The Effect of the Offshore VSC-HVDC Connected Wind Power Plants on the Unbalanced Faulted Behavior of AC Transmission Systems

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Abstract—This paper studies the effect of the negative sequence current control scheme of a VSC-HVDC system on the positive, the negative and the zero sequence voltage and current components of the AC transmission networks during sustained unbalanced AC faults. It is assumed for this paper that the protection schemes in the AC transmission network fails. Hence, the unbalanced fault is sustained for longer time period. In this frame the response of AC transmission system is observed for two different applied negative sequence current control strategies at the onshore converter station.

It is shown that the suppression of the negative sequence current, as it is mainly performed by vendors today or required by TSOs, might lead to difficulties in the detection and the isolation of the line to line AC faults. On the other hand, the case of negative sequence current injection proportionally to the negative sequence voltage, improves the ability to detect line-to-line faults close to the converter terminals. This paper uses detailed PSCAD/EMTDC time-domain simulations supported by a linear circuit analysis in the positive, the negative and the zero sequence circuits.

Index Terms—Negative sequence current control, VSC-HVDC, Offshore wind power plants, power system protection.

I. INTRODUCTION

For radial AC networks, the coordination of the overcurrent relays is performed by obtaining the correct short circuit current at the AC terminals where relays are installed. During unbalanced faults, any conventional generation unit behaves as a voltage source in the positive sequence circuit ensuring high fault currents. However, this is not the case for AC/DC converter interfaced generation and VSC-HVDC transmission units. They respond as a controlled current source in the positive and the negative sequence circuit, while the zero sequence circuit is mostly an open circuit due the transformer configuration. Most vendors today suppress the negative sequence current during unbalanced voltage conditions. This is done either to protect the switching valves from uncontrolled fault currents or following the grid code provisions made by the transmission system operators (TSO) who are responsible for the design of the protection schemes in the high voltage AC transmission lines.

Lately in [1] the authors have discussed the effect of the negative sequence current control scheme of full converter interfaced wind power plants on the AC transmission lines protection schemes. Based on the Network Code HVDC released by ENTSOe, the relevant TSO has the right to impose grid code requirements related to fault current contribution of the HVDC system during line to ground and line-to-line faults.

Different strategies for the control of the negative sequence current have been proposed in the literature in order to minimize the well documented negative effect that unbalanced grid voltages have on the response of AC-DC power converters [2-3]. In [4], a double synchronous reference frame control scheme is studied for a four-level VSC-HVDC system which provides elimination of double frequency power ripples. In [5] a current management control scheme is proposed in order to improve the overloading capability of the VSC-HVDC system during unbalanced faults. In [6] the effect of the unbalanced faults at the offshore AC collector grid for DC connected offshore wind power plants is demonstrated. Lately, negative sequence current control is extended towards the modular multilevel VSC-HVDC systems [7-8].

This paper gives insights on the effect of the negative sequence current control scheme of the VSC-HVDC system delivery of the offshore wind plants on the positive, the negative and the zero sequence voltages and currents measured at the 380kV AC transmission network. Single line-to-ground and line-to-line faults are studied by means of EMT type numerical simulations using PSCAD/EMTDC. Equivalent linear circuits of the AC-DC transmission system in the positive, the negative and in the zero sequence are presented in order to analyse and explain the obtained simulations results. Difficulties in the detection and protection of unbalanced fault are stressed and linked to the choice of the negative sequence current control.

II. DOUBLE SYNCHRONOUS REFERENCE CONTROL FOR INJECTION OF NEGATIVE SEQUENCE CURRENT

The common approach to control the positive and the negative sequence current injection of an AC-DC power
Suppression of the Negative sequence Current

The negative sequence current of the onshore converter station can be suppressed to the zero value during unbalanced voltages by applying the control reference as:

\[ i_{\text{ref}}^{d} = 0 \]  
\[ i_{\text{ref}}^{q} = 0 \]  

In this case the reference of positive sequence current in the positive SRF becomes [1-2]:

\[ i_{\text{ref}}^{d+} = \frac{2}{3} \frac{u_{s}^{d+} P_{\text{ref}} + u_{s}^{q+} Q_{\text{ref}}}{u_{s}^{d+}} \]  
\[ i_{\text{ref}}^{q+} = \frac{2}{3} \frac{u_{s}^{d+}}{u_{s}^{q+}} \]  

Where \( P_{\text{ref}} \) and \( Q_{\text{ref}} \) are the active and the reactive power references of the converter. As shown in [1], during the unbalanced fault period a double frequency component exists in the active and reactive power components. The second approach which is evaluated in this paper is the injection of negative sequence current proportionally to negative sequence voltage.

