A Novel Methodology for Effective Short-Circuit Calculation in Offshore Wind Power Plants Considering Converter Limitations

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Abstract—This paper deals with the short-circuit calculation of offshore wind power plants (OWPPs). The short-circuit calculation presented in this paper assumes the studied system achieves a new equilibrium state during the fault. The studied system is modeled with an element-based steady-state formulation where the grid-support control and potential current-saturated operation of wind turbine (WT) converters are included. In particular, the current-saturation modifies the converter control and represents various potential operation states of the converter. Then, an iterative methodology is proposed to identify the short-circuit equilibrium point that satisfies converters’ limitations and to obtain the current-saturation states of all power converters with a specific fault scenario in the studied system. The numerical case studies indicate that the WT converters operation has a significant influence to the system equilibrium point during the fault. In addition, the presented methodology is efficient for short-circuit calculation of a large-scale OWPP.

Index Terms—Offshore wind power plants, Voltage source converter, Short-circuit calculation, Current-Saturation

I. INTRODUCTION

Offshore wind generation has drawn increasing interest due to the advantage of higher wind speed, possibility of installing larger wind turbines (WTs) and less occupation of onshore area [1]. Most of the recently installed offshore wind power plants (OWPPs) are designed with full-scale voltage source converters (VSCs) for grid integration of WTs as VSCs allow grid-friendly operation by providing independent active and reactive power control and grid-support service [2]. However, the increased penetration of power electronics converters also results in higher complexity of the computational analysis in OWPPs as the converter saturates current in case of overload or faults. Such current-saturation represents different modes of converter operation and therefore must be considered in the short-circuit calculation of OWPPs.

Short-circuit calculation results could provide essential information in different aspects for the design and analysis of OWPPs. Electrical components (cables, transformers, circuit breakers, etc.) are securely sized based on the identified system operation points in different fault scenarios [3], [4]. Over-current protection schemes are tuned based on the current at different nodes during the fault [5]. The advanced control of power converters can be also designed based on the accurate estimation of short-circuit equilibrium points to enhance the system performance during the fault [6].

Short-circuit calculation of conventional power systems widely adopts Thévenin equivalent to characterize the studied power system at the fault location. This traditional equivalent fails to represent the operation of power converters and therefore is not suitable for the short-circuit calculation of OWPPs [7]. The IEC60909 standard suggests modeling power converters as current sources for fault analysis [8]. However, it has not been specified how to define the current angle for different short-circuit fault scenarios [9].

Steady-state computational analysis of OWPPs has been widely reported in the literature. A methodology for power flow calculation has been proposed for OWPPs in [10] including the frequency support control of WT converters. The reactive power management of offshore collection grid has been investigated in [11], [12]. Optimum power flow has been calculated for OWPPs in [13], [14]. However, it has not been clearly stated how to determine the current-saturation state of each WT converter in a specific short-circuit fault scenario. Therefore, the methodologies for steady-state calculation presented in [10]–[14] are not suitable for short-circuit calculation of OWPPs. As an alternative, [15]–[18] suggest to model WT converters as current sources for short-circuit calculation where the grid-support control and potential current-saturation of converters are included. Then, an iterative approach has been proposed to identify the system equilibrium point. However, it is not clear about the computing efficiency of the methodology presented in [15]–[18] when it is applied to a large-scale OWPP.

The authors of this paper have developed a different methodology for steady-state computational analysis of power systems with high penetration of VSCs [19], [20]. The proposed methodology has been adapted for short-circuit calculation of large-scale OWPPs. In particular, the studied system is modeled utilizing an element-based formulation in steady-state where the equations of converters’ operation are included. Then, an iterative approach is proposed to identify the short-circuit equilibrium point efficiently that satisfies the converters’ operation limits.

This paper addresses the challenge of OWPPs short-circuit calculation considering the grid-support control and potential current-saturated operation of WT converters. A novel methodology is proposed to identify the short-circuit equilibrium point. The studied system is analyzed with a balanced voltage
condition and is expressed in single-phase with per-unit values. The balanced three-phase to ground fault scenarios have been studied for short-circuit calculation.

