Overvoltage Phenomena in Offshore Wind Farms Following Blocking of the HVDC Converter

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***Abstract*—This paper presents measurement and simulation results in offshore wind farms following blocking of the HVDC converter used for connecting the wind farm to the main onshore grid. It is shown that the voltage will rise by approximately 30% within 50-100 ms in the ensuing island operation. The process is superimposed by transients caused by short but repetitive periods of saturation of the transformer resulting in excitation of the resonance frequency between transformer and cable capacitance predominantly in the zero sequence. It is demonstrated that in EMT type simulation the phenomena can be reproduced provided that the wind turbine control and the saturation of the transformer are properly modelled. A simulation tool has been used to demonstrate the effect of the level of wind farm loading at the instant of islanding on the observed phenomena.**

***Index Terms*—wind farm, HVDC, grid transients, transformer saturation**

I. INTRODUCTION

Germany has embarked on a large-scale development of offshore wind energy, which will result in additional generation capacity in the order of several thousand MW. An overview of the planned offshore wind farms in the North Sea can be found in [1]. Since many of the wind farm sites lie over hundred kilometers from the coast, only the Voltage Source Converter based High Voltage DC transmission technology (VSC-HVDC) comes into consideration for the grid connection [2]. The offshore converter (placed on an offshore platform) is designed to fulfill stringent technical requirements with regard to reliability of the components as well as environmental considerations [3]. Today submarine cables of up to 320 kV voltage are available for the DC power transmission. With two of these cables (one each for the positive and negative poles) and taking into account all technical constraints, today HVDC transmission units of up to 900 MW power capacity can be built. For the VSC-DC technology in offshore application and for this capacity range so far there are little operational experiences. It is therefore not surprising if certain phenomena were to be observed in the test and commissioning phases that were not anticipated at the design stage. One example of such an eventuality is the behavior of the offshore network in case the HVDC converter is blocked/tripped resulting in temporary islanded operation of the offshore grid. The AC part of the offshore network (when the converter is blocked) can be thought of as an inertialess system with negligible local load. As a result, particular attention needs to be paid for resonances and the risk of possible amplification by HVDC or wind turbine converter control.

In this paper the transient phenomena immediately following the blocking of the offshore HVDC converter will be elaborated. Blocking in this context means stopping the pulse sequence which controls semiconductor switching. The blocking itself may be prompted by different scenarios that require the protection of the HVDC converter, which for the present discussion are not relevant and thus will not be dwelt on. After the blocking, current flow in the DC circuit is only possible through the freewheeling diodes when the voltage on the AC side is higher than the DC voltage. But regardless of the status of the current flow, the line voltage generated by the wind farm is fully applied on the converter valves. This remains the case until either the converter is restarted and synchronized again with the offshore grid or the converter is physically disconnected from the offshore grid by the circuit breaker. In the latter scenario the interval between converter blocking and circuit breaker tripping may reach approximately 60-100 ms. During this period, the HVDC converter is exposed to the full range of voltage surges that can arise in the offshore grid. This raises the question as to what degree the wind turbines remaining connected contribute to the over-voltages. It is, therefore, of vital importance to understand the overvoltage phenomena fully in order to design countermeasures, if in deed this proves to be necessary.

In the following sections, the response of the offshore grid in terms of the full spectrum of overvoltage that may be caused after HVDC converter blocking will be investigated. First the measurement results showing the overvoltage will be presented and discussed. Then the physical phenomena behind the measurement results will be explained and corroborated using simulation models of the system. Due to the complexity of the phenomena, discussions will be limited to the transient processes in the offshore grid. The contribution of wind turbines will be the focus of a separate paper. Some notes about the requirements for modeling and simulation will also be presented.