Injection of negative sequence current proportionally to negative sequence voltage

The second approach which is evaluated in this paper is the injection of the negative sequence current proportionally to the negative sequence voltage at the PCC. The motivation for such approach is the enhancement of the ability to detect and isolate unbalanced faults close to the AC terminals of the converter station. A proportional controller is used here, with a proportional gain equal to \( k_{2} \). During balanced conditions, the \( dq \)-voltage components in the negative SRF are zero while during unbalanced faults they are increased. In this way the amplitude of the negative sequence voltage can be used in order to inject proportionally negative sequence reactive current. The applied conditions are:

\[ i_{\text{ref}}^{d'} = 0 \]  
\[ i_{\text{ref}}^{q'} = k_{2} \sqrt{(u_{s}^{d'})^{2} + (u_{s}^{q'})^{2}} \]  

III. Test System Used for Analysis

A detailed EMT type switch model of a two-level VSC-HVDC system has been used for assessment of the unbalanced fault response of the onshore converter station. The grid side VSC station (GSVSC) is connected to the infinite grid via a 30km transmission line at 380kV voltage levels. The 380kV line is connected to an infinite grid with a 30GVA short circuit power. The fault location for the different unbalanced faults will be the midpoint of the 380kV transmission line. The fault is self-cleared for this paper analysis. Although the focus is mainly placed on the onshore converter station, a complete model of the VSC-HVDC system and the connected wind plants is used as presented in figure 2. Finally, the classical chopper based method is utilized as FRT strategy of the VSC-HVDC system triggered at 1.05 p.u (pole-pole) DC link voltage.
IV. EFFECT OF THE VSC-HVDC NEGATIVE SEQUENCE CURRENT CONTROL ON POSITIVE, NEGATIVE AND ZERO SEQUENCE COMPONENTS

1) Single-line-to-ground fault (SLG) at the onshore converter

Figure 3 presents the positive, negative and the zero sequence circuits of the onshore transmission grid for the case of SLG fault as applied in figure 2. The step up transformer of the onshore converter station, which is a star/grounded-delta configuration, does not allow the transfer of the zero sequence current component to the external AC transmission system circuit. Hence, the applied control schemes at the onshore converter station affect only the positive and the negative sequence currents between the converter and the external grid for the single line to ground fault case.

When the negative sequence current at the delta side of the transformer is suppressed (given also that there is no zero sequence current at the delta side of the transformer) the fault current injection of the converter (i\text{VSC}) contains only the positive sequence current component. Its amplitude depends on the reactive current boosting gain (k_1 in figure 3) as given in most grid codes [1].

When the negative sequence current of the onshore converter station is suppressed (given also that there is no zero sequence current at the delta side of the transformer) the fault current injection of the converter (i_{\text{VSC}}) contains only the positive sequence current component. Hence, the applied control schemes at the onshore converter affects only the positive and the negative sequence. Hence, its behaviour needs to be carefully assessed, especially during unbalanced LL faults and be integrated in the protection schemes studies of the AC networks.

2) Line to line (LL) fault at the onshore converter

Figure 4 presents the onshore external circuit for a line to line fault (LL) applied at the onshore converter station and the external grid for the line-line fault case study. When the negative sequence current of the onshore converter station is suppressed (given also that there is no zero sequence current at the delta side of the transformer) the fault current injection of the converter (i_{\text{VSC}}) contains only the positive sequence current component. Hence, the applied control schemes at the onshore converter affects only the positive and the negative sequence. Hence, its behaviour needs to be carefully assessed, especially during unbalanced LL faults and be integrated in the protection schemes studies of the AC networks.
V. SIMULATION RESULTS AND DISCUSSION

A. Single line to ground fault

1) Simulation results for \( k_1=0 \) and \( k_2=0 \)

Initially it is assumed that the negative sequence current component of the onshore converter is suppressed applying references (1) and (2). Furthermore, for this case we assume that the converter is not injecting any positive sequence reactive current which means that the \( k_1 \) gain (which defines the reactive current injection) is also zero. Most grid codes require for reactive positive sequence current injection only during balanced three phase faults. In addition, in order to avoid unwanted transients, especially during the post-fault period the PI controller state of the direct voltage control loop is set to freeze mode during the unbalanced fault period. The FRT scheme is active takes care of DC overvoltages.

Figure 5 presents the results for this case study in the sequence components. Since, the negative sequence current is suppressed by the converter control scheme, \( i_{pcc} \) current consists of only the zero sequence (from the external grid) and the positive sequence from the converter. Figure 6 presents the instantaneous current of the converter station through the phase reactor \( i_{vsc} \). Figure 7 presents the instantaneous values of the currents at PCC (380kV terminal) and at the infinite grid terminals of the 380kV transmission line (\( i_{grid} \) and \( u_{grid} \)). Since the external grid is represented as a voltage source in the positive sequence circuit, the voltage and the current at the infinite grid terminals contain positive, negative and zero sequence components. Finally, the dynamic behavior of the HVDC link voltage, the active power at the onshore HVDC converter, the dissipated power at the chopper and the active power of the offshore converter is presented. In the response of the direct voltage it can be observed the presence of the second harmonic oscillation. Its amplitude does not justify the need for additional control loops as in [3,4,5] (at least not for faults in the AC transmission system). Finally, it is worth observing the operation of the FRT scheme (chopper in this case) during the unbalanced fault period. Since the positive sequence voltage drops to 0.5 p.u, the active power drops and this power imbalance in the HVDC link is balanced by the FRT scheme.

