Investigation of high-impact low-probability disturbances in offshore wind farms

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***Abstract*— The topic of this contribution is the investigation in quantitative terms of Offshore Wind Farm (OWF) disturbances due to cyber-attacks, physical attacks and natural causes leading to high-impact low-probability events. The impact of these disturbances was quantified with simulation models of OWFs and identified as service interruption and damage. Critical characteristics of these disturbances were determined by which a disturbance at wind turbine scale results in a disruption at OWF scale as a cascading/snowball effect. Accordingly, the results provide the quantitative signatures of the disturbances which are useful for the improvement of the OWF systems design and operation.**

Keywords—offshore wind farm, cyber-attacks, physical attacks, fault sensitivity and propagation, modelling and simulation, safety, security, resilience

I. INTRODUCTION

Offshore Wind Energy (OWE) exhibits a constantly increasing share within overall power supply, e.g. 4.9 % in 2020 in Germany[1]. The planned enormous 25-fold expansion of Europe's offshore wind capacity to 300 GW in 2050[2] underlines the continuous increase of the importance of OWE, turning OWE systems into critical infrastructures with its impact on the power grid dynamics and reliability [1], accompanied by rising complexity and sophistication.

Recent high-impact low-probability (HILP) disturbance events in Offshore Wind Farms (OWFs) underline this assumption, both through the direct impact of disturbances and through the decision-making process on management or regulatory level. A lightning strike on August 9, 2019 on the transmission network and the following simultaneous shutdown of a gas-fired power plant and the Hornsea OWF led to a nearly 1-hour power-down affecting more than 1 Million consumers in Great Britain after the activation of the automatic protections[3]. The energy production of the Alpha Ventus OWF near the German North Sea, providing power for about 68 000 households, was reduced to half after a substantial part of the nacelle housing of a wind turbine fell into the sea on April 6, 2018. As a precaution, the remaining wind turbines of the same type were put into idling mode (no power generation) for inspection even for weeks after the accident[4].

II. MATERIAL AND METHODS

This section presents the theoretical background of this contribution and the employed methodology for the quantitative investigation of the HILP disturbances within OWFs.

A. *Theoretical background*

OWF as coupled cyber-physical systems, i.e. infrastructures, are networks of interacting elements with non-linear behavior, feedback loops and nested system parts. Accordingly, the failure system dynamics due to disturbances is typically counterintuitive and cannot be inferred from component knowledge [2].

Thresholds, as a system resilience feature, are intrinsic tolerance limits of the system to disturbances where exceeding a threshold perpetuates a regime shift, structural (e.g. damage) or functional (e.g. partial/complete non-functionality). The nested nature of systems contributes to the possibility of cascading failure effects when a threshold at one scale is crossed and causes disruptions at other scales [3]. The degree of impairment, partial/complete non-functionality, depends on the degree of severity of the disruption and the disruption type [4].

Security, understood both in the usual terms of *safety* & *security*, of a power system was defined as the degree of risk in its ability to survive imminent disturbances without interruption of customer service [5]. Power system security goes beyond mere system stability, i.e. the power system must survive without service interruption also disturbances that cannot be classified as stability problems, e.g. damage to equipment due to explosive failure of a cable, fall of transmission towers due to ice loading or sabotage.

B. *Offshore Wind Farm basics*

A simplified model of the power system of a generic OWF connected to the AC onshore grid is presented in Fig. 1. At the left-hand side is an array of wind turbines, which are interconnected through internal AC subsea cables. The power generated by the wind turbines is transferred to the offshore substations. At the offshore substation the voltage is increased and then transferred to the onshore station through the subsea/unground export cables. If DC export cables are used an inversion from AC to DC power takes place on the offshore substations and then from DC to AC at the onshore substation. At the onshore substation the voltage level is

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[1] https://www.bdew.de/media/documents/20210322_D_Stromerzeugung 1991-2020.pdf

[2] https://ec.europa.eu/commission/presscorner/detail/en/ip_20_2096

[3] https://www.theguardian.com/business/2019/aug/16/national-grid-blackout-report-avoidable-faults-blamed

[4] https://w3.windfair.net/wind-energy/news/28299-alpha-ventus-nacelle-nacelle-housing-damage-repair-offshore-wind-farm

raised to level of the AC onshore grid by which the power generated by the OWF is fed into grid.