II. STATEMENT OF THE PROBLEM

Typical configuration of offshore wind farms with VSC-HVDC link to the onshore gird, as implemented in German

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offshore wind farms, is shown in Fig. 1. The wind turbines are connected to each other and to the offshore platform using a 33-kV collector network. At the platform this voltage is then stepped up to the transmission voltage level of 155 kV (usually using three winding transformers). This cable then runs to another larger offshore platform to which other wind farms may also be connected. The combined power is then exported to the main grid onshore using an HVDC transmission line fed by a converter.

The 155-kV submarine cables are usually compensated partially by shunt reactors at the wind farm ends of the cable. All in all the network has multiple resonance frequencies ranging from hundreds to some thousand Hz. The lower end resonance frequencies may interact with the HVDC and wind turbine converter controls and are, therefore, of special interest. As stated above, the blocking of the HVDC converter disconnects this part of the network to the link onshore. The blocking itself may be caused by grid side short circuits or other conditions related to the converter operation. The blocking signal is often coupled with OFF command sent to the corresponding circuit breaker. But converter re-synchronization with the grid before circuit breaker operation is also possible. After blocking and the islanding of the wind farm oscillations with characteristic oscillatory modes may ensue.

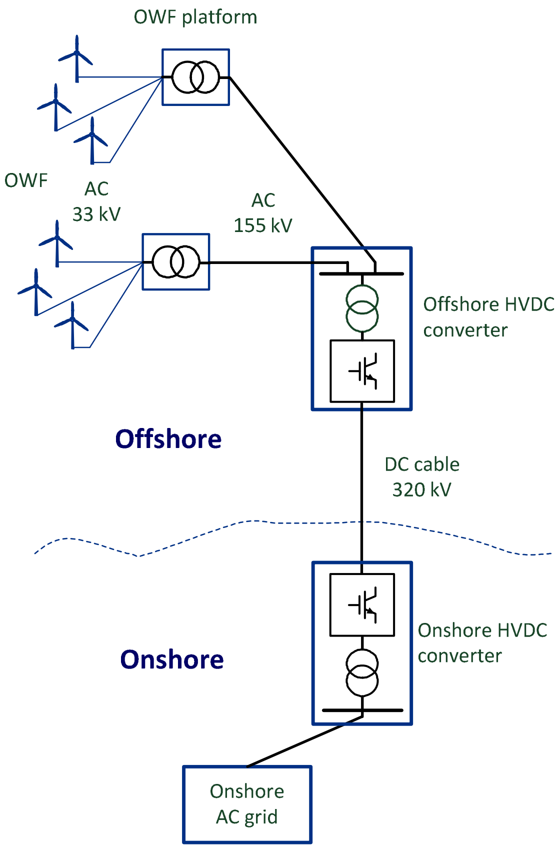

Fig. 1. Typical configuration of offshore wind farms connected via VSC-HVDC to the main grid

In this situation, the frequency of the islanded network is no longer controlled as the wind turbines currently are not equipped with such a control capability. Also, voltage control by the wind turbines as required by the respective grid codes [4] is not effective since the voltage deviation is not large enough to trigger an effective voltage reduction measure. Additionally, the voltage controllers in the present implementation perform voltage control indirectly by injecting reactive current. But injecting reactive current and thus effective voltage control is not possible in islanded offshore grid if no considerable local load exists and the link to the onshore grid is severed. The ineffectiveness of the current voltage control schemas in island operation will be the subject of another paper by the same authors [4].

The focus now is to show, based on measurement results and corroborated by simulation, the level of the overvoltage that can be caused after HVDC converter blocking. This can form the basis for design of possible mitigating control measures.