The rest of this paper is structured as follows. In Section II, the scheme of the studied OWPP and the WT converter equivalent model are introduced. Section III presents the formulation of studied system and an effective methodology for short-circuit calculation considering WT converter limitations. Section IV presents numerical case studies of short-circuit calculation in the studied OWPP following the proposed methodology. Finally, Section V summarizes the conclusion of this paper.

II. DESCRIPTION OF THE STUDIED OWPP

A. Scheme of the Studied System

The studied system analyzed in this paper has been built based on the French Fécamp OWPP with the equivalent scheme shown in Fig. 1. The parameters of the passive elements (transformers, MV and HVAC cables) of the OWPP can be found from [12], [21]. The system consists of 83 type 4 WTs with the capacity of 6 MW each. Each WT adopts a permanent magnet synchronous generator (PMSG), which is connected to the offshore MV collection grid through a full-size back-to-back VSC and a transformer boosting from LV to MV. The studied OWPP is connected to the onshore main grid, which is represented with the Thévenin equivalent, through an HVAC cable. The HVAC cable is represented with the II equivalent model and other passive components (transformers and collection cables) are represented with the equivalent impedance for the short-circuit analysis presented in this paper.

B. WT Converter Equivalent Model

Each WT is represented with its grid-side converter (which is VSC) in order to focus on the most relevant aspects related to the short-circuit analysis. However, when the short-circuit calculation deals with a fault location inside a WT, it is necessary to include the complete model of it. The WT converter equivalent model is expressed in this Section as it is an essential element in the studied OWPP which dominates the system performance with fault conditions. In particular, the WT converter equivalent model include the formula of power injection to the offshore AC grid, the converter control following the grid codes and the potential current-saturated operation.

The WT converter equivalent model is represented with a voltage source, $u_{\text{vsc}}$, connected in series with a phase reactor, $z_{\text{vsc}}$, as shown in Fig. 2. The converter current control is implemented in a $qd$ frame where $i_q$ represents the active current while $i_d$ is the reactive current. The active and reactive injection into the offshore collection grid from each WT converter, $p + jq$, has been regulated at the Converter Connection Point (CCP) such that:

$$p + jq = u^*_{\text{vsc}}$$

where $u^*_{\text{vsc}}$ is the voltage at CCP and $z_{\text{vsc}}$ is the WT converter current injection.

In normal operation, the WT converter follows the constant dispatched power references such that:

$$\begin{cases} p = p_{\text{disp}} \\ q = q_{\text{disp}} \end{cases}$$

where $p_{\text{disp}}$ and $q_{\text{disp}}$ are dispatched values for active and reactive power, which are set by the OWPP control.

In case of fault conditions, the WT converter still follows the constant active power reference while the reactive power injection will be manipulated in order to provide the voltage-support service required by the grid codes if the current-limitation is not reached. In particular, the reactive power controller will be frozen and hold a constant output current reference, $i_{d0}$, when the fault happens. This frozen reactive current reference, $i_{d0}$, is depending on the pre-fault system equilibrium point and is given as a known constant in this paper. In addition, a voltage-droop current, $i_{sp}$, will be added to the reactive current reference with the fault signal. Then, the WT converter power injection during the short-circuit fault can be expressed as:

$$\begin{cases} p = p_{\text{disp}} \\ q = u_{\text{con}} i_{d0} + k_{\text{sp}} [u_{\text{ref}} - u_{\text{con}}] \end{cases}$$
where \( k_{isp} \) and \( u_{ref} \) are the droop-gain and the voltage reference to determine the grid-support reactive current during the fault.