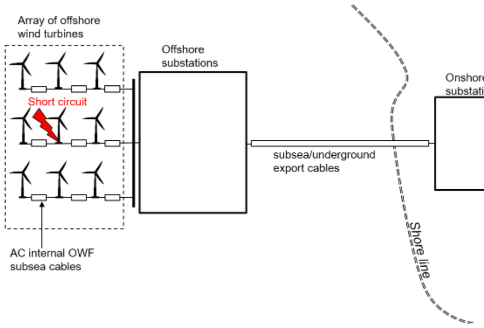

Fig. 1. Power system model of a generic OWF with the relevant electrical disturbances for this work OWF

As abovementioned OWF as coupled cyber-physical systems are networks of interacting components. The components can be grouped into several interacting sub-systems representing the main functional processes. These sub-systems represent energy generation and conversion, data acquisition, control and monitoring, and protection [6]. So, there is interaction within the components within each sub-system and between the sub-systems. In this way feedback loops are formed, e.g. through the control and protection sub-systems. Control and protection sub-systems ensure the desired functioning of the OWF and prevent from with undesired and dangerous values of the operational parameters.

Accordingly, the power system dynamics and the required performance of wind farms arise from the intricate, often nonlinear interactions among this large number of interconnected and spatially distributed components of different sub-systems and from different domains, i.e. physical and cyber [2]. Therefore, wind farms become exposed and vulnerable to many failures/faults and attacks occurring with certain probability, as typical for critical infrastructures, engineering and cyber-physical systems [2].

A failure/fault or an attack within a windfarm would cause transients within its power system dynamics. This means that the power flow of the affected component would be redistributed to other components according to circuit laws, and subsequently redistributed again according to automatic, manual control and protection actions [2]. These transients include deviations of power flows, frequency, currents and voltages accompanied by the corresponding operation or maloperation of protection devices, controls, operator procedures and monitoring and alarm systems. This would result eventually in component disconnection or network topology change [2].

C. Modelling and Simulation

The Simscape™ Electrical™ Specialized Power Systems was used under the MATLAB/Simulink environment for the quantitative investigation of HILP disturbances in OWFs [7]. The OWFs are modelled as large-scale (> 10 km) dynamical multi-domain systems, consisting of interacting sub-systems of elements for energy conversion, measurement, control and protection.

This enables the simulation of the transient system response of the whole OWF to disturbances in the different sub-systems, considering the coupled dynamics of all sub-systems. The models are dynamical cyber-physical representations of the OWF through the interaction of physical quantities, i.e. electrical and mechanical, and information, i.e. data and signals. In this way the failure system dynamics due to the disturbance was determined and evaluated according to the above theoretical background.

Two OWF models with a 25 km AC export cable and individual wind turbines (WTs) with squirrel-cage induction generators (SCIG) were used, as shown in Fig. 2. The first model consists of 3 strings with 3 WTs per string whereas the second model consists of 3 strings with 2 WTs per string. Three disturbances corresponding to HILP events were investigated through these two models, Fig. 2.

The first HILP scenario, further referred to as “HILP 1”, is realized through the manipulation of the control and protection systems of single WTs in the OWF model with 3 WTs per string, denoted as “OWF HILP 1” in Fig. 2. Three variations of the manipulation are investigated: manipulation of a single WT - WT23, manipulation of two WTs belonging to the same string – WT22 and WT23, manipulation of two WTs belonging to different strings – WT23 and WT33. The cause of the manipulation is a cyber-attack on the OWF. The scenario is modelled by imposing 0° of the pitch angle in the control system and switching off the protection system of the respective WTs between t = 80 s and t = 180 s. This scenario exploits the SCIG design weakness that the control of electrical power generation realized through the control of the mechanical power extraction. Therefore, a mechanical system disturbance results directly into an electrical system disturbance.