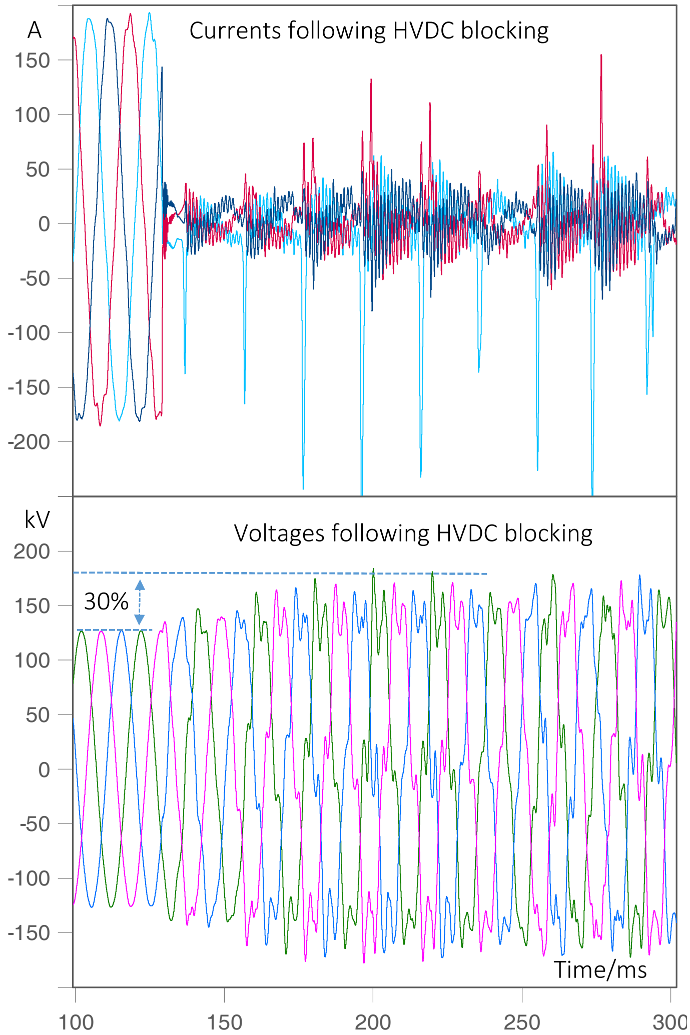

Fig. 2. Behavior of currents and voltages following HVDC blocking (measurement on 155 kV offshore grid level)

III. Phenomena following HVDC converter blocking

Fig. 2 shows the three phase voltages and currents on the 155 kV cable connecting the wind farm to the HVDC platform at the HVDC side of the cable. As can be seen, immediately after HVDC converter blocking the current drops to much smaller values and starts to oscillate. The fundamental frequency component is no longer discernible in the three phase currents. On top of this, there are high current peaks of very short duration. The physical process giving rise to this phenomena will be explained shortly. The voltage increases in ca. 50 ms to 130% of the initial value and contains high frequency components. Instances of the voltage reaching values of up to 2.0 p.u. (not shown here) were also observed.

The voltage rise can take place much more quickly when the wind farm supplies a higher power, as will be demonstrated in the next chapter. Combination of HVDC converter internal faults (e.g. AC or DC pole to ground internal faults) and overvoltages rising from the offshore grid after blocking of the HVDC converter will expose the HVDC converter even too higher overvoltages.

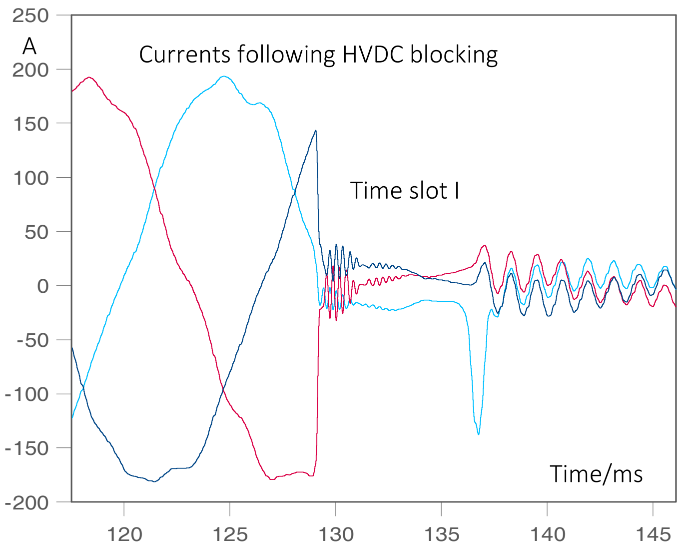

Fig. 3. Close-up view of time slot I (measurement on 155 kV offshore grid level)