In addition, the current-saturation is included into the WT converter control as shown in Fig. 2. Such saturation block limits the magnitude of the current reference generated by the outer control loop. Therefore, the power references expressed in (3) cannot be achieved when the VSC nominal current, \( i_{vsc}^{max} \), is reached. Instead, the actual current references followed by the current control loop will be limited by the saturation block in order to protect the converter. In particular, the WT converter operation can be divided into three current-saturation states: unsaturated (USS), partially saturated (PSS) and fully saturated (FSS). The following constraint equations apply for each state such that:

\[
\begin{align*}
\{ p \equiv p_{disp}; \quad &q = u_{con}[i_d + k_{isp}(u_{ref} - u_{con})] \quad \text{if USS} \\
&i_{vsc} = i_{vsc}^{max}; \quad q = u_{con}[i_d + k_{isp}(u_{ref} - u_{con})] \quad \text{if PSS} \\
&i_{vsc} = i_{vsc}^{max}; \quad p = 0 \quad \text{if FSS}
\end{align*}
\]  

(4)

where \( p_{ref} \) and \( q_{ref} \) are active and reactive reactive power references for the WT converter during the short-circuit fault. In this case, the active power element is reduced in a current-saturated state (PSS and FSS) in order to prioritize the reactive power element. However, the active power can be prioritized with a similar formulation.

C. WT Converter Operation Limits

The WT converter also sets limits to the system operation point. Such operation limits are different from the current-saturation presented previously as they are not included in the equivalent equations modeling the VSC operation. Instead, these constraints are adopted to discard the solutions of system equilibrium point, \( sol \), that violates VSCs operation limits. A function \( VOL \) is defined in this paper to identify if an obtained solution \( sol \) satisfies VSCs operation limits such that:

\[
VOL(sol) = \left( i_{vsc} \leq i_{vsc}^{max} \right) \land \left( u_{vsc} \leq u_{vsc}^{max} \right) \land \left( p_{min} \leq p \leq p_{max} \right) \land \left( q_{min} \leq q \leq q_{max} \right) \land \left( |p| \leq |p_{ref}| \right) \land \left( |q| \leq |q_{ref}| \right) \land \left( p \times p_{ref} \geq 0 \right) \land \left( q \times q_{ref} \geq 0 \right)
\]

where \( u_{vsc}^{max} \) is the upper limit of the switching bridge voltage, \( p_{min} \) and \( p_{max} \) are lower and upper bound of WT converter active power injection, \( q_{min} \) and \( q_{max} \) are lower and upper bound of reactive power. In particular, the function \( VOL \) returns \( true \) for a solution \( sol \) that satisfies the operation limits of all WT converters in the studied system.

III. METHODOLOGY FOR SHORT-CIRCUIT CALCULATION

A. Steady-State Formulation of The Studied System

The system of equations \( SE_f \) can be defined to model the studied system corresponding to each combination of WT converters’ current-saturation states. In particular, the 83 WT converters in the studied system yields \( F = 3^{83} \) possible combinations. Each system of equations \( SE_f \forall f \in [1, F] \) can be expressed as follows:

\[
SE_f := \left\{ \begin{array}{c}
\begin{bmatrix}
\bar{z}_{f-1} \\
\bar{z}_{f-A}
\end{bmatrix} = \begin{bmatrix}
\bar{Z}_{f-1} & \cdots & \bar{Z}_{f-A} \\
\bar{Z}_{A-1} & \cdots & \bar{Z}_{A-A}
\end{bmatrix} \begin{bmatrix}
\bar{u}_{f-1} \\
\bar{u}_{A-f}
\end{bmatrix} \\
H_f = [h_{f-1} \cdots h_{f-N}]
\end{array}
\right.
\]

(6)

where \( A \) is the number of buses in the studied system, \( i_{a-f} \) is the current injection at bus \( a \) and \( u_{a-f} \) is the voltage of bus \( a \), both corresponding to combination \( f \). The fault impedance, \( z_{ft} \), should be included into the corresponding admittance element in the \( Y \) matrix. The operator := defines the system of equations. Then, the short-circuit current can be expressed as: \( i_{sc} = u_{a-f} / z_{ft} \) for the fault inserted at bus \( a \). The subset of equations \( h_{f-1} \to h_{f-N} \) respectively define the current injections from the \( N \) WT converters corresponding to combination \( f \), which are obtained following the VSC equivalent model expressed in (1) and (3). The established system of equations, \( SE_f \), will be solved as a whole in order to include the converters operation. The constraint equations of WT converter1 in fault conditions, \( h_{1-1} \), for the three possible current-saturation states (USS, PSS and FSS) are expressed as follows as an example:

\[
h_{1-1} := \left[ \begin{array}{c}
\text{Re} \left( u_{1-1} i_{1-1}^{*} \right) = p_{disp} \\
\text{Im} \left( u_{1-1} i_{1-1}^{*} \right) = u_{1-1}[i_d + k_{isp}(u_{ref} - u_{1-1})]
\end{array} \right] \quad \text{if USS}
\]