The second HILP scenario (“HIPL 2”) is realized through the combination of two disturbances: a mechanical torque interruption on a single WT and a voltage drop at the connection point to the AC onshore grid of the OWF model with 2 WTs per string (OWF HILP 2 & 3) in Fig. 2. The cause for this scenario is the combination of a physical attack on the OWF and an external fault in the onshore grid. The torque interruption is modelled by imposing a zero value of the WT mechanical torque (interruption of the torque input to the generator) at WT22 between t = 15 s and t = 21.94 s. The voltage dip at the onshore AC grid connection point is modelled as a step decrease of 23 % lasting between t = 22.04 s and t = 22.549 s. The scenario exploits the abovementioned design weakness in the previous scenario HILP 1 due to which a mechanical system disturbance, here because of the physical attack, leads to an electrical system disturbance. The two individual disturbances were chosen with such characteristics that when applied separately they do not lead to persistent service interruption, i.e. power generation, even of a single WT, which is also shown in the next section.

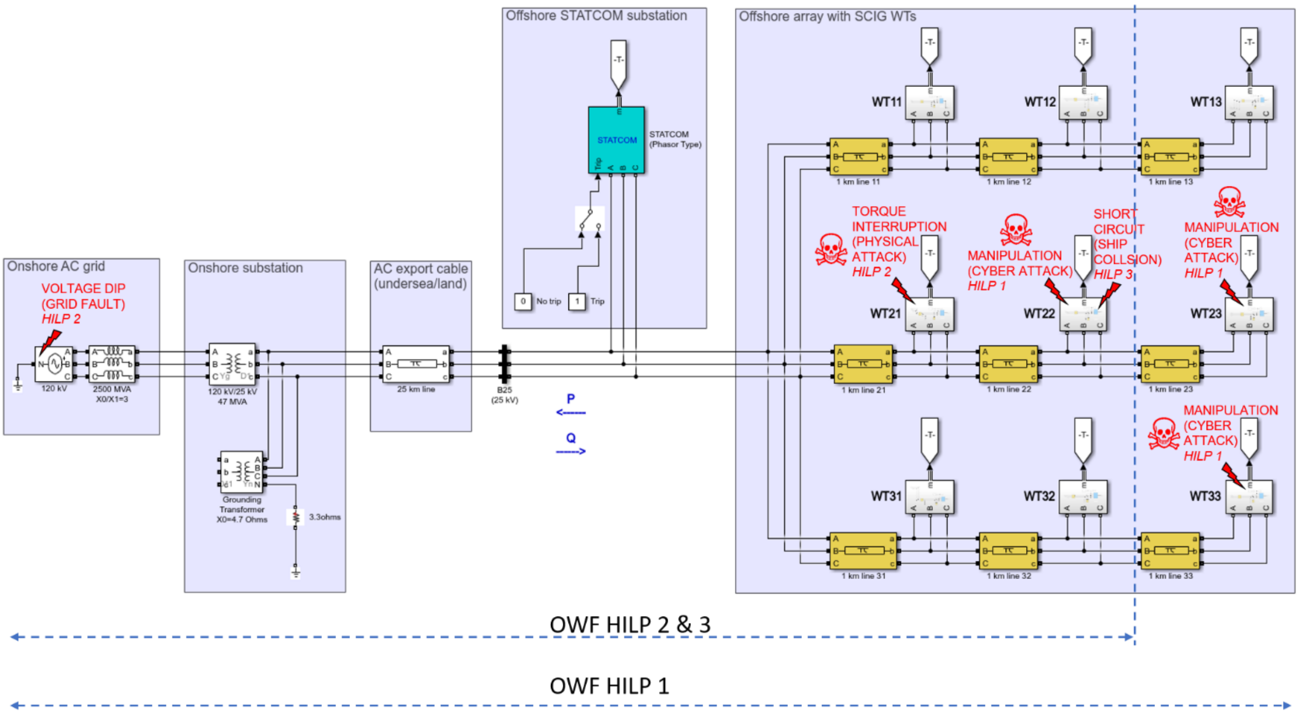

Fig. 2. WF models with 9 and 6 SCIG wind turbines, used for HILP 1 scenario and HILP 2 & 3 scenarios, respectively. The disturbances by the corresponding HILP scenarios are also indicated.