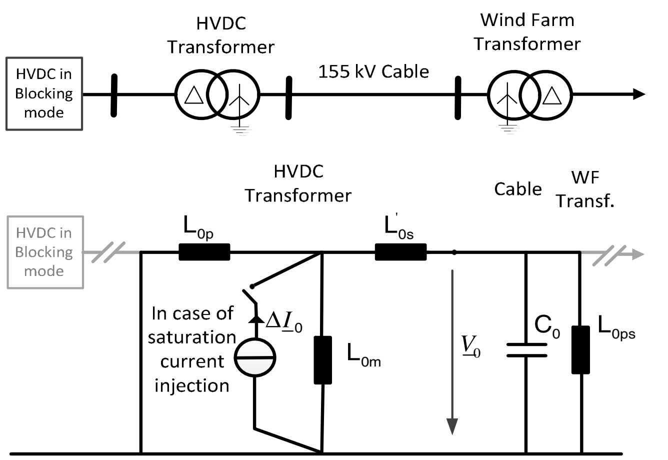

Fig. 4. Equivalent circuits with focus on the effect of saturation of the HVDC transformer in the zero sequence

Immediately after converter blocking the power flow to the transformer connecting the converter to the 155-kV cable drops to a small value corresponding to the magnetizing current of the transformer (Fig. 3). This current exhibits distorted waveform which can be explained by the time variation of the voltage (amplitude and phase). In addition, the current at the beginning contains high frequency harmonics (in this case 3300 Hz) originating from the composition of the remaining part of the network on the HVDC side. The first 5 ms immediately following the converter blocking (the interval: 130 – 135 ms in Fig. 3) is designated as "Time slot I". (The subsequent phases of the transient process are dubbed as "Time slot IIa" and "Time slot IIb"). This initial oscillation settles after a few milliseconds and is for further consideration not important. After about 5 ms a high current peak occurs in time slot IIa. This is due to the saturation of the converter transformer in one of the phases, as will be substantiated on the basis of simulation results in the next section. The saturation leads to different impedances in different phases and thus to an asymmetry in the three-phase impedance matrix of the transformer.

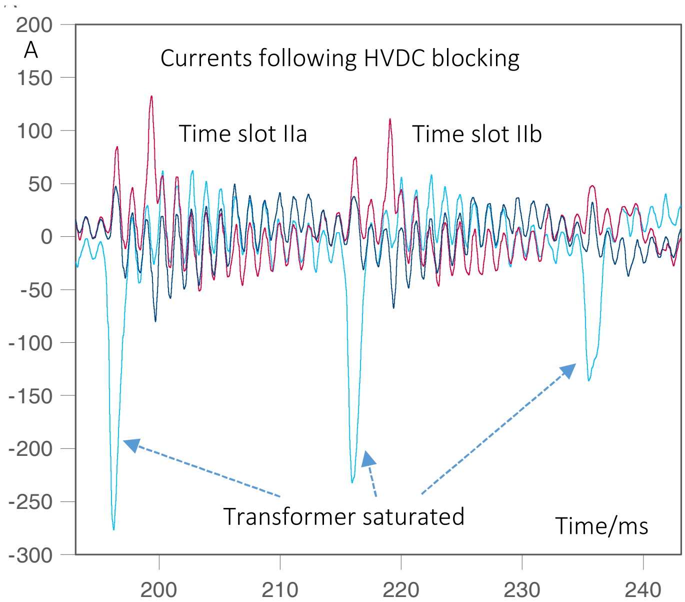

Fig. 5. Close-up view of time slots IIa and IIb (measurement on 155 kV offshore grid level)