(7)

\[
h_{1-2} := \left[ \begin{array}{c}
i_{1-2} = i_{vsc}^{max} \\
\text{Im} \left( u_{1-2} i_{1-2}^{*} \right) = u_{1-2}[i_d + k_{isp}(u_{ref} - u_{1-2})]
\end{array} \right] \quad \text{if PSS}
\]

(8)

\[
h_{1-3} := \left[ \begin{array}{c}
\text{Re} \left( u_{1-3} i_{1-3}^{*} \right) = 0 \\
i_{1-3} = i_{vsc}^{max}
\end{array} \right] \quad \text{if FSS}
\]

(9)

B. Identification of Short-Circuit Equilibrium Point

This Section introduces the methodology for short-circuit calculation of OWPPs, which consists of two different levels. In particular, the outer loop updates the combination of WT converters’ current-saturation states, \( f \), iteratively. The inner loop defines and solves the system of equations \( SE_f \) following the combination number \( f \) provided by the outer loop.

1) Iteration of WT Converters’ Current-Saturation States:

The current-saturation state of a WT converter in a specific short-circuit fault scenario is usually uncertain. In other words, the short-circuit equilibrium point might exist corresponding to any of the \( F \) possible combinations of WT converters’ current-saturation states. Therefore, the various potential current-saturation states of WT converters should be considered when identifying the short-circuit equilibrium point of the studied system. A possible approach is to go through all the \( F \) combinations and solve the corresponding systems of equations, \( SE_f \forall f \in [1, F] \), respectively in order to identify the system equilibrium point that satisfies the WT converters’ operation limits [19], [20]. However, this approach is not suitable for the system with a large number of converters as it is computationally burdensome to traverse all the \( F \) possible
combinations (e.g. the OWPP studied in this paper with 83 WT converters yields $F = 3^{83} = 3.99 \times 10^{39}$ combinations).

This paper proposed an iterative methodology to deal with the challenge of short-circuit calculation of OWPP with a large number of WT converters. This methodology goes through only selected combinations in order to identify the short-circuit equilibrium point efficiently. In particular, a system of equations, $SE_f$, is solved in each iteration numbered $n_t \in [1, N_{f}^{\text{max}}]$, where $N_{f}^{\text{max}} < F$ is the maximum iterations number. The obtained solution, sol, from each iteration $n_t$ will be adopted as the evidence to choose the tested combination of converters’ saturation states, $f$, for the next iteration, $n_t + 1$. In particular, the WT converters’ current-saturation states are updated based on the limits in terms of CCP voltage magnitudes such that:

$$
\begin{align*}
&\begin{cases}
    \sqrt{p_{ref}^2 + q_{ref}^2} \leq u_{con} & \text{if USS} \\
    |q_{ref}| \cdot u_{con} \leq v_{\text{vsc}} & \text{if PSS}
\end{cases} \\
&\begin{cases}
    u_{lim}^{\text{USS}} \leq u_{con} \leq p_{ref}^2 + q_{ref}^2 & \text{if USS} \\
    u_{lim}^{\text{PSS}} \leq u_{con} < \sqrt{p_{ref}^2 + q_{ref}^2} & \text{if PSS}
\end{cases}
\end{align*}
$$

where $u_{lim}^{\text{USS}}$ is the lower limit of the CCP voltage magnitude for converter operated in USS and $u_{lim}^{\text{PSS}}$ is the upper limit for FSS. The current-saturation state of a WT converter, $x_n$, can be updated based on an obtained solution, sol, utilizing a function, $DS(sol, n)$, which is expressed as follows:

$$
x_n = DS(sol, n) = \begin{cases}
0 & \text{if } u_{lim}^{\text{USS}} - u_{con-1} < x_{n-1} \\
1 & \text{if } u_{lim}^{\text{PSS}} - u_{con-1} < x_{n-1} < u_{lim}^{\text{USS}} \\
2 & \text{if } u_{con-1} < u_{lim}^{\text{PSS}}
\end{cases}
$$

where $u_{con-1}$ is the CCP voltage magnitude of WT converter $n$, $u_{lim-1}$, and $u_{lim-1}^{\text{FSS}}$ are voltage limits for different current-saturation states of converter $n$ which can be calculated following (10). It should be noticed that only the current-saturation states of those converters whose operation limitations are violated in the solution from current iteration, $n_t$, will be modified in the next iteration $n_t + 1$.

2) Overall Process for Short-Circuit Calculation: The methodology to identify the short-circuit equilibrium point of OWPPs is summarized as shown in Algorithm 1. The proposed methodology requires the admittance matrix of the studied system circuit, $Y$, the constraints equations of WT converters, $H$, the function of VSCs operation limits, $VOL$, the function to update VSCs current-saturation states, $DS$, the initial combination, $f_0$, and the maximum iteration number, $N_t^{\text{max}}$, as the input information.

This methodology starts with an initial combination, $f_0$, and the corresponding system of equations, $SE_{f_0}$, will be solved in the first iteration. In particular, the Levenberg-Marquardt algorithm is adopted in this paper in order to solve the established system of equations, which can be implemented using the $fsolve$ function in MATLAB. Other iterative solver can be also adopted. The initial combination, $f_0$, is selected corresponding to all WT converters operated in USS for example in this paper. The tested combination $f$ for the upcoming iteration, $n_t + 1$, will be updated based on the solution, sol, obtained from the current iteration and following the $DS(sol, n)$ function expressed in (11). The iterative procedure will be terminated when a solution that satisfies all WT converters’ operation limits has been obtained and validated as the system equilibrium point. Besides, the iteration will be interrupted when the selected combination for the upcoming iteration, $f$, is repeated with any of the combinations tested previously to avoid the endless loop. In this case, a new combination number will be assigned in order to continue the iterative procedure. This new combination $f_{new}$ can be defined by the user or randomly selected from the combinations that have not been tested.

![Algorithm 1: The Methodology to Identify Short-Circuit Equilibrium Point](image)

<table>
<thead>
<tr>
<th>Algorithm 1: The Methodology to Identify Short-Circuit Equilibrium Point</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>input</strong>: Admittance matrix $Y$, Constraints $H$, VSCs operation limits $VOL$, Function to Update VSCs States $DS$, initial combination $f_0$, maximum iteration number $N_t^{\text{max}}$</td>
</tr>
<tr>
<td><strong>output</strong>: Identified equilibrium (eq.) point $EP$</td>
</tr>
<tr>
<td>$f = f_0$; begin</td>
</tr>
<tr>
<td>for $n_t \leftarrow 1$ to $N_t^{\text{max}}$ do</td>
</tr>
<tr>
<td>$F(t_n) = f$; // Save each tested combination No.</td>
</tr>
<tr>
<td>$SE_f := [Y; H]$;</td>
</tr>
<tr>
<td>sol = $fsolve(SE_f); \ [i_{\text{vsc}}, p, q] = sol; \ U_{\text{vsc}} = U_{\text{con}} + IVSCZ_{\text{vsc}}$;</td>
</tr>
<tr>
<td>if $VOL(i_{\text{vsc}}, p, q, u_{\text{vsc}})$ then</td>
</tr>
<tr>
<td>$EP = sol$; return $EP$; Break;</td>
</tr>
<tr>
<td>else</td>
</tr>
<tr>
<td>for $n \leftarrow 1$ to $N$ do</td>
</tr>
<tr>
<td>$x_n = DS(sol, n)$; // Evaluate states of all VSCs for the next iteration</td>
</tr>
<tr>
<td>$f = \sum_{n=1}^{N} g(n-1) x_n + 1$; // Update combination No.</td>
</tr>
<tr>
<td>if $find(f \in F_t)$ then</td>
</tr>
<tr>
<td>$f = f_{\text{new}}$; // Avoid endless loop</td>
</tr>
<tr>
<td>end</td>
</tr>
<tr>
<td>if $EP == \text{null}$ then</td>
</tr>
<tr>
<td>return ‘No Equilibrium Point’;</td>
</tr>
<tr>
<td>end</td>
</tr>
<tr>
<td>end</td>
</tr>
</tbody>
</table>