The last HILP scenario ("HILP 3") is realized through rare electrical fault at a single WT the OWF model with 2 WTs per string (OWF HILP 2 & 3) in Fig. 2. A possible cause for such an event could be a collision of a ship with the WT. The scenario is modelled by applying a 3-phase short circuit (phase-to-ground) at the terminals (in the low voltage region) of WT22 at t = 10 s with 4 increasing values of the short-circuit duration - 0.088 s, 0.089 s, 0.098 s and 0.099 s.

III. Results and Discussion

This section presents the obtained results and their discussion.

A. *HILP 1 scenario*

The manipulation of the parameters of the WT control and protection systems disrupts feedback loops realized through these systems. The consequence of this disruption is a disturbed functioning of the WT mechanical system, resulting abnormal mechanical and electrical values of the affected WT. This unusual impairment on WT scale is shown on Fig. 3 (top diagram) in the case where only WT23 is manipulated - power is actually not generated at WT23 but consumed during the manipulation, expressed by the corresponding negative values. Besides this the rotor speed values at WT23 (not shown) sustained during the manipulation correspond to structural damages and even destruction, because they are more than twice the maximum allowed values. The fault effect of the abnormal electrical values at the manipulated WT does not propagate to the remaining WTs so they remain in service, as seen on the top diagram in Fig. 3. Accordingly, the impairment is observed only on WT level, the OWF remains partially functional. After the end of manipulation WT23 is disconnected at t = 180 s due to rotor overspeed.

If the control and protection systems of 2 WTs within the OWF model are manipulated the abovementioned impairment on WT scale is observed again by the manipulated WTs. This is shown on the middle diagram in Fig. 3 for the case, when WT22 and WT23 are simultaneously manipulated, and on the bottom diagram of Fig. 3, for the case when WT23 and WT33 are manipulated, by the corresponding negative values of the generated power. Again, the rotor speed values at the manipulated WTs (not shown) exceed more than twice the maximum allowed values in a sustained manner during the manipulation correspond to structural damages and even destruction. However, due to the increased severity of the disturbance through the increased number of manipulated WTs the fault effect of abnormal electrical values at the manipulated WTs propagates to the remaining WTs, so they are tripped by their protection systems at around t = 91.1 s due to AC undervoltage. Now the impairment is observed on OWF scale and the OWF becomes completely non-functional, no power is generated by the OWF, shown by the time evolutions on both the middle and the bottom diagram in Fig. 3. This is an example of a cascading/snowball effect when a disruption at OWF system scale is caused by a disturbance at a lower WT scale by the manipulated WTs. Besides this, the disruption at OWF system scale is independent whether the manipulated 2 WTs belong to the same string or not.

B. *HILP 2 scenario*

The second HILP scenario (HILP 2) represents the impact by a combination of a physical attack on a single WT in the model with 2 WTs per string and a grid fault, "OWF HILP 2 & 3" in Fig. 2. If only the physical attack occurs a torque interruption at WT21 is the consequence which leads to a temporary interruption of the power generation of the WT21 expressed by the corresponding zero values of the generated power, shown on the top diagram in Fig. 4. However, WT21 remains in service thought-out the attack (it does not get disconnected