The impedance asymmetry in abc coordinates obviously is carried over to sequence (012) components after transformation from natural to symmetrical components. The discussion from this point onwards will be based on symmetrical components. In the zero sequence the saturation can be interpreted as injection of a zero sequence current as shown in Fig. 4. Saturation can also take place at the wind farm transformer as well, but in Fig. 4. only a constant zero sequence impedance representation is used for simplicity. In understanding the subsequent oscillations (Time slots "IIa" and "IIb" in Fig. 3.), the cable capacitance (C_0 in Fig. 4.) plays a key role. Due to the injection of zero sequence current (this happens always close to the maximum of the corresponding flux) an oscillation

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between the circuits comprising of cable capacitance and the transformer inductances (of both transformers) and forming a parallel resonance ensues. In this particular case the frequency of oscillation is about 830 Hz, as can easily be calculated with good accuracy using the well- known Thomson formula. The oscillation represents a zero sequence as the oscillating current in all three phases have almost the same phase angle. However, it should be mentioned that there is also an oscillation in the positive and negative sequences, but the frequency and the amplitude are much smaller due to the higher inductance of the transformers in this sequences.

The saturation occurs repeatedly as can be seen in Fig. 5. In this particular case it is affecting mostly the phase C, but in general all three phases can be involved. The reason for the saturation of the transformer is the flux bias resulting from converter blocking on the one hand and the voltage rise due to the inadequate control behavior of the wind turbines remaining active during converter blocking on the other.

IV. Simulation Results

The objective of the simulation is, first of all, studying the phenomena observed in a real system and, secondly, to estimate the worst case scenario by analyzing different operating conditions. For this purpose, EMT type model of a real wind farm including HVDC link has been used for simulation by the software package PowerFactory [4]. The wind turbines are all of Type 4 and were modeled in detail including the converters and the corresponding control systems [5]. It was observed that the exact representation of the wind turbine current controllers including the actual limits and those of the modulation index are of great importance. For the HVDC and wind farm transformers the magnetization characteristics (excluding hysteresis) were considered in the modelling. The simulated system was not the exact representation of the wind farm for which the measurement were shown in the previous section. The aim here was not to reproduce the measurement results but the identification and characterization of the physical phenomena that have been observed in the measurements.

The first figure (Fig. 6) shows the same quantities as in the measurement in Fig. 2. As can be seen, the behavior in the simulation is very similar to the measurement. After converter blocking and a short transition period the first peak of the saturation current can be observed, which leads to the excitation of the resonance frequency between the transformer and the cable zero sequence capacitance. The phenomenon is repeated whenever any of the phases goes into saturation. The fast transient process immediately following the blocking, which can be observed in the measurement, is not to be seen in the simulation result since a simplified model was used for the HVDC converter.

In the simulation, in contrast to the measurement, the transformer fluxes can be accessed. These are shown together with the zero-sequence current and zero-sequence voltage of the transformer in Fig. 7. As can be seen, the current peak occurs whenever the saturation limit for the flux (shown in plot with pink background) is exceeded. The occurrence of the zero-sequence oscillations can also be interpreted as an indicator of the saturation of the transformer.

Since the main cause of the saturation is the voltage rise, which in turn is caused by wind turbines, the effect of the steady state load (prior to converter blocking) was investigated. Three alternative scenarios, low (28 MW), medium (72 MW) and high (144 MW) wind farm power, are shown in Fig. 8.

The simulation results show that the voltage rise is faster when the converter blocking takes place from an operating point with high wind farm power output. The final settling value, however, is approximately the same in all three cases (about 1.21 pu). This leads to the general conclusion that the response time of the wind turbine converter controllers to reach the limitations and the DC link hardware design are probably the major influencing factors in the observed transient process. The transient peak of the voltage reaches 2.3 p.u. immediately after converter blocking for maximum wind farm initial loading. The voltage peak at the later stage of the transient process lies in the range 1.5 – 1.6 p.u. regardless of the pre-disturbance load.

