converters are used for ac-grid control, the converter dc-link voltage is now controlled by the machine side converter, as shown in fig. 3. The torque producing current I_{Gq} is used as a control action to regulate the dc-link voltage E_{Bi}, with some additional compensation terms. Optimal C_p is now achieved by setting the reference for P^*_{WT} [12].

In practice, grid forming converters behave, up to some extent as voltage sources (or synchronous generators), with additional features to limit overcurrents (inner current loops).

The basic control structure of a grid forming converter is shown in fig. 4. The inner current control loops are the same as those used for the grid following wind turbine in fig. 2. Conversely, the outer P+R voltage loop calculates the required current references, so as to control the voltage V_c to certain voltage magnitude ($|V^*_C|$) and phase (δ^*).

Active and reactive power is shared amongst grid forming converters by means of droop control:

$$|V^*_C|(s) = V_0 + K_q(Q^*_{WT}(s) - Q_{WT}(s)) \tag{1}$$

$$\theta^*_C(s) = K_p(P^*_{WT}(s) - P_{WT}(s)) + \frac{1}{s}\omega_0 \tag{2}$$

IV. Black-start Sequence

It is assumed that, at least, one grid forming wind turbine is capable of self-starting, i.e., run its own auxiliaries, align itself to the wind and charge the converter dc-link capacitors. From this point onwards, the black-start sequence is as follows.

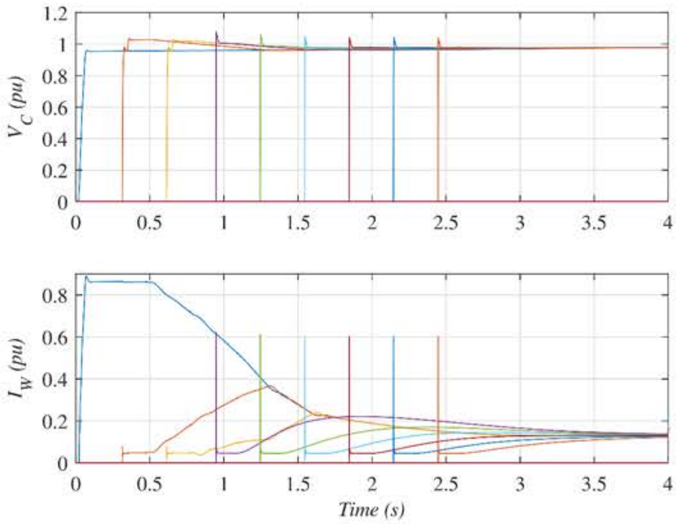

Fig. 5. String energisation. Wind turbine voltage and current magnitudes

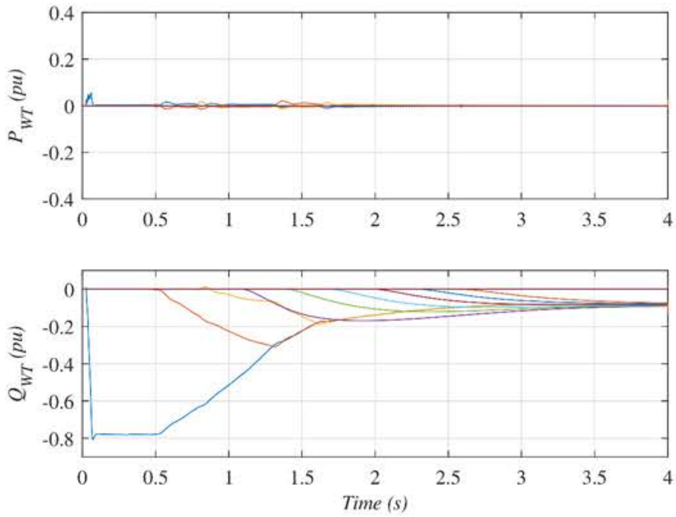

Fig. 6. String energisation. Wind turbine active and reactive power

A. Array Energisation

1) First grid forming wind turbine in an array energizes its own transformer and the string cable.
2) Second grid forming wind turbine transformer is connected to the grid created by the first wind turbine, after the transient, the second wind turbine synchronises itself to the grid and starts sharing voltage and frequency control with the first wind turbine.
3) The third grid forming wind turbine in the string is connected, in the same way as the second.
4) The six remaining (grid following) wind turbines in the string are then sequentially connected to the string cable. Grid following wind turbines contribute to overall reactive power sharing through the wind farm voltage controller.
5) Once the first string is up, the second string, consisting of 9 grid forming wind turbines is connected to the collector bus.
6) The rest of the wind turbines are connected to the collector bus string by string.