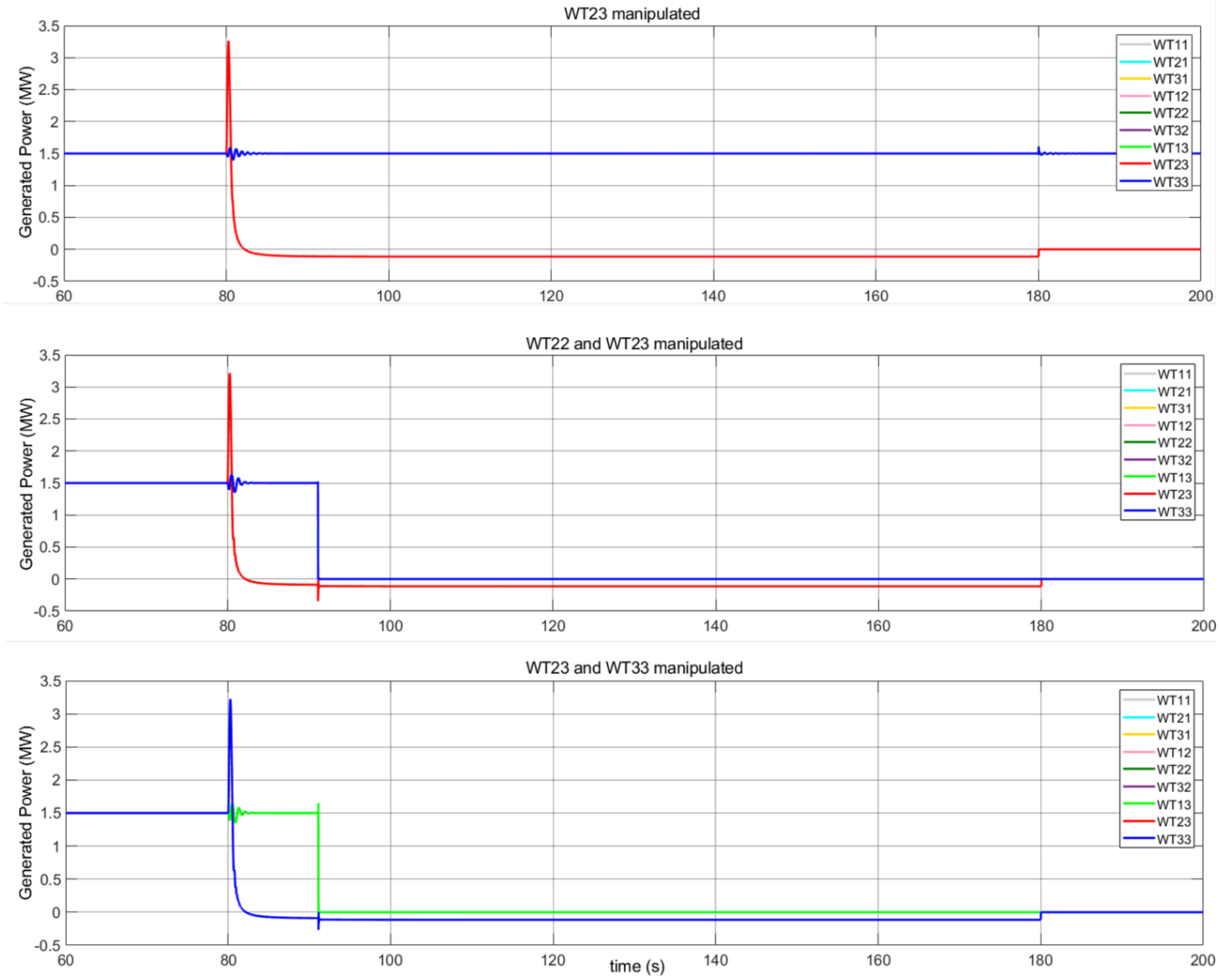

Fig. 3. Time evolutions of the generated power at the individual WTs before, during and after the three manipulations.

by its protection system) – once the torque interruption stops the generated power by WT21 bounces back to its pre-disturbance level. The functioning of remaining WTs gets only slightly perturbed as well, so no WT in the OWF experiences a persistent service interruption, i.e. disconnection.