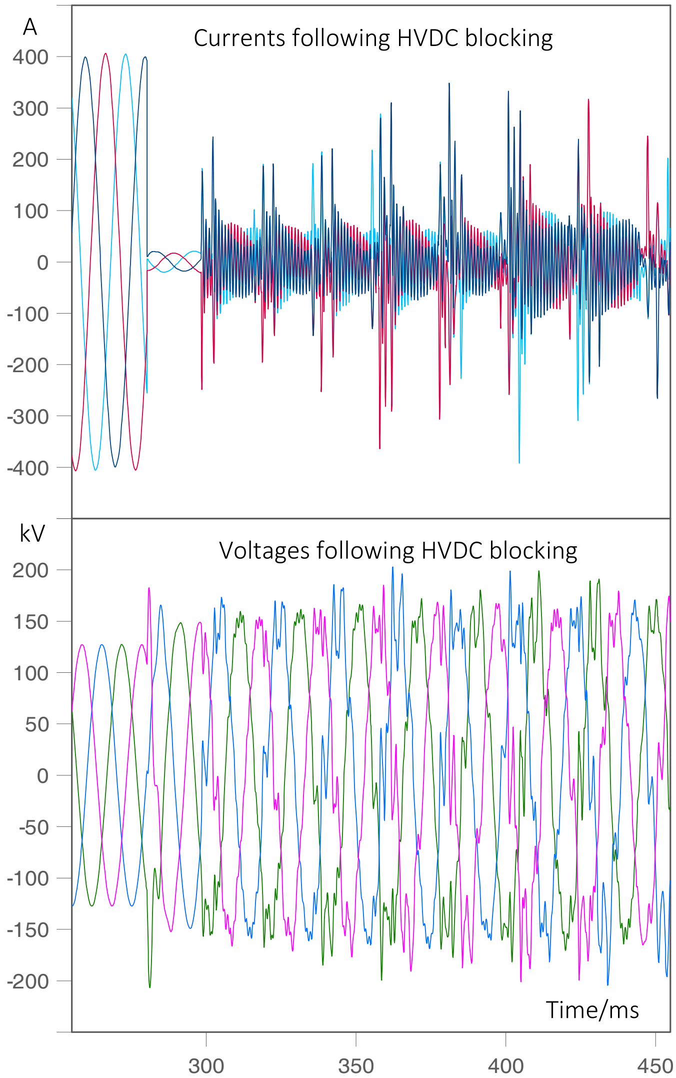

Fig. 6. Behavior of currents and voltages following HVDC blocking (simulation results on 155 kV offshore grid level, WF power =72 MW)