B. Export Cable Energisation

7) Off-shore ac-grid voltage is reduced to 0.2 pu.
8) Off-shore sub-station transformer is energised by closing breaker BK_{T1}.
9) On-shore substation transformer is connected to the cable by closing breaker BK_{T3}
10) Export cable and on-shore transformer station are energised by closing breaker BK_{T2}.
11) Finally, the on-shore load is connected by closing BK_{T4}

During the complete procedure, all grid following wind turbines active power reference is set to zero.

C. Results: String Energisation

Figures 5 and 6 show the energisation of the first string of the wind power plant. Initially, the first grid forming wind turbine energises its transformer and then the string cable. Once the string cable is energised, the second and third grid forming grid turbines are energised, followed by the remaining grid following wind turbines, as per the array energisation sequence explained before.

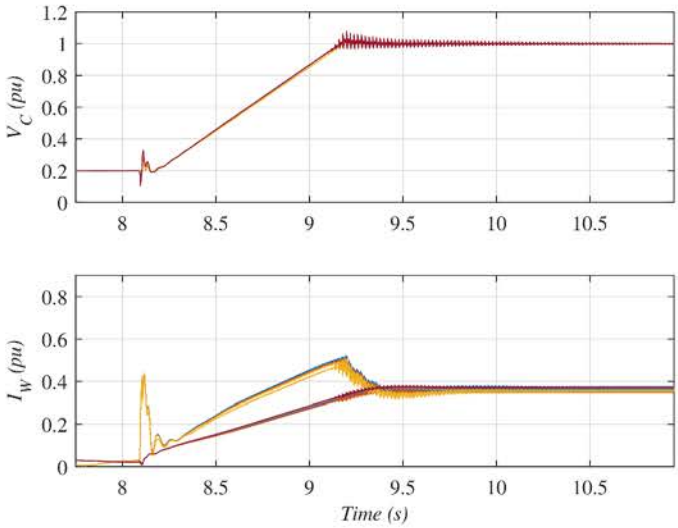

Fig. 7. Connection of on-shore substation transformer and HVAC export cable

The grid forming wind turbines naturally share the reactive power needed to bring up the string cable. Moreover, the WPP controller also changes the Q^*_{WT} set points of the grid following wind turbines in order to contribute to reactive power sharing. It has been assumed that WPP controller communication delay is 25 ms. Wind turbine connection has been carried out at 0.3 s intervals, in order to keep simulation times within reasonable limits. The string cable is not compensated and, in this particular case, it can be energised by a single wind turbine.

Once the first string is energised, the rest of the strings are energised sequentially.

D. Results: Export cable energisation

Figures 7 to 10 show the procedure carried out for export HVac cable energisation.

Interaction between cable capacitance and transformer saturation during substation and export cable energisation might lead to large in-rush currents, overvoltages and oscillations [13], [14], [15]. Mitigating solutions such as pre-insertion resistors and point-of-wave breakers can be used in order to