If only the grid fault occurs the resulting voltage dip at the connection point to the AC grid perturbs collectively the functioning of all WTs only slightly, shown on the middle diagram in Fig. 4. No interruption of service is observed by any WT by this disturbance, too. So, neither of the disturbances alone leads to the interruption of service even of a single WT.

The impact of the combination of these two disturbances, torque interruption and voltage dip, is shown on the bottom diagram in Fig. 4. All WTs get disconnected by their protection systems – there is a service interruption of the whole OWF by this disturbance combination. So, the disturbance of the mechanical system at WT21 through the physical attack disturbs the electrical system at WT21 and through this the electrical system in the entire OWF. The superposition of the deviations due to this disturbance and of the deviations due to the consequent voltage dip leads to AC undervoltage by all WTs because of which the WT protection systems disconnect all of them.

C. HILP 3 scenario

The last HILP scenario (HILP 3) is the occurrence of a 3-phase short-circuit disturbance at a single WT in the model with 2 WTs per string and a grid fault, “OWF HILP 2 & 3” in Fig. 2. The short circuit occurs at terminals of WT22, i.e. on the low voltage side (690 V) prior the WT transformer (not depicted). The duration of the short circuit is varied by increasing for the investigation.

If the short-circuit duration is short enough, e.g. 0.088 s, the power generation of the WTs is only perturbed but there is no WT disconnection, and through this no service interruption, as seen on the top diagram in Fig. 5. Increasing the duration to 0.089 s leads to AC undervoltage at the directly affected by the short circuit WT22. Accordingly, it gets disconnected by its protection system, shown on the second from the top diagram in Fig. 5.

Increasing further the disturbance severity through the increase of the disturbance duration to 0.098 s leads to such abnormal electrical values that WT22 gets disconnected first and shortly after that WT21 gets disconnected, too, both due to AC undervoltage. This is shown on the third from the top diagram in Fig. 5. This means that the disturbance is so severe that it propagates from the low voltage region at WT22 through the much higher medium voltage (25 kV) region of the internal cable between WT21 and WT22 to the low voltage region of WT21, causing there these abnormal values leading to the disconnection.