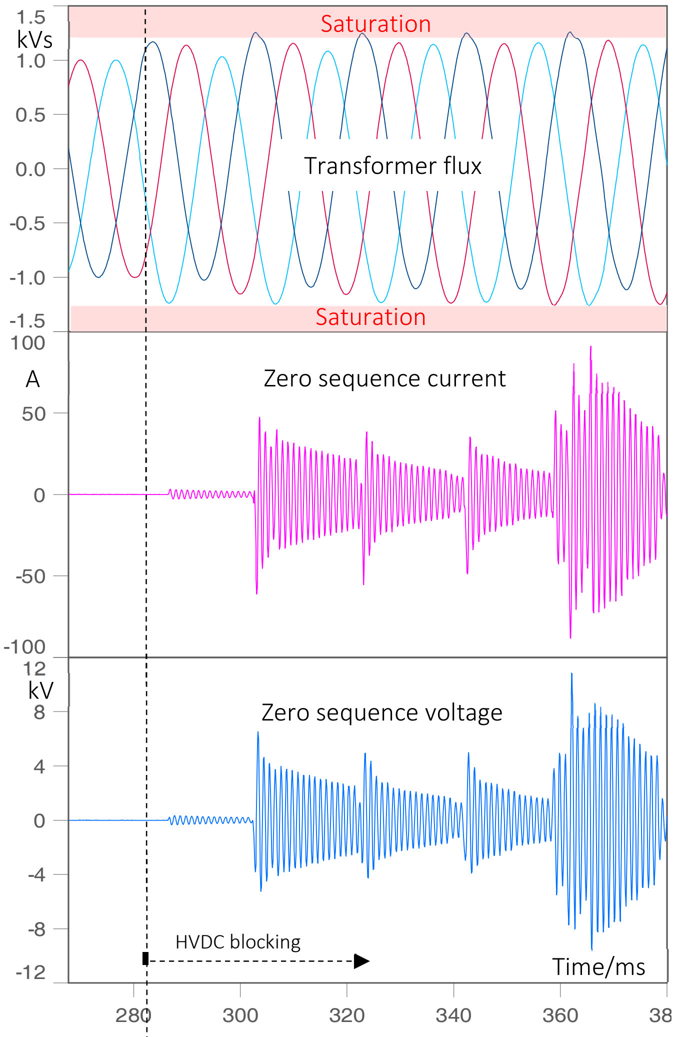

Fig. 7. Simulated behavior of transformer flux, zero sequence current and voltage following converter blocking

V. CONCLUSIONS AND OUTLOOK

In this paper the overvoltage phenomena following HVDC converter blocking has been demonstrated. The measurements on real wind farms have shown that the voltage at the wind turbine terminal, on average, may increase by 30% during this phase. Other transient processes superimposing this phenomena may contribute to the voltage rise so that the voltage can spike up to 2.0 p.u.. The major cause of the overvoltage is the voltage rise at the wind turbines which then can be amplified by the distortion induced by the saturation of the transformers. For the proper design of HVDC converter the knowledge of the voltage stress arising from the spike is required, especially when HVDC converter internal faults occur additionally. In this paper, the transient phenomena on the wind farm collector network side were presented and explained. It was also demonstrated that the transient process can be detected with an EMT type simulation. Also, a preliminary evaluation regarding the influence of the initial load on the transient process has been provided.

With the developed simulation model, additional influencing factors of the overvoltage phenomenon have been studied. The ultimate objective is to identify and test the effectiveness of possible modifications in the wind turbine controls in limiting the overvoltages. From the perspective of the HVDC, it is of practical significance to simulate different fault scenarios in the AC and possibly in the DC part of the network.

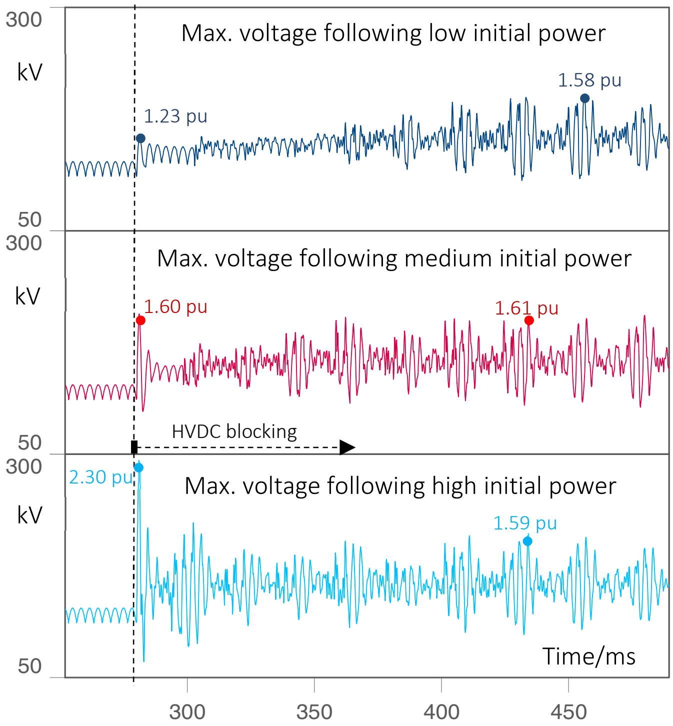

Fig. 8. Maximum transient voltages for different wind farm initial power following HVDC blocking

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