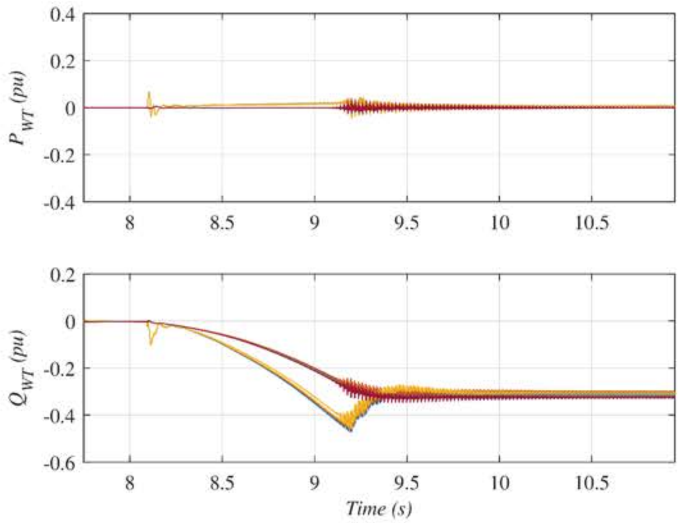

Fig. 8. Connection of on-shore substation transformer and HVAC export cable

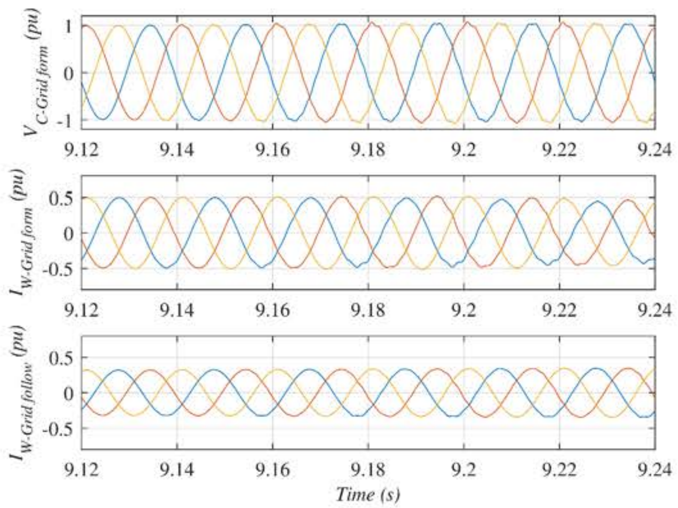

Fig. 9. Connection of on-shore substation transformer and HVAC export cable

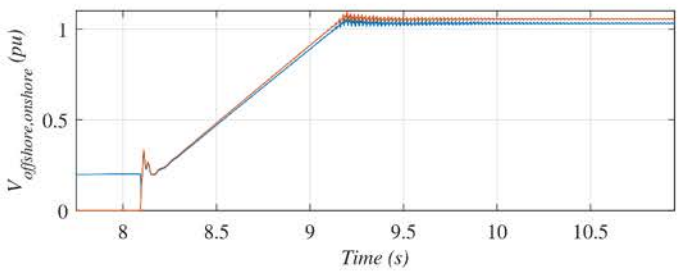

Fig. 10. On-shore and off-shore cable end voltages

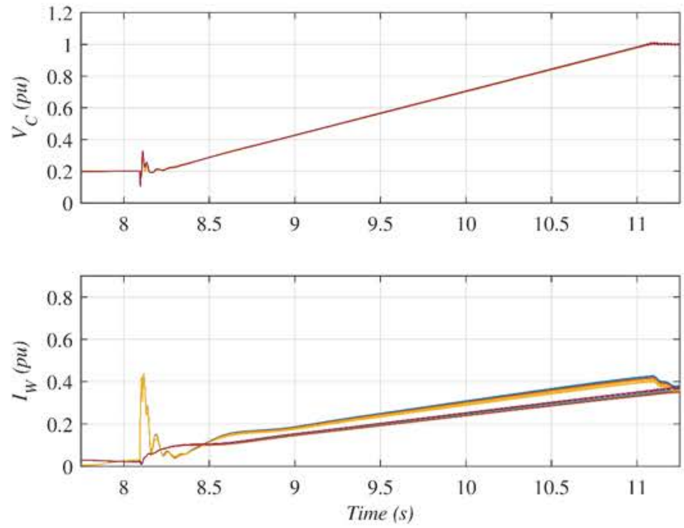

Fig. 11. Connection of on-shore substation transformer and HVAC export cable

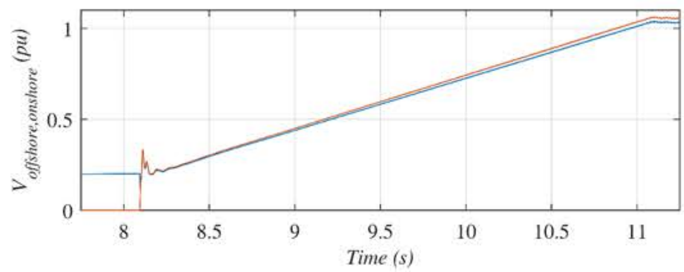

Fig. 12. On-shore cable voltage

reduce the aforementioned effects. In this case, the presented solution consists on low voltage connection of transformers and cables, so both saturation and in-rush currents are greatly diminished.

Therefore, once the complete wind power plant is energised, the off-shore ac-grid voltage reference is set to 0.2 p.u. and the off-shore ac-substation is connected by closing breaker BK_{T1}. Then the export cable and on-shore transformer station are energised at the same time, by closing first BK_{T3}, then BK_{T2} and, finally, ramp up the voltage to 1 pu in about 1 second. For the cable compensation, only the on-shore reactor is connected.

Clearly, as the connection of the complete system is carried out at reduced voltage, transformer in-rush currents are kept to a minimum. However, remanent flux or dc-flux created during the connection are present in the transformer core. As the voltage is increased, so it is the transformer flux and then, eventually, existing dc-flux in the transformer will lead to saturation and to overvoltage caused by interaction between transformer saturation and cable capacitance. These effects can clearly be seen in figs. 7 to 10, at $t = 9.14$ s approximately. In-rush currents and overvoltages affect both grid-forming and grid following wind turbines, as clearly seen in fig. 10.

Also, it can be clearly seen that grid following wind turbines contribute to overall reactive power requirements, albeit with much slower dynamics.

A slower voltage ramp rate can be used in order allow the dc-flux in the transformer to disappear and hence prevent transformer saturation when a high voltage is reached. The