1) Simulation result with the case where \( k_1=0 \) and \( k_2=2 \)

The alternative approach is to control the negative sequence as in (5) and (6). As it can be observed in figure 8, during a single line to ground fault, the negative sequence voltage component rises and in this way triggers the injection of the negative sequence current. In this case, the negative sequence current is present in the PCC point and the converter behaves similar to a conventional generation unit. The current at the PCC point is the sum of the positive, the negative and the zero sequence current. At the phase reactor, the sum of the positive and the negative sequence current must be always below or equal to the overcurrent capacity of the converter station. The zero sequence current is not present at the phase reactor due to the transformer as explains above.

![Figure 5. Response of the VSC-HVDC link for a single-line to ground fault. From top to bottom, the sequence voltages and currents at PCC, the current at infinite grid terminal of the AC transmission and the dq-currents in the negative sequence frame.](image)

![Figure 6. Response of the VSC-HVDC onshore station for a single-line to ground fault. From top to bottom, the sequence voltages and currents at PCC, the current at infinite grid terminal of the AC transmission and the dq-currents in the negative sequence frame.](image)
injected proportionally to the negative sequence voltage.

B. Line-to-line fault

1) Case where \(k_1=0\) and \(k_2=0\)

Again the reactive current boosting gain \(k_1\) is set to zero, where the negative sequence current is suppressed as shown in figure 9. Since there is no negative sequence current contribution from the converter, the positive sequence voltage at the PCC of the converter station is almost equal to the negative sequence voltage with only difference the voltage drop at the half of the transmission line (see figure 4), which is here marginal. The negative sequence current component drops to zero as a result of the negative sequence controls while the positive sequence is equal to the steady state value since the \(k_1\) is zero. In this way it can be seen that the fault current contribution of the converter is the steady state value.

1) Case where \(k_1=0\) and \(k_2=2\)

Finally, the case where the converter injects negative sequence current as in (5) and (6) is presented in figure 10. A \(k_2\) gain of value 2 p.u is chosen for this case. The injection is provided only to the negative sequence q-axis component as it can be seen in figure 10. Contrary to the results of figure 9 where \(k_1\) is zero, in the present case, the converter current is asymmetrical as both negative and positive current injections are present. Hence, additional current limitation control schemes need to be applied in order to ensure that the combined positive and negative sequence current injection would be limited to 1.1p.u. This is the typical overcurrent capacity that VSC-HVDC vendors provide and is adopted here.

VI. DISCUSSION

During single line to ground faults at the 380kV transmission system, the fault current at the PCC consists of only the zero and the positive sequence component in case that the negative sequence component is suppressed. The zero sequence current cannot be affected at all by the converter control scheme due to the transformer configuration. The zero sequence is determined by the external transmission system.
parameters (i.e. transformer grounding resistance and overhead lines electrical parameters). In cases where the infinite grid short circuit power is low, it might lead low zero sequence currents. When the negative sequence current is injected proportionally to the negative sequence voltage, the fault current at the PCC is increased by the amount of negative sequence current provided by the converter. The latter does not depend on the external grid conditions and enhances the capability to detect and isolate single line to ground faults as it increases the amplitude of fault current measured at the PCC. Moreover, for line-to-line faults, since there is no zero sequence current present at all in the external grid, the suppression of the negative sequence current leads to fault currents that are in the steady state value. In that prospect, the injection of the negative sequence current proportionally to the negative sequence voltage enhances significantly the amplitude of the fault current at the PCC.

The challenge for the implementation of the negative sequence current injection would be the need for additional over-current capacity at the converter station (above the typical 1.1pu value vendors provide today). Since most of the VSC-HVDC converters shall continue to provide a positive sequence active current during unbalanced faults, the injection of a negative sequence current next to the positive sequence current during unbalanced faults might be only marginal due to limited overcurrent capacity (usually 1.1pu). Hence, in order to provide a parallel negative sequence current injection either the positive sequence active or reactive current should be reduced or the overcurrent capacity of the converter could be increased to facilitate the unbalanced fault current. Although, the reduction of the active current seems as a more logical solution (as it is already the approach followed during symmetrical faults where active current is reduced to provide reactive current), it might create frequency stability concerns, let alone that it increases the stresses at the FRT scheme. Reduction of the positive sequence reactive current is possible only if it does not infringe the fast positive sequence reactive fault current injection as a matter of voltage support. All these solutions might increase the cost of the equipment.

VII. CONCLUSIONS

This paper presents the effect of the negative sequence current control of the VSC-HVDC system delivery of the offshore wind power plants on the unbalanced faulted response of the 380kV AC transmission system. Single line to ground and line to line faults are studied. Two cases are evaluated, namely the negative sequence current suppression and the negative sequence current injection. It is shown that negative sequence current injection enhances the fault detection capability which would improve the protection schemes performance. This becomes important in future power systems where the short circuit power levels will be dramatically reduced as a result of the power electronic interfaced generation fleet. Finally, future research efforts will assess the dynamic response and the protection needs at the isolated offshore AC collector grid system.

VIII. REFERENCES