IV. NUMERICAL CASE STUDIES

Numerical case studies of short-circuit calculation have been presented in this Section for the studied OWPP with different locations and depths of fault. The parameters of the studied system are shown in Table II from the Appendix.

A. Short-Circuit Fault at WT Converter Connection Point

The short-circuit is implemented with the fault location at the LV network by inserting a fault impedance $z_{ft}$ to the CCP of WT converter 82. The short-circuit fault is firstly
tested with a moderate perturbation by inserting a high fault impedance, $\Delta z_{ft} = j2$ pu. The identified solutions obtained for each iteration following Algorithm I are shown in Table I. In particular, the current injection magnitude, power injections, power references, CCP voltage magnitudes and the voltage limits expressed in (10) of WT converter 1 and WT converter 82 are listed in order to illustrate the iterative procedure for short-circuit equilibrium point identification. The invalid solution is marked in gray and the specific value that violates the converters’ operation limits is highlighted in red. The short-circuit calculation initializes with the combination where all WT converters operate in USS (corresponding to Iteration 1 in Table I). The obtained solution for Iteration 1 is invalid as it violates the current-limitation of WT converter 82. Therefore, the current-saturation state of this converter is updated to PSS in Iteration 2 following the criterion expressed in (10) ($v_{ucon82} < u_{con82} < v_{USS82}$). The WT converter 1 remained in USS as its operation limits are not violated with the obtained solution. The solution obtained in Iteration 2 is identified as the short-circuit equilibrium point that satisfies all WT converters’ operation limits and the iterative procedure is terminated. The current-saturation states of all WT converters in this moderate fault scenario are marked with different colours in Fig. 3.

The methodology presented in this paper shows advantage in computing efficiency compared to the iterative approach proposed in [15]–[18] (the latter takes 10 iterations for short-circuit calculation of the studied system with only two WT converters). This is because different combinations of converters’ current-saturation states are modeled with different systems of equations in this paper and converters’ saturation states are updated in each iteration instead of modifying current reference values (the latter option might take several iterations for the same combination of saturation states).

The obtained short-circuit equilibrium point is also shown in Fig. 4 in terms of WT converter CCP voltage magnitude, $u_{con}$, converter current injection, $i_{vsc}$, as well as active and reactive power injections, $p$ and $q$. It can be observed that the seven WT converters with the closest distance to the fault location inject higher amount of grid-support reactive power during the fault in response to the reduced voltage. Therefore, they reduce the active power injections instead of following the constant dispatched value in order to prioritize the reactive power within the converter current limitation.

![Fig. 3. WT Converters’ Current-Saturation States During the Moderate Perturbation at LV Network](image)

![Fig. 4. Identified Short-Circuit Equilibrium Point with the Moderate Perturbation at LV Network](image)