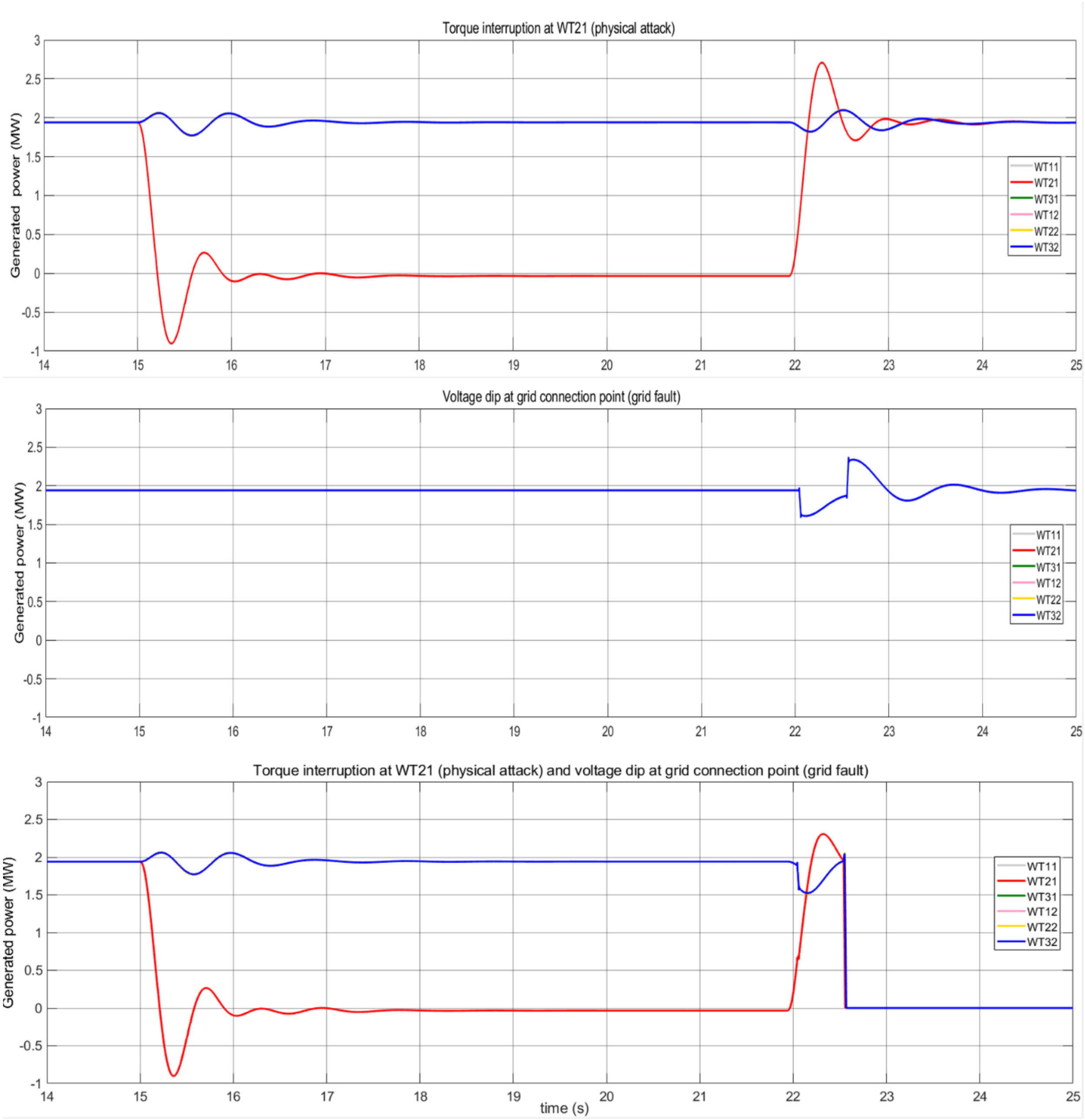

Fig. 4. Time evolutions of the generated power at the individual WTs before, during and after the disturbances – physical attack, grid fault, combination of physical attack and grid fault

Finally, a short-circuit duration of 0.099 s leads to such abnormal values which propagating within the OWF cause the disconnection of all WTs by their protection systems (again due to AC undervoltage), shown on the bottom diagram in Fig. 5. In this way a service interruption on OWF system scale caused by the surpassing of limit values at the lower WT scale.

IV. CONCLUSIONS

In this paper three different HILP disturbances provoked by a cyber-attack, a physical attack and a grid fault, and a natural event) leading to OWF service interruption and damage were investigated in a quantitative way through simulations.

The three disturbances showed three different failure dynamics with same impact of OWF service interruption, affecting drastically the power system security of the OWF. The increase of disturbance severity lead to the increase of intensity, propagation and scale of the impact.

Critical characteristics of these disturbances were also determined. First, by a manipulation at WT scale which results in a disruption at OWF scale (cascading/snowball effect), as an example of regime shifts due to surpassing of intrinsic system thresholds. Second, by a combination of a WT torque interruption and a voltage dip at the grid connection point which leads to an interruption of service of the whole OWF, whereas none of these disturbances interrupts individually the service operation even of a single WT. And third, when a disturbance at a single WT propagates to the remaining WTs affecting so the whole OWF. Apart from this, the same design weakness of SCIG WTs, i.e. regulation of the electrical power generation system through the regulation of the mechanical power extraction, was exploited in different ways by the cyber and physical attacks. In both case the disturbance of the WT mechanical system propagates first to the WT electrical system and then to the OWF electrical system, affecting so the service provision of the whole OWF.