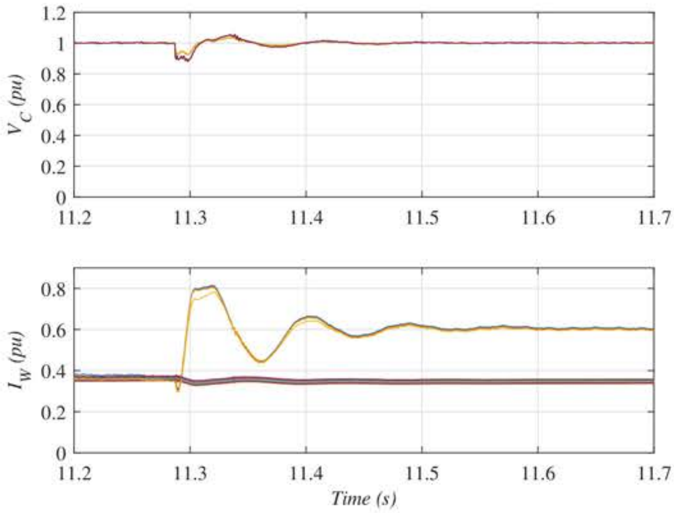

Fig. 13. Connection of on-shore load

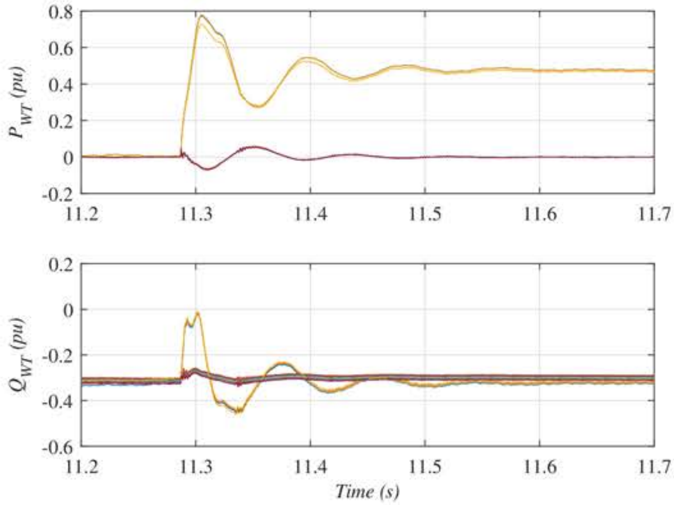

Fig. 14. Connection of on-shore load

results are shown in figs. 11 to 12. Clearly, in this case, oscillations due to transformer saturation and cable interaction are practically eliminated, in the voltage and current magnitudes at the wind turbines and also in the voltages at both ends of the cable.

E. Results: On-shore load energisation

Finally, a 0.1 pu on-shore resistive load is connected by closing its breaker, in this way, the voltage dynamic response of the complete system can be assessed. Figure 13 shows the voltage and current magnitude of the wind turbines. Clearly, grid forming wind turbines are the ones to increase their active power in reaction to the voltage drop caused by the resistive load.

During the direct connection of the load, the voltage V_C drops to a maximum of 0.9 p.u., at the expense of grid forming wind turbine currents increasing up to 0.8 p.u (fig. 13). Voltage profiles on-shore show that maximum drop is around 10%.

Figs. 13 and 14 show that the grid following wind turbines contribute to overall reactive power requirements.

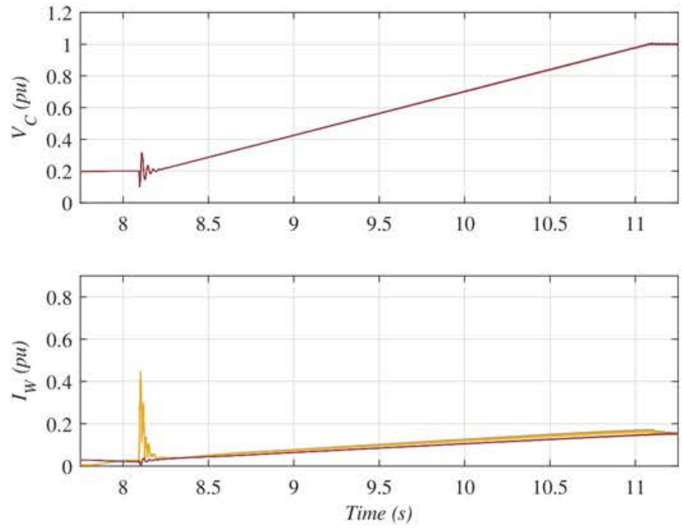

Fig. 15. Connection of on-shore substation transformer and HVAC export cable. Compensation at both ends

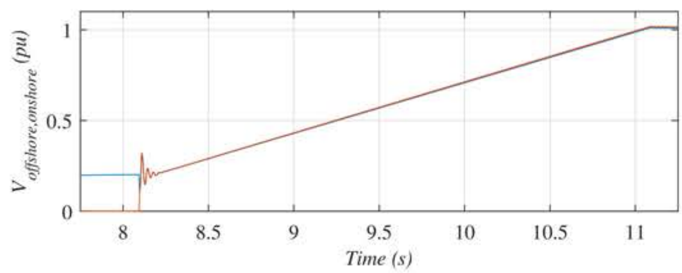

Fig. 16. On-shore and off-shore cable voltages. Compensation at both ends

F. Results: cable compensation at both ends

Finally, cable energisation transients were repeated considering the export cable to be compensated at both ends. Figures 15 to 18 show the corresponding results.

Figure 15 shows clearly that now the current delivered by the wind turbines is smaller, as the additional cable compensation reduces the reactive power requirements of the wind turbines. However, the I_W current peak remains largely the same, at about 0.42 p.u.

Voltage magnitude at both ends of the cable are now basically equal, as expected (see Fig. 16).