**TABLE I**

<table>
<thead>
<tr>
<th>Solutions</th>
<th>Iteration 1</th>
<th>Iteration 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT Converter 1 State</td>
<td>USS</td>
<td>USS</td>
</tr>
<tr>
<td>$i_{vsc1}$</td>
<td>0.0111</td>
<td>0.0111</td>
</tr>
<tr>
<td>$p_{f1}$</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>$q_{f1}$</td>
<td>0.0018</td>
<td>0.0018</td>
</tr>
<tr>
<td>$u_{vcon1}$</td>
<td>0.9178</td>
<td>0.759</td>
</tr>
<tr>
<td>$u_{vcon1}$</td>
<td>0.8469</td>
<td>0.8467</td>
</tr>
<tr>
<td>$u_{vcon1}$</td>
<td>0.1509</td>
<td>0.1499</td>
</tr>
<tr>
<td>WT Converter 82 State</td>
<td>USS</td>
<td>USS</td>
</tr>
<tr>
<td>$i_{vsc82}$</td>
<td>0.0160</td>
<td>0.0162</td>
</tr>
<tr>
<td>$p_{f82}$</td>
<td>0.01</td>
<td>0.0083</td>
</tr>
<tr>
<td>$q_{f82}$</td>
<td>0.0042</td>
<td>0.0042</td>
</tr>
<tr>
<td>$u_{vcon82}$</td>
<td>0.7754</td>
<td>0.563</td>
</tr>
<tr>
<td>$u_{vcon82}$</td>
<td>0.9032</td>
<td>0.9033</td>
</tr>
<tr>
<td>$u_{vcon82}$</td>
<td>0.3483</td>
<td>0.3486</td>
</tr>
</tbody>
</table>

| Satisfying all converters’ Operation Limits? | \(\times\) | \(\sqrt{\checkmark}\) |
short-circuit calculation is also finished in the second iteration utilizing the proposed methodology. In this case, all of the WTs are operated with a saturated current during the fault as shown in Fig. 7. In particular, WT1-7 are operated in FSS while other WTs in PSS. This is because WT1-7 are close to the fault location. Therefore, they inject 0 active power in order to prioritize the reactive power injection required for grid voltage support during the fault as shown in Fig. 8.

C. Short-Circuit Fault at Onshore Grid

The short-circuit has also been tested with the fault location at the onshore grid by inserting a fault impedance, $\bar{z}_{ft} = j0.01$ pu, at the connection point to the onshore main grid as indicated in Fig. 9. The short-circuit equilibrium point is also identified in the second iteration following Algorithm 1. The identified short-circuit equilibrium point indicates that all of the WT converters are operating in FSS in this case as shown in Fig. 9. This is because the voltage levels among the whole offshore network have been severely reduced during this onshore grid short-circuit fault. In particular, the WT

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**Fig. 5.** WT Converters’ Current-Saturation States During the Severe Fault at LV Network

**Fig. 6.** Identified Short-Circuit Equilibrium Point with the Severe Fault at LV Network

**Fig. 7.** WT Converters’ Current-Saturation States During the Severe Fault at MV Network

**Fig. 8.** Identified Short-Circuit Equilibrium Point with the Severe Fault at MV Network
converters with closer distance to the WPP collector operate with a lower voltage at the converter connection points, which can be observed from the equilibrium point shown in Fig. 10. As a result, they also inject lower reactive power compared to the WT converters with further distance to the offshore collector under the limitation of current.

The identified short-circuit equilibrium points with different fault scenarios can be adopted as the basic information for protection design and WT converter control tuning of OWPPs. Further studies can be carried out to include the unbalanced voltage conditions in short-circuit analysis. In addition, the possible tripping-off of WT converters can be considered in short-circuit calculation using the similar methodology as proposed in this paper. Also, the adopted system formulation can be revised to include the DC link and generator of each WT.

APPENDIX

Part of the studied system parameters are listed in Table II.

V. CONCLUSION

This paper presents a novel methodology for short-circuit calculation of OWPPs, which are penetrated with a large number of VSCs. The studied system is modeled with an element-based formulation where the grid-support control and potential current-saturated operation of WT converters are included. Then, the short-circuit equilibrium point is identified following the iterative algorithm proposed in this paper. In particular, the current-saturation state of each WT converter is updated iteratively in order to obtain the system operation point that satisfies all converters’ operation limits.

Numerical case studies indicate that the proposed methodology is able to identify the short-circuit equilibrium point efficiently for the studied system with a large number of WT converters. Also, the WT converters with a close distance to the fault location are more likely to operate in a current-saturated state during the fault. This is because they are required to inject a high amount of reactive power to support the grid voltage. This is especially critical with a severe fault where all WT converters are saturated.

### REFERENCES