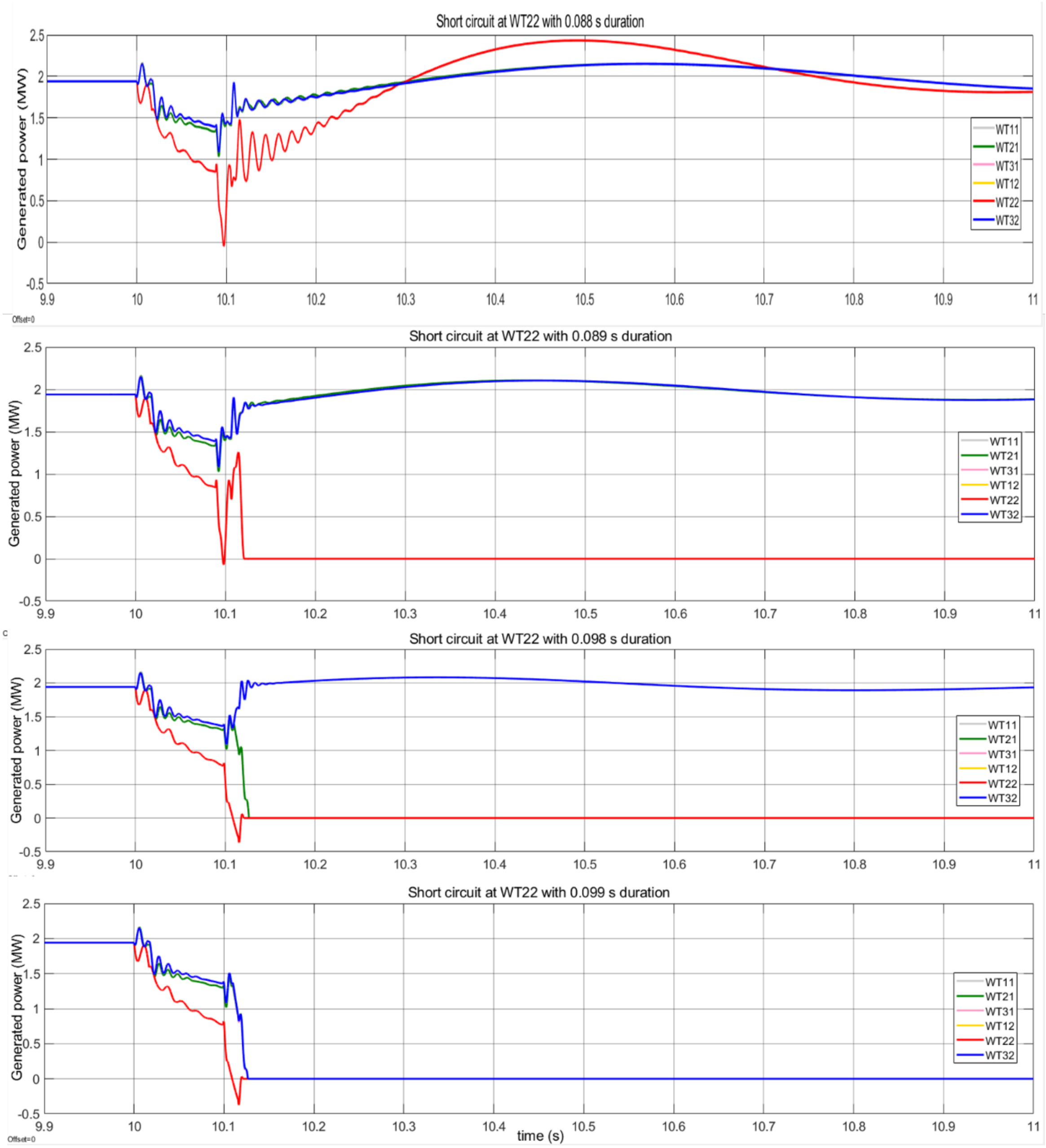

Fig. 5. Time evolutions of the generated power at the individual WTs before, during and after the short-circuits at WT22 by increasing short-circuit duration.

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