Figures 17 and 18 show the behaviour of the system when the 0.1 p.u. on-shore load is connected. Maximum voltage drop is consistently smaller than 10%. However, current in fig. 17 shows smaller oscillations and settles at a smaller value than that in fig. 13. The peak current to be delivered by the wind turbine converters is now 0.7 p.u., slightly smaller than when only on-shore side compensation is considered.

Again the reactive power requirements in fig. 18 are clearly smaller than those in fig. 14.

Finally, it is worth stressing that all controllers were the same in both cases, therefore, the wind turbine current dynamic response is different in figs. 17 and 13.

V. Discussion and Conclusions

In this paper, a case study of the technical viability for off-shore grid self-start operation and on-shore grid service restoration has been presented. Clearly, the two most challenging stages of black-start operation have been export cable

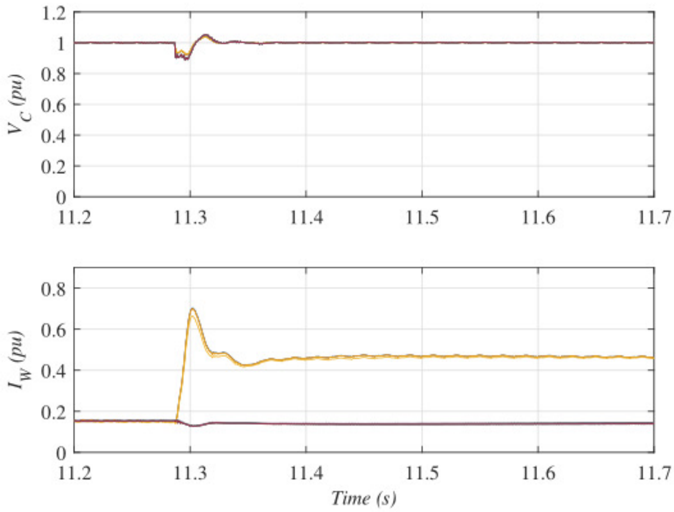

Fig. 17. Connection of on-shore load. Compensation at both ends

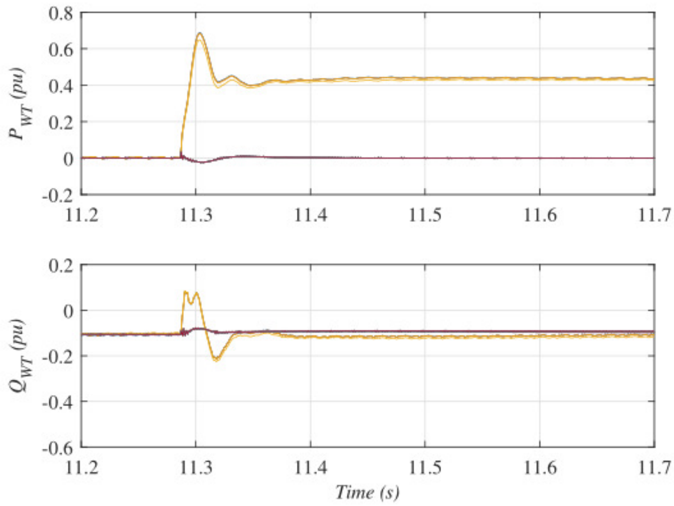

Fig. 18. Connection of on-shore load. Compensation at both ends

energisation, which might lead to cable-transformer saturation interaction and load connection rejection.

The strategy used for sub-station transformer and cable energisation has consisted on connection at a very reduced voltage and then ramp up the voltage to 1 p.u. with a rate that ensures the transformer dc-flux does not cause saturation at high voltage.

Grid forming wind turbines voltage control loops have been designed for a maximum 10% voltage drop for a 0.1 p.u. on-shore resistive load connection.

In the studied case, the minimum amount of grid forming wind turbines required is determined by load rejection, i.e. the maximum load step and voltage drop to be considered.

For the case of compensation at both ends, maximum grid forming wind turbine current is 0.7 pu, so required grid forming power would be around 20%. Smaller amounts of grid forming power can be required if either load is connected at smaller steps or voltage sag requirements are relaxed.

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